Wetting hydraulic properties of cracked soils

Sugeng Krisnanto

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OF CRACKED SOILS**

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**SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY**

SINGAPORE

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ABSTRACT

In the field, desiccation cracks in soil occur commonly at the ground surface. The presence of cracks results in an increase in water flow rate in this zone due to lesser resistance to flow of water through crack openings. Some models have been proposed previously to analyse flow through cracked soils. However, a model to quantify lateral flow rate through a cracked soil and a model to analyze change of water content of cracked soil incorporating an actual crack network in the soil has not been fully developed. Laboratory experiments to investigate performance the model also need to be performed. In addition, variation of crack network in the soil need to be incorporated in the model.

In this study, a framework to analyze lateral flow through cracked soil was developed. The framework consists two aspects: a model to calculate flow rate through the crack network and a method to analyze change in water content and matric suction of a cracked soil. In this study, the crack network in the soil is idealized as series of linear cracks. In the proposed model to calculate flow rate through the crack network, the flow through a single crack is modelled as a flow through parallel plates and the flow rate through the idealized crack network is calculated by incorporating the conservation of mass principle and the additional head losses due to the change in crack aperture. In the proposed method to analyse change in water content of cracked soils, the idealized crack network is modelled as head boundary conditions and the boundary conditions are then incorporated in a numerical analysis. In addition to that, average water content and average matric suction was proposed to represent the variation in water content and matric suction in a horizontal plane of a cracked soil.

Experiments were performed to investigate performance of the proposed model. The experiments mainly consisted of small and large scale lateral flow tests. Small scale and large scale lateral flow apparatuses were developed to perform the tests.

The large scale lateral apparatus was developed to capture large number of cracks in the specimens. Cracked soil specimens were obtained by desiccating the soil in room temperature. Flow rates were measured during the lateral flow tests. Water contents were measured during and at end of tests. Instrumentations were utilized to measure change of water content during one of the large scale lateral flow tests.

Numerical analyses were performed to investigate performance of the proposed model to analyze change in water content and matric suction of the cracked soil. The results obtained from numerical analyses were compared with those obtained from laboratory experiments.

A parametric study was performed to investigate the effect of variation of crack network on change in water content and matric suction of cracked soils. A computer code to generate random crack networks was developed. The computer code generates random crack network from the statistical parameters of the crack network. Connectivity among cracks endpoints are incorporated in the calculation to imitate the desiccation crack network in soils which is interconnected each other. Numerical analyses using the proposed method of change in water content were performed incorporating variation of crack networks.

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 crack network quite well. Proposed method to analyze change in water content and matric suction of a cracked soil was also able to predict change in water content and matric suction of cracked soils. The results were closer to the measured values than those obtained by modelling the cracked soil as a continuum. This finding indicated that in order to model change in water content and matric suction of cracked soils, the cracks should be modelled as head boundary conditions. In addition, the parametric study showed that with the same statistical parameters of crack network, different average of water content and matric suction can be obtained. Values of maximum variations in average water content and average matric suction were found in this study.

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LIST OF SYMBOLS

a_f	= fitting parameter in Fredlund and Xing soil-water characteristic equation that is primarily a function of air-entry value of soil
b	= crack aperture
e	= voids ratio
err_b	= error ratio of the representative crack aperture
err_h	= error ratio of the head loss
g	= gravitational constant
h_c	= capillary height
h	= head difference
h_l	= additional head loss due to aperture change in a single crack
h_{lc}	= head loss due to crack aperture contraction
h_{le}	= head loss due to crack aperture enlargement
h_w	= hydraulic head
i	= hydraulic gradient
k	= coefficient of permeability
k_s	= saturated coefficient of permeability
k_{sc}	= calculated saturated coefficient of permeability
k_w	= unsaturated coefficient of permeability
$k_w(\theta_w)_i$	= predicted water coefficient of permeability for a volumetric water content, θ_w , corresponding to the i th interval (m/s)
m_f	= fitting parameter Fredlund and Xing soil-water characteristic equation that is primarily a function of the residual water content
n_f	= fitting parameter Fredlund and Xing soil-water characteristic equation that is primarily a function of the rate of water extraction from soil once the air-entry value has been exceeded
n	= porosity
p	= water pressure
q	= flow rate through a single crack

List of Symbols

t_s	= soil thickness
t	= time
$(u_a - u_w)$	= matric suction
v	= water flow velocity
w	= gravimetric water content
w_s	= saturated gravimetric water content
x	= x -axis (i.e., horizontal)
y	= elevation
A	= cross section area
A_c	= the area of the vena contracta
A_d	= adjusting constant in the indirect computation of permeability function
K_c	= the head loss coefficient due to contraction.
K_e	= the coefficient of head loss due to crack enlargement
G_s	= specific gravity
H_j	= total head at crack intersection point
LL	= liquid limit
M	= mass of the soil specimen
M_s	= mass of solids
M_w	= mass of water
PL	= plastic limit
R^2	= coefficient of determination
Q	= flow rate through the crack network in the soil specimen
S	= degree of saturation
SL	= shrinkage limit
V	= volume of soil
V_s	= volume of solids
V_v	= volume of voids
V_w	= volume of water
γ_d	= dry unit weight of soil
θ_s	= saturated volumetric water content
θ_w	= volumetric water content
ρ_w	= density of water

ρ_s	=	density of solids
ν	=	kinematic viscosity of water

CHAPTER 1

INTRODUCTION

1.1 Research Background

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 soil to shrink. Shrinkage causes tensile stress to develop in the soil. Desiccation cracks are then formed. Cracks occur at locations where the soil tensile strength cannot sustain tensile stress. Because of the heterogeneity of the soil, the locations where tensile stress is greater than soil tensile strength are difficult to predict. A random distribution function can be used to characterize crack networks (e.g., Li and Zhang, 2010).

The presence of cracks results in an increase in the water flow rate through the soil due to the lower resistance of water to flow through crack openings. When water fills the cracks in the soil and flows laterally through the crack network, the pore-water pressure or matric suction in the soil matrix will change as water seeps laterally from the cracks into the soil matrix. Changes in matric suction will result in changes in shear strength and consequently in the stability of earth structures. Numerous studies have shown that lateral flow can influence hillside hydrology (Sinai and Dirksen, 2006; Torres et al., 1998; McCord and Stephens, 1987; Sinai et al., 1981; Hewlett and Hibbert, 1963). Cracks can increase lateral flow rate through agricultural fields (Inoue, 1993). Cracks can also increase lateral flow rate through cracked soil beneath an impermeable slab (Fredlund et al., 2010). The increase in lateral flow rate indicates that the method of seepage analysis for intact soil cannot be directly used to predict lateral flow rate or analyse changes in matric suction due to flow in cracked soil. Therefore, there is a need to study the characteristics of water flow through the crack network of cracked soil and changes in matric suction in the matrix of cracked soil.

Several researchers have proposed methods to analyse flow through cracked soil. Generally, there are two methods of analysing flow through cracked soil: the first method is to model cracked soil as a continuum (e.g., Li et al., 2011, Fredlund et al., 2010) and the second method is to model the cracks and soil matrix separately (e.g., Novak et al., 2000; van Dam, 2000).

In the first method, the cracks are considered as macropores. The soil-water characteristic curve (SWCC) and permeability function are the properties of the continuum that represents the cracked soil. The SWCC of the cracked soil is generated by combining the SWCC of the intact soil matrix and the SWCC of the crack network. Several methods have been proposed to compute the permeability function incorporating the SWCC of the soil matrix and the aperture of the cracks.

In the second method, water directly fills the cracks and seeps into the soil matrix. The crack network is then modelled as parallel cracks (e.g., Novak et al., 2000) or polygons (e.g., van Dam, 2000).

The previous studies only analysed flow through cracked soil with limited aspects. Some studies only considered the development of a theory and implemented the theory using a hypothetical crack network in numerical analyses (e.g., Li et al., 2011; Fredlund et al., 2010; Novak et al., 2000). Some studies only considered the measurement of water content in cracked soil (e.g., Bronswijk et al., 1995; Beven and Germann, 1982). In some research, lateral flow rate measurements in cracked soil were only performed in saturated conditions (e.g., McKay et al., 1993). In other works, the idealized crack networks used in the analyses were only obtained from estimation (e.g., Novak et al., 2000; van Dam, 2000). A comprehensive study to develop a framework to analyse flow through cracked soil that includes obtaining a crack network from the cracked soil specimen, developing a model to predict the lateral flow rate through cracked soil, developing a model to analyse changes in water content and matric suction in the matrix of cracked soil, and performing laboratory tests and numerical analyses to assess the performance of the model has not been performed.

1.2 Statement of Problems

A theory that provides a framework to analyse lateral flow rate through cracked soil needs to be developed. This theory should incorporate a method of obtaining and idealizing a crack network in cracked soil, a model to predict the lateral flow rate through cracked soil, and a method to analyse changes in the water content and matric suction in the matrix of cracked soil. Laboratory experiments and numerical analyses are then needed to assess the performance of the proposed theory.

1.3 Objectives

The objective of this study is to propose a theory that provides a framework to analyse lateral flow rate through the crack network of cracked soil and to analyse changes in the water content and matric suction in the matrix of cracked soil. The theory should also include a method for obtaining an idealized crack network from the crack network observed in the soil.

1.4 Methodology and Scope of the Research

The research mainly consists of the development of a theory, laboratory experiments, and numerical analyses investigating the performance of the theory. The theory includes a model to predict the lateral flow rate through the crack network of cracked soil and a model to analyse changes in the water content and matric suction in the matrix of cracked soil due to lateral flow. In the development of the theoretical model, the method for the idealization of the actual crack network was developed first. The model to predict the flow rate through the crack network of cracked soil and the method to analyse changes in water content and matric suction of the matrix of cracked soil were then developed. The model was based on the non-continuum approach. The idealized crack network was also incorporated into theory development.

In the laboratory experiments, the soil type used in the experimental programme was characterized. A large-scale lateral flow test apparatus was developed. Lastly, lateral flow tests were performed. The lateral flow rate and water content were measured at several locations in the cracked soil specimen.

The performance of the model to predict the lateral flow rate through cracked soil was assessed by comparing the results obtained from the tests and the results obtained using the proposed model. Numerical analyses were also performed to further investigate the performance of the model.

The performance of the method to analyse changes in the water content and matric suction in the matrix of cracked soil was assessed by performing numerical analyses and comparing the water content values obtained from the laboratory tests and those obtained from the numerical analyses. In addition, a parametric study was performed to investigate the effect of variation in the crack network to changes in the water content and matric suction of the cracked soil.

1.5 Outline of the Thesis

This thesis consists of seven chapters and is organised in the following manner:

Chapter 1 presents the research background, a statement of problems, the objectives, the methodology, the scope of the research, and an outline of the thesis.

Chapter 2 summarizes the literature review about water movement through unsaturated soil, the formation of cracks in soil, the quantification of crack networks, and the existing methods of analysis of flow through cracked soil

Chapter 3 explains the development of the theory providing a framework to analyse lateral flow through cracked soil, specifically a model to predict the flow rate through the crack network of cracked soil and a method to analyse changes in the water content and matric suction in the matrix of cracked soil.

Chapter 4 describes the research programme including the laboratory tests, the design of the lateral flow test apparatus, the numerical analyses, and the parametric study.

Chapter 5 presents the results of laboratory experiments. The lateral infiltration test results, desiccation test results, and elemental test results (SWCC and saturated permeability) are presented.

Chapter 6 presents a discussion about the results obtained from the laboratory tests, the application of the proposed model to predict lateral flow rate, and the use of the proposed method to analyse changes in water content and matric suction.

Chapter 7 presents the conclusions drawn from this study. Recommendations for future research are also presented in this chapter.

Three appendices are included with this thesis as follows:

Appendix A presents details of the laboratory test results.

Appendix B presents calibration chart for ICT instrument used in the large-scale lateral flow test.

Appendix C presents the scripts of the computer code developed to generate the crack networks and an example of input and output files.

2CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the results from previous studies that are relevant to the present study. A review of the literature on water movement through unsaturated soils is presented first in Section 2.2. A review of the literature on the formation of cracks in soil and quantification of crack networks is then presented in Section 2.3. A review of the existing methods of analysis of flow through cracked soil is presented in Section 2.4. Finally, the concepts used in this study are presented in Section 2.5.

2.2 Water Movement through Unsaturated Soils

2.2.1 Soil-water Characteristics Curve

Soil-water characteristic curve (SWCC) describes the relationship between water content and matric suction in soil. For each matric suction in soil, there is a corresponding water content. SWCC is formulated as a plot of water content against matric suction. SWCC can be identified using some parameters such as the air-entry value (AEV), transition zone, residual water content and residual suction, as shown in Figure 2.1. AEV is defined as the matric suction value at which air first enters the pores of the soil in the drying path (Brooks and Corey, 1964). The residual water content is defined as the water content at which further increases in matric suction do not result in significant decreases in the water content. The matric suction corresponds to the residual water content is called residual matric suction. The transition zone lies between the AEV and the residual matric suction. In transition zone, there is a significant decrease in water content as the matric suction increases.

Figure 2.1 Typical drying SWCC (Fredlund et al., 2012)

There are two paths of SWCC, the drying and wetting paths (Figure 2.2). In the drying path, the water content of a soil decreases as its matric suction increases. In the wetting path, the water content of a soil increases as its matric suction decreases. SWCC follows different paths during drying and wetting processes. The difference paths between the drying and wetting SWCCs can be explained using the capillary rise model as shown in Figure 2.3. The presence of the bulb at the midheight of the capillary height, h_c , prevents water from rising up beyond the base of the bulb (Figure 2.3c). This condition represents the wetting process. On the other hand, the capillary height, h_c , can be fully developed if the bulb is filled by submerging the tube below the water surface and then raising it above the surface (Figure 2.3d). This condition represents the drying process.

Figure 2.2 Typical SWCC for silt (Fredlund et al., 2012)

Figure 2.3 Height of capillary rise (from Taylor, 1948)

SWCC data is obtained by measurements made in the laboratory. The measured data (Figure 2.1) are then fitted using a fitting curve equation. Fredlund and Xing (1994) fitting equation is one such fitting curve equation. This equation has the form:

$$\theta_w = \theta_s \left[\frac{1}{\ln \left[\exp(1) + \left(\frac{\psi}{a_f} \right) \right]^{n_f}} \right]^{m_f} \quad (2.1)$$

where:

a_f = fitting parameter in Fredlund and Xing soil-water characteristic equation that is primarily a function of air-entry value of soil

n_f = fitting parameter Fredlund and Xing soil-water characteristic equation that is primarily a function of the rate of water extraction from soil once the air-entry value has been exceeded

m_f = fitting parameter Fredlund and Xing soil-water characteristic equation that is primarily a function of the residual water content

This equation has been found to perform well for fitting SWCC data of different soils (Leong and Rahardjo, 1997) and is therefore used in this study.

2.2.2 Permeability Function

The flow through saturated soil can be described using Darcy's law (D'Arcy, 1856):

$$v = ki \quad (2.2)$$

where:

v = the water flow velocity

k = the coefficient of permeability

i = the hydraulic gradient

Darcy's law also applies to unsaturated soil (Childs and Collis-George, 1950). However, instead of having a constant k , in unsaturated soil k varies with matric suction. The variation of permeability with matric suction is called the permeability function (Fredlund and Rahardjo, 1993).

This measurement can take a long time (Fredlund and Rahardjo, 1993). To overcome this problem, an indirect method may be used (Fredlund and Rahardjo, 1993). In this method, the permeability function is computed from a SWCC. The computation is performed following these steps:

- Divide the SWCC into a number of water content interval and find the midpoint of the water content for each water content interval (Figure 2.4)
- Find the matric suction corresponding with each midpoint of water content
- Apply Eq. (2.3) to calculate the permeability for each value of matric suction.

Figure 2.4 Calculation of the water coefficient of permeability function from the SWCC (after Marshall, 1958; Kunze et al., 1968)

$$k_w(\theta_w)_i = \frac{k_s}{k_{sc}} A_d \sum_{j=1}^m \left\{ (2j+1-2i)(u_a - u_w)_j^{-2} \right\} \quad (2.3)$$

$$i = 1, 2, 3, \dots, m$$

where:

$k_w(\theta_w)_i$ = predicted water coefficient of permeability for a volumetric water content, θ_w , corresponding to the i th interval (m/s)

i = interval number, which increases as the volumetric water content decreases

j = a counter from " i " to " m "

m = the total number of intervals between the saturated volumetric water content, θ_s , and the lowest volumetric water content on the experimental SWCC, θ_l

k_s = measured saturated coefficient of permeability

k_{sc} = calculated saturated coefficient of permeability

A_d = adjusting constant

The value of k_{sc} is computed as follows:

$$k_{sc} = A_d \sum_{j=1}^m \left\{ (2j+1-2i)(u_a - u_w)_j^{-2} \right\} \quad (2.4)$$
$$i = 1, 2, 3, \dots, m$$

A value of A_d equal to 1.0 was recommended by Fredlund and Rahardjo (1993) in their calculations of the unsaturated coefficient of permeability.

2.2.3 Seepage through Soils

Seepage of water into intact soil is calculated using a differential equation. The differential equation is discussed in Section 3.4.

2.2.4 Lateral Flow through Intact Soils

Some previous studies have indicated the existence of lateral flow through intact soils. Sinai and Dirksen (2006), Hewlett and Hibbert (1963), Sinai et al. (1981), McCord and Stephens (1987), and Torres et al. (1998) have reported the occurrence of downslope lateral flow in sloping soil even under unsaturated conditions. Therefore, it is clear that lateral water flow through intact soil on a sloping surface can influence hillside hydrology.

2.2.5 The Presence of Cracks Changes the Nature of Flow through Soil

The presence of cracks can change the nature of infiltration into soil. The presence of cracks in soil significantly modifies the transport processes that occur in the soil profile. For example, cracks often result in preferential flow and faster movement of gas, water, solutes, and particles than would be expected from the soil matrix properties (Allaire et al., 2009). Bronswijk (1990) indicated that soil cracking results in high potential infiltration rates and storage capacities due to the formed bypass flow.

The volume of cracks increases the retention of water during rain. The increase of water retention prevents the formation of surface runoff (Allaire et al., 2009;

Simunek et al., 2003; Chertkov and Ravina, 1999; Novak, 1999; Favre et al., 1997; Tuong et al., 1996; Mitchell and van Genuchten, 1993; Bouma and Wosten, 1984). The permeability of cracked soils is typically several orders of magnitude greater than that of intact soils (Albrecht and Benson, 2001; Boynton and Daniel, 1985).

2.2.6 Lateral Flow through Cracked Soils

When rainwater enters cracked soil on a sloping surface, it flows laterally through the crack network and seeps into the soil matrix. As water moves through the crack network 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 occurrence of cracks in the soil mass influences the lateral water flow through the soil. McKay et al. (1993) performed a lateral flow test and found that cracks increase the saturated permeability of soil. These studies indicate that cracks change the flow characteristics of soil. A study of flow through cracked soil is therefore needed.

2.3 Formation of Cracks in Soil and Quantification of Crack Networks

2.3.1 Formation of Cracks in Soil

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). Formation of cracks in soil has been investigated in previous studies. Ruland et al. (1991) and Morris et al. (1992) investigated the development of desiccation cracks and found that cracks are mostly vertical. Konrad and Ayad (1997) investigated the development of desiccation cracks and found that two stages of crack development occurred: primary and secondary stages. The crack networks resembled polygon shapes.

Kodikara et al. (2000) found that cracks grow in a predominantly orthogonal and sequential manner. Primary cracks occur first, followed by secondary cracks that subdivide the initial crack network. The crack network were quantified using

equal-sided polygons such as squares, triangles, and hexagons. The soil matrices enclosed by cracks were described as "blocks" or "cells".

Atique et al. (2010) performed desiccation tests to observe the initiation of cracks, the propagation of cracks, the water content when cracks initiated, the influence of specimen thickness, and the shape and base of the specimen containers. They found that the water content at the initiation of cracks increased as the specimen thickness increased. They also found that the cracks first divided the soil into large cells and subsequent desiccation divided the cells into smaller cells. A soil matrix enclosed by cracks was described as a "cell." In addition, skeletonisation processes on pictures of cracked soils were performed and the length and average width of the crack network were measured.

Li and Zhang (2010) investigated the mechanisms of initiation and development of desiccation cracks. The results show that desiccation cracks developed in three stages: initial stage, primary stage, and steady state stage. The cracks were found to repeat during three drying–wetting cycles.

Tang et al. (2011) performed experimental tests of shrinkage and desiccation cracking in thin clay layers and found that:

- Shrinkage only occurs from vertical deformation before crack initiation. After crack initiation, the vertical deformation rate decreases while the lateral shrinkage rate increases.
- Most of the cracks and volume shrinkage occur during the constant rate of the evaporation period while the specimen is still saturated. Cracking and volume shrinkage terminate when the shrinkage limit is reached.

Lau (1987) performed desiccation tests on specimens at water content close to their liquid limit. Changes in matric suction during desiccation tests were measured using tensiometer embedded in the soil specimens. However, the presence of tensiometers influenced the initiation of cracks in most of the tests.

2.3.2 Quantification of Crack Networks

In some previous studies, crack network were quantified using random distribution function. Hudson and Priest (1979) studied fracture-length distribution and found that crack length varies either exponentially or lognormally. D'Astous et al. (1989) investigated the crack formation in a clayey soil and found that there was one crack every 2 cm distance. The cracks were mostly vertical. A histogram was used in analyzed the crack vertical orientation. Perret et al. (1999) scanned cracked soils and characterized the crack length and crack orientation using frequency distribution curves. Huysmans et al. (2006) studied the effect of excavation induced fractures in clay layers. They found that crack orientation follows a normal distribution with a mean of 53° and a standard deviation of 11° .

Polygons were also used to quantify crack network in some previous studies. Bezant and Cedolin (1991) proposed a theoretical network of desiccation cracks as parallel cracks and equal-sided polygons, such as squares, triangles, and hexagons. Konrad and Ayad (1997) quantified cracks as polygons with spacing from 10 cm to 24 cm. van Dam (2000) developed a numerical model to analyze changes in water content in cracked soil. In the analysis, the crack network was modelled as six-sided polygons.

Dershowitz and Einstein (1988) summarized several methods to describe crack networks in rocks. Distribution functions and polygons were the common methods to describe crack networks in rocks.

Wong and Einstein (2009) used a high speed camera to study the crack initiation, propagation and coalescence in rocks. In the study, frame rates of 1000 to 24000 frames/s and resolution of 256 x 512 to 1024 x 1024 pixels were used. The rock specimens were prismatic laboratory-moulded gypsum and Carrara marble specimens that contained either a single or a pair of artificial flaws. The specimens were tested under uniaxial compression. The presence of flaws triggered crack development.

Some studies did not indicate the method to quantify crack network. However, interconnectivity among cracks were observed. Ruland et al. (1991) found that there was one crack every 1 cm distance and that the cracks were interconnected with each other. Morris et al. (1992) observed desiccation cracks in mine tailings and found that cracks tend to intersect at an angle close to 90° and have a spacing about 1 m. McKay et al. (1993) found that cracks were mostly vertically oriented and tended to intersect at 90° . It was found that there were 40 cracks per meter.

Tang et al. (2008) performed a study of cracked soil and used the following method to idealize a crack network from a photograph of cracked soil:

- A colour photograph of the cracked soil specimen was changed to grayscale.
- The greyscale photograph was then changed to black and white by assigning a value to the grey threshold.
- The black area was assigned as cracks and the white area was assigned as the soil matrix.
- The boundary between the crack side and the soil matrix was named as the crack boundary. The crack aperture was determined by calculating the shortest distance from a randomly chosen point on one crack boundary to the opposite boundary of a crack. A total of 15000 stochastic points were selected from each crack network.
- A line was then used to represent a crack. This process is called the skeletonisation of the crack network. In this process, the middle line of the crack segment was selected as the skeleton of the crack network.
- The crack length was determined by calculating the distance between intersections after the image was skeletonised.

The image processing for this method is shown in Figure 2.5. A computer program was developed to perform the image processing and the idealization of the crack network from the photograph of the cracked soil specimen. The idealization of the crack network was performed only for the cracks at the ground surface.

Figure 2.5 Image processing of a photograph of a cracked soil specimen (Tang et al., 2008): (a) Initial image; (b) Black and white image; (c) Skeleton of crack network

Li and Zhang (2010) investigated a desiccation crack network in soil and found that the crack length, crack orientation, and crack midpoint coordinates followed a lognormal, uniform, and uniform distribution, respectively.

- A crack was represented by its location, length, aperture, and orientation.
- A crack was approximated by a straight line. The length of a crack is defined as the length of the straight line that approximates that crack.
- The crack location is indicated by the coordinates of the midpoint of the straight line representing that crack.
- The aperture of a crack is represented by the average of three aperture measurements taken at three different locations along that crack.
- The orientation of a crack is defined as the angle between the cracks in the selected global coordinate system.

AutoCAD software was used in the idealization of the crack network. Idealization was performed only for cracks at the ground surface. An example of an idealized crack network is shown in Figure 2.6.

Figure 2.6 Idealization of the crack network (Li and Zhang 2010)

2.3.3 Distribution Functions in Statistics

Three distribution functions were considered in this study: uniform distribution, normal distribution, and lognormal distribution. The basic definitions from statistics (e.g. Montgomery and Runger, 2007) are utilized in this study as presented in the following sub-sections.

2.3.3.1 Uniform Distribution

A uniform random distribution is a continuous random variable with the following probability density function:

$$f(x) = \frac{1}{(b-a)} \quad a \leq x \leq b \quad (2.5)$$

where:

x = uniform random variable

a = lower bound of the interval of x

b = upper bound of the interval of x

A plot of a uniform probability density function is shown in Figure 2.7. The mean of the uniform random variable, x , is defined as:

$$\mu = \frac{(a+b)}{2} \quad (2.6)$$

where:

μ = mean of a uniform random variable

The standard deviation of the uniform random variable, x , is defined as:

$$\sigma = \sqrt{\frac{(b-a)^2}{12}} \quad (2.7)$$

where:

σ = standard deviation of a uniform random variable

Figure 2.7 Plot of a uniform distribution function (Montgomery and Runger, 2007)

2.3.3.2 Normal Distribution

A normal random variable is a continuous random variable, x , with the following probability density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \quad (2.8)$$

where:

x = normal random variable

μ = mean of a uniform random variable

σ = standard deviation of a uniform random variable

A standard normal random variable, z , is a random variable with mean, μ , equal to zero and a variance, σ^2 , equal to one. A standard normal random variable, z , is related to the normal random variable, x , by the following relationship:

$$z = \frac{x - \mu}{\sigma} \quad (2.9)$$

An example of a plot of a uniform probability density function is shown in Figure 2.8.

Figure 2.8 Plot of a normal distribution function (Montgomery and Runger, 2007)

2.3.3.3 Lognormal Distribution

If x is a random normal distribution function with mean θ and variance σ^2 , then w is a lognormal random variable. A lognormal random variable, w , is related to x by the following relationship:

$$w = \exp(x) \quad (2.10)$$

where:

x = normal random variable

w = lognormal random variable

The lognormal probability density function is defined using the normal random variable, x , as follows:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\theta)^2}{2\sigma^2}\right) \quad -\infty < x < \infty \quad (2.11)$$

An example of a plot of a uniform probability density function is shown in Figure 2.9.

Figure 2.9 Plot of a log-normal distribution function (Montgomery and Runger, 2007)

2.3.3.4 Cumulative Distribution Function

A cumulative distribution function represents a summation of a distribution function up to the value of a random variable, x . The cumulative distribution function of x is defined as:

$$P(X \leq x_j) = \int_{-\infty}^x f(u) du \quad -\infty < x < \infty \quad (2.12)$$

where:

$P(X \leq x_j)$ = cumulative distribution function lower than x_j

A cumulative distribution function has a value ranging from 0 to 1.

2.3.3.5 Inverse Transform Method

A random number between 0 and 1 is generated. This random number represents the cumulative distribution $F(u)$. The inverse transform method generates random numbers based on a distribution using the following relationship:

$$x_i = F_X^{-1}(u)_i \quad i = 1, 2, 3, \dots, n \quad (2.13)$$

where:

j = rank of the corresponding x data

x_i = random numbers based on a distribution function

$F_x^{-1}(u)$ = inverse of a distribution function

The process of calculation is shown in Figure 2.10.

Figure 2.10 Inverse transform method (Ang and Tang, 1984)

2.3.3.6 Probability Plot

The appropriateness of a probability distribution function for representing a set of data can be assessed using a probability plot. An example of a probability plot is shown in Figure 2.11. The x-axis represents the measured variable ranked from the lowest to the highest value. The y-axis represents the standard random variable z .

$$P(Z \leq z_j) = \frac{j - 0.5}{n} \quad (2.14)$$

where:

j = rank of the corresponding x data

$F(x) = P(Z \leq z_j)$ = cumulative distribution function lower than z_j

The performance of a function representing a set of data can be assessed by assessing the performance of the linear regression to fit the data in the probability plot. In this study, the coefficient of determination was used to assess the performance of the linear regression to fit the data in the probability plot.

Figure 2.11 Example of a probability plot (Montgomery and Runger, 2007)

2.3.3.7 Coefficient of determination (R^2)

In this study, the performance of the linearization in the probability plot was assessed using the coefficient of determination, R^2 . The value of R^2 ranges from 0 to 1. R^2 equal to 1 indicates that the linear regression fits all the data, whereas R^2 equal to 0 indicates that the linear regression fits none of the data. The coefficient of determination, R^2 , is defined as:

$$R^2 = 1 - \frac{SS_E}{SS_T} \quad (2.15)$$

where:

R^2 = coefficient of determination

SS_E = error sum of squares

SS_T = total sum of squares

The error sum of squares, SS_E is defined as:

$$SS_E = \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (2.16)$$

where:

y_i = y obtained from measurement

$\hat{y}_i$ = value of y calculated using the linear regression equation

The total sum of squares, SS_T is defined as:

$$SS_T = \sum_{i=1}^n (\hat{y}_i - \bar{y})^2 \quad (2.17)$$

where:

$\bar{y}$ = average value of y_i

$\hat{y}_i$ = value of y calculated using the linear regression equation

2.3.4 Numerical Generation of Random Crack Network

The generation of a random crack network using the method proposed by Long et al. (1982) is shown in Figure 2.12. The midpoint coordinate of each crack is set within the generated region (Figure 2.12a). The orientation of each crack is determined next (Figure 2.12b) and followed by the determination of the length of each crack (Figure 2.12c). The crack length is determined following a selected random distribution. Finally, apertures are assigned to each of crack (Figure 2.12d). The midpoint coordinate of each crack, crack orientation, crack length and crack aperture are determined following a selected random distribution.

Figure 2.12 Generation of a random crack network as proposed by Long et al. (1982): (a) Crack midpoints coordinates; (b) Crack orientations; (c) Crack lengths; (d) Crack apertures

Oda (1986) and Stietel et al. (1996) generated crack networks numerically following the method proposed by Long et al. (1982). In these two studies, crack midpoint coordinate and crack length were modelled using a uniform distribution whereas crack orientation was modelled using normal distribution. The crack networks were then used to assess whether a rock sample with cracks can be represented as a continuum.

Huysmans et al. (2006) performed numerical analyses to model radioactive flow from a deep underground tunnel to the surrounding clay. The underground tunnel surfaces exhibited cracks due to the progress of the tunnel excavation equipment. In one of the numerical models approaches, the numerically generated crack networks were incorporated to model the cracks as shown in Figure 2.13. Ten numerical models with different crack networks were analyzed. Each crack network was generated by generating crack length, crack spacing and crack orientation independently following a particular distribution function. The cracks are then superimposed to form a crack network. The crack length was modelled using uniform distribution, the crack spacing was modelled using normal distribution, and the crack orientation was modelled using normal distribution.

Figure 2.13 Numerically generated model of cracked soil (Huysmans et al., 2006)

Several previous studies also utilized the distribution functions to generate crack networks numerically. The distribution functions used in the studies vary among the studies as summarized in Table 2.1.

Li and Zhang (2007) built a computer program to numerically generate a crack network based on Long et al. (1982) method. Crack networks were generated incorporating the statistical parameters measured by Perret et al. (1999) (probability density function, mean, and standard deviation).

Table 2.1 Distribution functions used to numerically generate crack network in several previous studies

Crack Network Parameters	Studies	Distribution Function Used in the Corresponding Study
Crack orientation	Anderson and Dverstorp (1987)	Fisher distribution
	Wei et al. (1995)	Normal distribution
	Priest (1993)	Negative binomial distribution
Crack length	Wei et al. (1995)	Negative exponential distribution
	Priest and Hudson (1981)	Exponential distribution
	Bridges (1976), McMahon (1971)	Lognormal distribution
Crack spacing	Priest and Hudson (1981)	Normal distribution
	Sen and Elissa (1992)	Exponential and lognormal distributions
	Bridges (1976)	Lognormal distribution
	Wallis and King (1980)	Exponential distribution

2.4 Existing Methods of Analysis of Flow through Cracked Soil

Two approaches are available: modelling the cracked soil as a continuum and modelling the cracked soil as a non-continuum.

2.4.1 Analysis of Cracked Soil Considering the Cracked Soil as a Continuum

2.4.1.1 Saturated Permeability of Crack Network

In the calculation of the saturated permeability of crack network, the soil matrix is considered impermeable. Therefore, water can only flow through the crack network. Previous studies can be divided into two main categories: theoretical developments and laboratory tests.

Bear (1972) proposed a method to describe directional permeability using the equation of an ellipsoid. Long et al. (1982) developed a method to distinguish whether a crack network can be considered as a continuum or must be treated as a collection of cracks. A crack network can be considered as a continuum if the directional saturated permeability of the crack network is close to an ellipse. To determine this, idealized crack networks with a constant crack aperture were developed. The matrix was considered impermeable. The saturated permeability at each crack was then calculated using cubic law. The analysis was performed numerically. Li and Zhang (2007) developed a method to obtain the directional permeability of a model crack network. Crack networks were generated numerically incorporating the method proposed by Long et al. (1982). The crack length, crack orientation, and crack midpoint coordinates were characterized using a lognormal, normal, and uniform distribution, respectively. The statistical parameters of the crack network (probability density function, mean, and standard deviation) were obtained from the literature.

Kranz et al. (1979) measured the saturated permeability of a rock sample with one crack parallel to the flow. The rock matrix is considered to be impermeable. The crack aperture was also measured. The measured permeability was then compared with the saturated permeability predicted using cubic law incorporating the measured crack aperture. It was found that the predicted permeability was four order of magnitude greater than the measured permeability. The variation in crack aperture in the crack surface was believed to be the cause of the difference. Witherspoon et al. (1980) investigated the validity of cubic law. They found that cubic law was valid. However, in order to make the predicted and measured flow rates the same, the predicted flow rate should be divided by a factor f which varied from 1.04 to 1.65 in that study. No method to calculate factor f was proposed.

2.4.1.2 Saturated Permeability of Cracked Soils

In the calculation of the saturated permeability of cracked soil, the soil matrix is considered permeable. Therefore, water can flow through the crack network and

soil matrix. Previous studies can be divided into two main categories: theoretical development and field tests.

Huysmans et al. (2006) proposed a method to calculate the saturated permeability of cracked soil. The method was intended for infiltration cases. Four approaches were proposed. In the first approach, cracked soil was modeled as a homogeneous material with a higher permeability than intact soil. The permeability values varied from 1 to 10^6 times the permeability of intact soil. In the second approach, the equivalent hydraulic conductivity for the total thickness of the soil is defined as the weighted harmonic mean of the hydraulic conductivity values of the permeable zone and the undisturbed soil. In the third approach, the saturated permeability of the cracked soil was calculated considering the saturated permeability of the intact soil matrix, the saturated permeability of the cracks, the crack aperture, and the crack spacing. In the fourth approach, the cracks were modelled as inclined cracks and the permeability was calculated for the cracked soil. Li et al. (2009) proposed a method to determine the REV of cracked soil in terms of saturated permeability.

Matsuo (1953) performed a field determination of saturated permeability. Although it was not explicitly stated, this method can be used to measure the saturated permeability of cracked soil in the field. Keller et al. (1986) investigated the saturated permeability of intact unweathered clayey till and the permeability of the clayey till layer. They obtained the value of intact saturated permeability from oedometer tests and the value of saturated permeability from slug tests. They found that the unweathered clayey till layer had a vertical and horizontal saturated permeability two orders of magnitude higher than that for intact permeability, indicating the presence of cracks in the soil although they were not visible.

2.4.1.3 SWCC and Permeability Function of Cracked Soils

Various methods to calculate SWCC and permeability function have been proposed in the previous studies. Peters and Klavetter (1988) methods superimpose the SWCC for the intact portion of the soil with another independent analysis for the cracked portion. The resulting SWCC has also been used to estimate the

permeability function of cracked soil. Gerke and van Genuchten (1993) proposed a method to develop a permeability function of cracked soil. Zhang and Fredlund (2003) suggested a method to determine the water retention curve for a discontinuous material based on the pore size distributions of the fractures and the rock matrix.

Fredlund et al. (2010) proposed a model of SWCC and permeability function of a cracked soil. SWCC have a bimodal shape. In the generation of SWCC it is assumed that the combined matrix and fracture medium qualified as a continuum with the same suction value being applied for the two overlapping porous continua. The procedure to obtain SWCC of cracked soils is:

- Obtain SWCC for intact soil matrix
- First, the width of the cracks and the spacing between cracks are assumed for one cubic meter of soil.
- Obtain saturated water content of cracked soil
- Estimate air entry value of cracks utilizing the width of the cracks
- Assume a nearly vertical slope for SWCC of fractured portion (made on the basis of SWCC computed by Wang and Narasimhan, 1985).
- Obtain some points of SWCC of crack network
- Obtain points of SWCC of intact soil matrix
- Apply SWCC fitting equations (two equations were proposed), one equation with a correction factor to yield a suction of 10^6 kPa at zero water content and one equation without a correction factor:

$$w = w_s \left[V \left(\frac{1}{\ln \left(\exp(1) + \left(\frac{a_f}{u_a - u_w} \right)^{n_f} \right)^{m_f}} \right) + (1 - V) \left(\frac{1}{\ln \left(\exp(1) + \left(\frac{j_f}{u_a - u_w} \right)^{k_f} \right)^{l_f}} \right) \right] \left(1 - \frac{\ln \left(1 + \frac{u_a - u_w}{3000} \right)}{\ln \left(1 + \frac{1000000}{3000} \right)} \right) \quad (2.18)$$

$$w = w_s \left[V \left(\frac{1}{\ln \left(\exp(1) + \left(\frac{a_f}{u_a - u_w} \right)^{n_f} \right)^{m_f}} \right) + (1-V) \left(\frac{1}{\ln \left(\exp(1) + \left(\frac{j_f}{u_a - u_w} \right)^{k_f} \right)^{l_f}} \right) \right] \quad (2.19)$$

where:

- w_s = saturated water content (either volumetric or gravimetric)
- a_f = curve-fitting parameter related to the air-entry value of the intact soil matrix portion
- j_f = curve-fitting parameter related to the air-entry value of the crack network portion
- n_f = curve-fitting parameters related to the slope of the intact soil matrix portion
- k_f = curve-fitting parameters related to the slope of the crack network portion
- m_f = curve-fitting parameters related to the residual water content of the intact soil matrix portion
- l_f = curve-fitting parameters related to the residual water content of the crack network portion
- V = normalized volume of the intact portion to the total volume

The hydraulic permeability function for a cracked soil cannot be obtained by simply integrating along the bimodal SWCC. Rather, it is necessary to treat the cracked soil portion and the intact soil portion independently. The procedure to obtain permeability function of cracked soils is:

- Calculate the saturated hydraulic permeability of the cracked portion of soil using Kozeny-Carman equation (Kozeny, 1927; Carman, 1939)

$$k = \frac{2}{f.A^2} \frac{e^3}{1+e} \quad (2.20)$$

where:

- k = the saturated hydraulic permeability of the cracked portion of soil
- e = void ratio of crack network portion

f = angularity factor

A = the specific surface area, which can be computed as:

$$A = \frac{6}{\sqrt{d_1 d_2}} \quad (2.21)$$

where:

d_1 = crack width (Figure 2.14)

d_2 = width of intact portion (Figure 2.14)

- Obtain saturated permeability of intact soil matrix
- Calculate average coefficient of hydraulic conductivity of the cracked soil based on proportional volumes between fractures and intact portion with equation:

$$k_{avg} = \frac{k_1 d_1 + k_2 d_2}{d_1 + d_2} \quad (2.22)$$

where:

k_{avg} = saturated hydraulic conductivity of cracked soil

- Obtain permeability of the cracked soil based on Irmay (1971):

$$k_r = \theta^{3.0} \quad (2.23)$$

where:

k_r = relative permeability

θ = normalized water content

- Obtain bi-model permeability function using modified Campbell method (Campbell, 1973) or Leong and Rahardjo (1997) method.

However, in Fredlund et al. (2010) only a parametric numerical study for evaporation and infiltration case was performed. The theory was not verified with the measurement from flow through actual cracked soil.

Figure 2.14 Horizontal flow through a cracked soil (Fredlund et al., 2010)

Li et al. (2011) proposed a method to calculate the SWCC and permeability function of cracked soil. The cracked soil is viewed as an overlapping continuum of a crack network system and a soil matrix system. Two conditions of cracks were considered: cracks that change in aperture due to wetting and cracks that does not change in aperture due to wetting. The SWCC of the cracked soil that does not change in aperture due to wetting is calculated as the sum of the SWCCs for the two material phases weighted by their volume porosities:

$$\theta(\psi) = \theta_{sm} \Phi \left(\frac{\ln \left(\frac{C}{\psi} \right) - \lambda_m}{\zeta_m} \right) + \theta_{sc} \Phi \left(\frac{\ln \left(\frac{C}{\psi} \right) - \lambda_c}{\zeta_c} \right) \quad (2.24)$$

where:

ψ = suction

θ_{sm} = volumetric water content when the soil matrix is fully saturated

θ_{sc} = volumetric water content of the cracks when the cracks are fully saturated

Φ = cumulative function of the standard normal distribution

λ_m = mean of $\ln(r)$ for the soil matrix

ζ_m = standard deviation of $\ln(r)$ for the soil matrix

λ_c = mean of $\ln(r)$ for the crack aperture

ζ_c = standard deviation of $\ln(r)$ for the crack aperture

r = pore radius

$$C = 2T \cos \alpha \quad (2.25)$$

where:

T = surface tension of water

α = angle of contact between water and soil particle.

The volumetric water content of a fully saturated soil mass, θ_s , is,

$$\theta_s = \theta_{sm} + \theta_{sc} \quad (2.26)$$

The permeability function for the cracked soil does not change in aperture due to wetting can be calculated by superimposing permeability of the crack network and permeability of the soil matrix:

$$k^{(s)}(\psi) = k^{(c)}(\psi) + (1 - w_c)k^{(m)}(\psi) \quad (2.27)$$

where:

$k^{(s)}$ = permeability function for the cracked soil

$k^{(c)}$ = permeability function for the crack network

$k^{(m)}$ = permeability function for the soil matrix

$$w_c = \frac{V_c}{V_t} \quad (2.28)$$

where:

w_c = volumetric weighting factor

V_c = total volume of the cracks

V_t = total volume of the medium including the crack network and the soil matrix

2.4.2 Analysis of Cracked Soil Considering the Cracked Soil as a Non-Continuum

Field Measurement of Water Content

Bronswijk et al. (1995) studied changes in water content due to infiltration into desiccated unsaturated cracked soil. Water was applied by spraying the ground

surface of the study area (30 m x 15 m). The water content was measured at 15 locations within the study area at a depth of 0-1 m on days 6, 46, 209, 335, and 572. The water contents at 15 locations were then averaged to represent the water content at each depth and each time. Mitchell and van Genuchten (1993) investigated the behaviour of water filling cracked soil during irrigation. It was found that water filled the cracks then seeped into soil matrix. Zhan et al. (2007) measured the water content of cracked slopes and found that the water content of soil samples at the same elevation were different. This was due to the presence of cracks, but no method of analysis was proposed.

Numerical Analyses

van Dam (2000) developed a numerical model using the idealization of a crack network as hexagons. He then used the model to analyze changes in water content in the soil matrix using the data from Bronswijk et al. (1995). Novák et al. (2000) developed a numerical model using the idealization of a crack network as parallel cracks.

Zhang and Zhang (2010) performed numerical analyses to model rainfall infiltration into a cracked ground surface. The soil mass was modelled using 2-D quadrilateral elements and the cracks were modelled by 1-D linear elements. The results indicated that after water ponded on the ground surface, the pore water pressure increment in the cracks was much greater than in the soil mass. The cracks were filled with water and a positive pore water pressure occurred very soon. However, the method for obtaining the crack network used in the numerical analysis from the actual crack network in cracked soils was not mentioned.

Figure 2.15 Modelling cracks as saturated materials (from Zhang and Zhang, 2010):
 (a) Geometry of the finite element mesh; (b) Pore water pressure contour at 3 hours
 of rainfall

2.5 Concluding Remarks

Based on the above literature, a model for predicting lateral flow through cracked soil has not been fully developed. Laboratory measurements are needed to investigate the performance of the existing models. In addition, there are two approaches for analyzing changes in water content in cracked soil: modelling the cracked soil as a continuum and modelling the cracks and soil matrix differently. Laboratory measurements are also needed to investigate the performance of these models.

In this study, a non-continuum approach is used to develop a model to predict lateral flow rate and changes in the water content and matric suction of cracked soil. A method for obtaining an idealized crack network from the crack network in soil is proposed. The idealized crack network is used in the model to predict lateral flow and the method to analyse change in water content and matric suction of cracked soil.

3 CHAPTER 3

THEORY

3.1 Introduction

This chapter presents the development of a theory providing a framework to analyze lateral flow through cracked soil, specifically a model to predict the flow rate through cracked soil and a method to analyze changes in the water content and matric suction of cracked soil. The proposed theory consists of idealizing the crack network in soil, analyzing the lateral flow rate through cracked soil, analyzing changes in the water content and matric suction of cracked soil, and analyzing the effect of variation in the crack network on the water content and matric suction of a cracked soil. The proposed method to obtain an idealized crack network is presented first in Section 3.2, followed by the proposed model to predict the lateral flow rate through cracked soil utilizing the idealized crack network (Section 3.3). The proposed method to analyze changes in the water content and matric suction of cracked soil is then presented in Section 3.4. Related theory regarding unsaturated seepage into soil is also presented. The proposed method to analyze the effects of variation in the crack network on the water content and matric suction of a cracked soil is then described in Section 3.5.

3.2 Proposed Method to Develop Idealized Crack Network

In this study, an idealized crack network is used in the proposed model to predict the lateral flow rate through cracked soil (Section 3.3) and in the proposed method to analyze changes in the water content and matric suction of cracked soil (Section 3.4). Lateral flow occurs in cracked soil (Figure 3.1a) due to head differences (Figure 3.1b).

The crack network in the soil is idealized into a set of linear cracks (Figure 3.1a). The idealized cracks in the network are subdivided into three categories (Figure 3.1c):

- (1) The cracks located between two intersection points.
- (2) The cracks that have only one intersection point.
- (3) The isolated cracks that have no intersection points.

In the proposed model to predict lateral flow through cracked soil (Section 3.3), only cracks from the first category contribute to the model. In the proposed method of analysis of changes in the water content and matric suction of cracked soil (Section 3.4), the cracks from the first and second categories contribute to the analysis. In addition, a crack that varies in aperture is idealized as having a constant aperture. In this study, the constant crack aperture is referred to as the “representative aperture”.

Figure 3.1 An idealized soil element considered in the lateral flow test: (a) Three categories of idealized cracks in the network; (b) Plan view of lateral flow through cracked soil; (c) An idealized cracked soil element considered in the lateral flow analysis (Krisnanto et al., 2014)

A flow diagram of the method for scanning the crack network in the soil, which is used to obtain the digitized crack network and the idealized crack network proposed in this study, is shown in Figure 3.2. To obtain an idealized crack network from an actual crack network in the soil, four consecutive steps are performed:

- (1) Scanning and obtaining a photo of the crack network in the soil.
- (2) Digitizing the results of scanning and obtaining a photo of the crack network, then combining both digitized crack networks.
- (3) Skeletonising the digitized crack network.
- (4) Idealizing the skeleton of the crack network.

Each step is explained in the following paragraphs.

Figure 3.2 Flow diagram of the method to develop an idealized crack network

The idealization process begins with scanning and obtaining a photo of the crack network in the soil. Scanning results in a file that contains groups of points that represent the cracked soil. The surface of the soil matrix is described as a group of points having a distance equal to the resolution of the scanner, whereas the cracks

are described as spaces without points. This file can be processed using a computer aided design (CAD) program. However, the cracks that have an aperture less than the finest resolution of the scanner will be represented by points equal to the finest resolution of the scanner, causing the aperture of these cracks to be incorrectly represented. Therefore, in addition, a photo of the crack network in the soil is obtained for digitization. The photo is obtained to incorporate the cracks that have an aperture less than the finest resolution of the scanner.

The results of scanning and the photo are digitized separately to obtain a digitized crack network. The digitizing process is performed by representing the actual crack wall lines as a series of digitized crack wall lines (Figure 3.3). This process is performed using a CAD program. From the results of scanning, lines are drawn along points that represent crack walls. The lines representing the crack walls are called the digitized crack wall lines. The same process is also performed on the photos. Lines are drawn in the photos along the crack wall lines. Two results are thus obtained: the digitized crack network obtained from scanning and the digitized crack network obtained from the photo. The result from scanning is used as a reference since it provides more precise dimensions of the cracked soil specimen. The digitized crack networks obtained from the two methods are then superimposed to create one digitized crack network.

Figure 3.3 Digitizing process

The skeletonising process is then performed on the skeleton of the crack network. Skeletonising is a process to represent a crack network of varying widths with a single line (Tang et al., 2008; Atique et al., 2010). In this study, this process is performed by first drawing lines from a starting point on one side of the digitized crack wall line at different angles (Figure 3.4a). An arbitrary angle variation equal to 0.1 degrees is used in this study. Next, the shortest line connecting the starting point (point O in Figure 3.4a) 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. This process is performed at each endpoint of the digitized crack wall lines of a crack (e.g., points A to D and points E to H in Figure 3.3). These lines are obtained from the digitized crack network, as explained in Figure 3.3. Several skeleton points and crack apertures along a crack are then obtained. The skeleton points are then connected to obtain the skeleton of the crack network. As a result, the variation in the aperture along a crack and the skeleton of the crack network are obtained (Figure 3.4b). After the crack network is skeletonised (Figure 3.4c), this network is idealized by connecting the two intersection points of the crack network with a straight line (Figure 3.4d).

Finally, an idealized crack network is obtained. A crack is defined as the crack between two intersection points (as crack no. 1 in Figure 3.1c) or the crack between one intersection point and the other endpoint (as crack no. 2 in Figure 3.1c). This definition was also used by Li and Zhang (2010). Crack length, L_i , is defined as the distance between two intersection points (Figure 3.4d). Crack orientation, α_i , is defined as the angle between the crack and the horizontal axis (Figure 3.4d). The procedure to obtain the representative crack aperture is explained in Section 3.3. The length and orientation are obtained for each crack. The idealized crack network is then characterized using the probability density function, mean, and standard deviation of the crack length and crack orientation.

(a)

(b)

(c)

Figure 3.4 Idealization of a crack network: (a) Calculation of crack aperture (Krisnanto et al., 2014); (b) Development of skeleton of crack network; (c) Skeleton of crack network; (d) Idealized crack network

3.3 Proposed Model to Predict the Lateral Flow Rate through the Crack Network

An idealized cracked soil element experiencing lateral flow is shown in Figure 3.1a. 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 the two planes in the XY plane (Figure 3.1b).

The following conditions are assumed when developing the proposed model to predict the lateral flow rate through cracked soil:

- The flow into the soil matrix is assumed to be small compared to that through the crack network. Therefore, the flow through cracked soil can be represented by the flow through the crack network.
- The cracks extend from the top to the bottom of the soil layer with a constant aperture.

- The aperture of the cracks remains constant during the lateral water flow.
- The lateral flow through the crack network is under steady state flow conditions.

The lateral flow rate through a crack network is predicted by first calculating the head values at each crack intersection point using the conservation of mass principle, i.e. the summation of the mass of water that flows into a crack intersection point and the mass of water that flows from a crack intersection is equal to zero. This principle was also used in work by Indraratna and Ranjith (2001), Li and Zhang (2007), and Li et al. (2009) in calculating flow through a crack network. Since water is considered incompressible, this principle implies that the summation of the flow rate into a crack intersection point and the flow rate out from a crack intersection point are equal to zero:

$$\left(\sum_{j=1}^{m_k} q_{jk} \right)_k = 0 \quad k = 1, 2, 3, \dots, n \quad (3.1)$$

where:

q_{jk} = the flow rate through the j^{th} crack at the k^{th} intersection point

m_k = the number of cracks intersecting the k^{th} intersection point

n = the number of crack intersection points

The flow through a single crack is considered as flow through parallel plates and the flow rate through each single crack is computed as (Taylor, 1948; Snow, 1968; Snow, 1969):

$$q = \frac{gb^3}{12\nu} i \quad (3.2)$$

where:

q = the flow rate through a single crack ($m^3/s/m$)

g = the gravitational constant (m/s^2)

b = the crack aperture (m)

ν = the kinematic viscosity of water (m^2/s)

i = the hydraulic gradient between the two end points of a crack

The application of Eq. (3.1) results in n simultaneous linear equations with n unknowns, where n represents the head values at the crack intersection points.

The flow rate calculated using Eq. (3.2) is based on the assumption that the crack has a constant aperture. In reality, the aperture varies along the crack (e.g., Tang et al., 2008; Atique et al., 2010). In this study, a representative crack aperture of an actual crack is proposed as the value that should be used in Eq. (3.2). The representative crack aperture is assumed to be constant for a single crack.

In this study, cracks are modelled as parallel plates. A single crack that varies in aperture is modelled as a parallel plate that varies in distance. The variation in distance between the parallel plates implies that there is variation in the cross-section along the flow path. This variation in cross-section could generate head loss (Streeter, 1961). In the proposed model, additional head loss due to changes in crack aperture is incorporated to calculate the hydraulic gradient i and the representative crack aperture b to be used in Eq. (3.2). However, it is assumed that the crack is linear between each two crack intersection points. Therefore, additional head loss due to curvature in the crack is not considered in the analysis.

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

Additional Head Loss due to Crack Aperture Enlargement

Figure 3.5a shows flow through an enlargement in the crack aperture. The Borda-Carnot equation (Streeter, 1961; Massey and Ward-Smith, 1998) is derived for a circular cross-section of pipe and is used to quantify head loss due to changes in the crack cross-section. The resultant of the forces on the right-hand side of Eq. (3.3) is equal to the rate of increase in momentum in the same direction:

$$p_1 A_1 + p_1 (A_2 - A_1) - p_2 A_2 = \rho_w q (v_2 - v_1) \quad (3.3)$$

$$p_1 - p_2 = \rho_w \frac{q}{A_2} (v_2 - v_1) \quad (3.4)$$

$$p_1 - p_2 = \rho_w v_2 (v_2 - v_1) \quad (3.5)$$

where:

p_1 = the water pressure at section 1

p_2 = the water pressure at section 2

A_1 = the area of section 1

A_2 = the area of section 2

ρ_w = the density of water

q = the flow rate

v_1 = the velocity at section 1

v_2 = the velocity at section 2

(a)

(b)

Figure 3.5 Flow through an enlargement and contraction of the crack aperture: (a) Flow through an enlargement of the crack aperture; (b) Flow through a contraction of the crack aperture (Krisnanto et al., 2014)

The following equation can be written by applying the Bernoulli equation to the head loss associated with crack aperture enlargement:

$$\frac{p_1}{\rho_w g} + \frac{v_1^2}{2g} + z_1 - h_{le} = \frac{p_2}{\rho_w g} + \frac{v_2^2}{2g} + z_2 \quad (3.6)$$

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

$$\frac{p_1}{\rho_w g} + \frac{v_1^2}{2g} - h_{le} = \frac{p_2}{\rho_w g} + \frac{v_2^2}{2g} \quad (3.7)$$

$$h_{le} = \frac{p_1 - p_2}{\rho_w g} + \frac{v_1^2 - v_2^2}{2g} \quad (3.8)$$

where:

h_{le} = the head loss due to aperture enlargement.

Substitution of Eq. (3.5) into Eq. (3.8) gives:

$$h_{le} = \frac{v_2(v_2 - v_1)}{g} + \frac{v_1^2 - v_2^2}{2g} \quad (3.9)$$

$$h_{le} = \frac{(v_1 - v_2)^2}{2g} \quad (3.10)$$

Continuity of the flow rate requires:

$$A_1 v_1 = A_2 v_2 \quad (3.11)$$

Substitution of Eq. (3.11) into Eq. (3.10) gives the head loss due to crack aperture enlargement as:

$$h_{le} = \frac{v_2^2}{2g} \left(\frac{A_2}{A_1} - 1 \right)^2 \quad (3.12)$$

Eq. (3.12) can be simplified as:

$$h_{le} = K_e \frac{v_2^2}{2g} \quad (3.13)$$

where:

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

$$K_e = \left(\frac{A_2}{A_1} - 1 \right)^2 \quad (3.14)$$

Additional Head Loss due to Crack Aperture Contraction

Figure 3.5b 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 same procedure used to calculate the head loss due to crack enlargement, the head loss due to crack contraction can be represented as follows:

$$h_{lc} = \frac{v_2^2}{2g} \left(\frac{A_2}{A_c} - 1 \right)^2 \quad (3.15)$$

where:

h_{lc} = the head loss due to crack aperture contraction

A_c = the area of the vena contracta (Figure 3.5b)

Eq. (3.15) can be simplified as:

$$h_{lc} = K_c \frac{v_2^2}{2g} \quad (3.16)$$

where:

K_c = the head loss coefficient due to contraction.

In this study, the head loss coefficient due to contraction, K_c , for the pipe proposed by Streeter (1961) as shown in Figure 3.6, is used in Eq. (3.16). 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 (Eq. (3.13)) and the additional head loss due to crack contraction (Eq. (3.16)):

$$h_l = \sum_{j=1}^l K_e \frac{v_{j+1}^2}{2g} + \sum_{k=1}^m K_c \frac{v_{k+1}^2}{2g} \quad (3.17)$$

where:

h_l = the additional head loss due to aperture change in a single crack

j = the counter indicating the cracks enlarging in aperture

l = the number of cracks enlarging in aperture

k = the counter indicating the cracks contracting in aperture

m = the number of cracks contracting in aperture

Figure 3.6 Head loss coefficient due to aperture contraction K_c (data from Streeter, 1961)

The hydraulic gradient i in Eq. (3.2) is calculated as:

$$i = \frac{(H_j - H_k - h_l)}{L} \quad (3.18)$$

where:

H_j = the head at the two crack intersection point j

H_k = the head at the two crack intersection point k

L = the length of the corresponding crack.

The additional head loss h_l is calculated using Eq. (3.17).

To calculate the representative crack aperture b in Eq. (3.2), the total head difference between the two crack endpoints is calculated via the summation of the head differences at each crack segment (Figure 3.7):

$$h = h_1 + h_2 + h_3 + \dots + h_n + h_l \quad (3.19)$$

where:

h = the head difference between two crack intersection points

h_1 = the head difference at crack section 1

h_2 = the head difference at crack section 2

h_3 = the head difference at crack section 3

h_n = the head difference at crack section n

(a) Head values along a crack

(b) Plan view of a crack

Figure 3.7 Head and plan view of a crack: (a) Head along a crack; (b) Plan view

(Krisnanto et al., 2014)

From the definition of hydraulic gradient:

$$i = \frac{h}{L} \quad (3.20)$$

where:

i = the hydraulic gradient

h = the head difference

L = the path length where the head difference occurs

Eq. (3.20) can be rewritten as:

$$h = iL \quad (3.21)$$

Substituting Eq. (3.21) into Eq. (3.19) gives:

$$i_{avg} \cdot L = i_1 L_1 + i_2 L_2 + i_3 L_3 + \dots + i_n L_n + h_l \quad (3.22)$$

where:

i_{avg} = the average hydraulic gradient between two crack endpoints

i_1 = the hydraulic gradient at crack segment 1

i_2 = the hydraulic gradient at crack segment 2

i_3 = the hydraulic gradient at crack segment 3

i_n = the hydraulic gradient at crack segment n

L = the length of the crack

L_1 = the length of segment 1

L_2 = the length of segment 2

L_3 = the length of segment 3

L_n = the length of segment n

Darcy's law (D'Arcy, 1856) can be expressed as follows:

$$i = \frac{v}{k} \quad (3.23)$$

where:

v = the velocity between the endpoints of a crack

k = the saturated coefficient of permeability

Substitution of Eq. (3.23) into Eq. (3.22) gives:

$$\frac{v}{k_{eq}} L = \frac{v_1}{k_1} L_1 + \frac{v_2}{k_2} L_2 + \frac{v_3}{k_3} L_3 + \dots + \frac{v_n}{k_n} L_n + h_l \quad (3.24)$$

where:

v_1 = the velocity at crack segment 1

v_2 = the velocity at crack segment 2

v_3 = the velocity at crack segment 3

v_n = the velocity at crack segment n

k_{eq} = the equivalent saturated permeability of a single crack

k_1 = the saturated coefficient of permeability of the crack at crack segment 1

k_2 = the saturated coefficient of permeability of the crack at crack segment 2

k_3 = the saturated coefficient of permeability of the crack at crack segment 3

k_n = the saturated coefficient of permeability of the crack at crack segment n

Substituting Eq. (3.17) into Eq. (3.24) gives:

$$\frac{v}{k_{eq}} L = \frac{v_1}{k_1} L_1 + \frac{v_2}{k_2} L_2 + \frac{v_3}{k_3} L_3 + \dots + \frac{v_n}{k_n} L_n + \sum_{j=1}^l K_e \frac{v_{j+1}^2}{2g} + \sum_{k=1}^m K_c \frac{v_{k+1}^2}{2g} \quad (3.25)$$

Since:

$$v = \frac{q}{b(1)} \quad (3.26)$$

Substituting Eq. (3.26) into Eq. (3.25) gives:

$$\frac{q}{b(1)k_{eq}} L = \frac{q_1}{b_1(1)k_1} L_1 + \frac{q_2}{b_2(1)k_2} L_2 + \frac{q_3}{b_3(1)k_3} L_3 + \dots + \frac{q_n}{b_n(1)k_n} L_n + \sum_{j=1}^l K_e \frac{q_{j+1}^2}{b_{j+1}^2(1)^2 2g} + \sum_{k=1}^m K_c \frac{q_{k+1}^2}{b_{k+1}^2(1)^2 2g} \quad (3.27)$$

where:

- q_1 = the flow rate at section 1
- q_2 = the flow rate at section 2
- q_3 = the flow rate at section 3
- q_n = the flow rate at section n
- b_1 = the crack aperture of section 1
- b_2 = the crack aperture of section 2
- b_3 = the crack aperture of section 3
- b_n = the crack aperture of section n

Continuity of flow requires $q = q_1 = q_2 = q_3 = q_n$, thus Eq. (3.27) becomes:

$$\frac{L}{bk_{eq}} = \frac{L_1}{b_1k_1} + \frac{L_2}{b_2k_2} + \frac{L_3}{b_3k_3} + \dots + \frac{L_n}{b_nk_n} + \sum_{j=1}^l K_e \frac{q_{j+1}}{b_{j+1}^2(1)^2 2g} + \sum_{k=1}^m K_c \frac{q_{k+1}}{b_{k+1}^2(1)^2 2g} \quad (3.28)$$

$$\frac{L}{bk_{eq}} = \frac{L_1}{b_1k_1} + \frac{L_2}{b_2k_2} + \frac{L_3}{b_3k_3} + \dots + \frac{L_n}{b_nk_n} + \sum_{j=1}^l K_e \frac{q_{j+1}}{2b_{j+1}^2g} + \sum_{k=1}^m K_c \frac{q_{k+1}}{2b_{k+1}^2g} \quad (3.29)$$

Equation (3.26) can be rewritten as:

$$v = qb \quad (3.30)$$

Equation (3.23) can be rewritten as:

$$v = ki \quad (3.31)$$

Substituting Eq. (3.31) into Eq. (3.30) gives:

$$q = kib \quad (3.32)$$

Substituting Eq. (3.32) into Eq. (3.2) gives:

$$kib = \frac{gb^3}{12\nu} i \quad (3.33)$$

$$k = \frac{gb^2}{12\nu} \quad (3.34)$$

Substituting Eq. (3.34) into Eq. (3.29) gives:

$$\frac{L}{b \frac{gb^2}{12\nu}} = \frac{L_1}{b_1 \frac{gb_1^2}{12\nu}} + \frac{L_2}{b_2 \frac{gb_2^2}{12\nu}} + \frac{L_3}{b_3 \frac{gb_3^2}{12\nu}} + \dots + \frac{L_n}{b_n \frac{gb_n^2}{12\nu}} + \sum_{j=1}^l K_e \frac{q_{j+1}}{2b_{j+1}^2 g} + \sum_{k=1}^m K_c \frac{q_{j+1}}{2b_{k+1}^2 g} \quad (3.35)$$

$$\frac{L}{b^3} = \frac{L_1}{b_1^3} + \frac{L_2}{b_2^3} + \frac{L_3}{b_3^3} + \dots + \frac{L_n}{b_n^3} + \sum_{j=1}^l K_e \frac{q_{j+1}}{24\nu b_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{j+1}}{24\nu b_{k+1}^2} \quad (3.36)$$

$$b^3 = \frac{L}{\frac{L_1}{b_1^3} + \frac{L_2}{b_2^3} + \frac{L_3}{b_3^3} + \dots + \frac{L_n}{b_n^3} + \sum_{j=1}^l K_e \frac{q_{j+1}}{24\nu b_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{j+1}}{24\nu b_{k+1}^2}} \quad (3.37)$$

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

$$b = \sqrt[3]{\frac{L}{\frac{L_1}{b_1^3} + \frac{L_2}{b_2^3} + \frac{L_3}{b_3^3} + \dots + \frac{L_n}{b_n^3} + \sum_{j=1}^l K_e \frac{q_{j+1}}{24\nu b_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{j+1}}{24\nu b_{k+1}^2}}} \quad (3.38)$$

To predict the lateral flow rate through a crack network, the head values at each crack intersection point are calculated using Eqs. (3.1) and (3.2) with the representative crack aperture calculated using Eq. (3.38). The calculation is performed iteratively since the head loss depends on the velocity and the velocity depends on the head difference between two crack intersection points. In the first iteration, the additional head loss h_l in Eq. (3.18) is assumed to be zero. Therefore,

the factor $\sum_{j=1}^l K_e \frac{q_{j+1}}{24\nu b_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{k+1}}{24\nu b_{k+1}^2}$ in Eq. (3.38) is also assumed to be zero.

The simultaneous linear equations are then solved to obtain the head values at each

crack intersection point. With these values, the flow rate in each crack can now be calculated using the hydraulic gradient, i , calculated from Eq. (3.18). Substituting i into Eq. (3.2) gives the flow rate per 1 m thickness of soil. Therefore, the velocity at each crack segment can be calculated as:

$$v_j = \frac{q}{b_j t} \quad (3.39)$$

where:

v_j = the velocity at crack segment j

q = the flow rate in a crack calculated using Eq. (3.2)

t_s = the soil thickness

Knowing the velocity at each crack segment, the head loss due to changes in aperture can now be calculated using Eq. (3.17) and the representative crack aperture is calculated using Eq. (3.38). The calculation of the new crack aperture results in a new value for the additional head loss, h_l , and the representative crack aperture, b , at each crack. The error ratios for the head loss and the representative crack aperture are defined as:

$$err_h = \frac{|h_{lk-1} - h_{lk}|}{h_{lk-1}} \quad (3.40)$$

$$err_b = \frac{|b_{k-1} - b_k|}{b_{k-1}} \quad (3.41)$$

where:

err_h = the error ratio of the head loss

h_{lk-1} = the head loss calculated in the $k-1^{th}$ iteration

h_{lk} = the head loss calculated in the k^{th} iteration

err_b = the error ratio of the representative crack aperture

b_{k-1} = the representative crack aperture calculated in the $k-1^{th}$ iteration

b_k = the representative crack aperture calculated in the k^{th} iteration

The iteration process is performed by changing the assumed head loss values of each crack until both error ratio values are small. An error ratio of 0.001 is used as the criterion to stop the iteration process 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 crack network in the soil specimen is then calculated as a summation of the flows through the cracks that intersect the outflow boundary:

$$Q = \sum_{j=1}^m q_j \quad (3.42)$$

where:

Q = the flow rate through the crack network in the soil specimen

q_j = the flow rate of the cracks intersecting the outflow boundary (Figure 3.8)

m = the number of cracks intersecting the outflow boundary

Figure 3.8 Plan view of lateral flow through an idealized crack network (Krisnanto et al., 2014)

All cracks that have two intersection points or cracks that are connected to inflow / outflow boundary were considered in the calculation of water flow. In Figure 3.8 the flow rate, q is indicated only on the cracks that intersect the outflow boundary to emphasize that in this study, the calculation of flow rate through the crack network,

Q is performed by summing the flow rates, q through the cracks that intersect the outflow boundary (Eq.(3.42)). Calculation of Q can also be performed by summing the flow rates, q through the cracks that intersect the inflow boundary.

3.4 Proposed Method to Analyze Changes in Water Content and Matric Suction of Cracked Soil

In addition to the lateral flow rate through a crack network, the presence of cracks causes the pattern of water content and matric suction of soil during lateral flow to be different from the pattern of water content and matric suction of an intact soil matrix (Zhan et al., 2007; Bronswijk et al., 1995). A method to analyze changes in water content and matric suction of cracked soils is proposed in this section of the study.

Consideration of Infiltration into Cracked Soil

When water infiltrates cracked ground soil, it infiltrates the soil matrix at the ground surface and flows directly to the bottom of the cracks (Figure 3.9). Water then fills the cracks and water seepage into the soil matrix occurs in two directions: vertical seepage from the ground surface and bottom of the cracks to the soil matrix and lateral seepage from the crack walls to the soil matrix (Novak et al., 2000; van Dam, 2000).

Figure 3.9 Infiltration into cracked ground soil

The cracks shown in Figure 3.9 represent the actual crack conditions which have different crack apertures from the ground surface to the bottom of the cracks as

described in Novak et al. (2000) and van Dam (2000). In this study, the idealized crack was assumed to have a constant aperture from the ground surface to the bottom of the crack as shown in Figure 3.10.

The vertical flow from the bottom of the cracks may change the pattern of water content and matric suction of the lower intact layer as compared to the pattern if the cracks did not exist. There is vertical seepage from the ground surface as well as vertical seepage from the bottom of the cracks (Figure 3.10). This process emphasizes the need for a method to model changes in the water content and matric suction of cracked soil.

Figure 3.10 Idealized cracked soil layer during infiltration

Consideration of an Element in the Differential Equation for Unsteady State Seepage

The value of the matric suction of intact soil can be calculated utilizing the value of the head of intact soil. The head of intact soil experiencing seepage can be quantified using the following differential equations for unsteady state seepage for intact soil (Fredlund and Rahardjo, 1993):

$$\frac{\partial}{\partial x} \left(k_{wx} \frac{\partial h_w}{\partial x} + k_{wxy} \frac{\partial h_w}{\partial y} \right) + \frac{\partial}{\partial y} \left(k_{wyx} \frac{\partial h_w}{\partial x} + k_{wy} \frac{\partial h_w}{\partial y} \right) = m_2^w \rho_w g \frac{\partial h_w}{\partial t} \quad (3.43)$$

where:

h_w = hydraulic head

y = elevation

x = x-axis (i.e., horizontal)

$k_{wxx} = k_{w1} \cos^2 \alpha + k_{w2} \sin^2 \alpha$

$k_{wxy} = (k_{w1} - k_{w2}) \sin \alpha \cos \alpha$

$k_{wyx} = (k_{w1} - k_{w2}) \sin \alpha \cos \alpha$

$$k_{yyy} = k_{w1} \sin^2 \alpha + k_{w2} \cos^2 \alpha$$

k_{w1} = major coefficient of permeability

k_{w2} = minor coefficient of permeability

α = angle between direction of k_{w2} to the x -axis

m_2^w = coefficient of water volume change with respect to a change in matric suction ($u_a - u_w$)

ρ_w = density of water

g = gravitational constant

t = time

For an isotropic soil matrix, Eq. (3.43) can be simplified as:

$$\frac{\partial}{\partial x} \left(k_w \frac{\partial h_w}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_w \frac{\partial h_w}{\partial y} \right) = m_2^w \rho_w g \frac{\partial h_w}{\partial t} \quad (3.44)$$

where:

k_w = water permeability in the x - and y -directions

The differential equation that describes an unsteady state flow 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), as shown in Figure 3.11. The REV's are then applied as finite-sized elements of a continuum which can be combined to form a continuum model (Fredlund et al., 2012). Boundaries are then assigned to enclose the continuum. These boundaries include flux and head boundaries.

Figure 3.11 REV considered in an unsteady state flow

The REV of cracked soil includes cracks as well as the soil matrix (Li et al., 2009). Therefore, the REV of cracked soil is larger than that of intact soil. One example of an REV of cracked soil is shown in Figure 3.12. When water enters unsaturated cracked soil, the cracks will be filled with water. The cracks will thus be in a saturated condition with a positive pore water pressure. Water then seeps into the unsaturated soil matrix. In other words, cracks behave as head boundaries to the intact soil matrix.

Figure 3.12 REV of cracked soil compared to REV of intact soil

In this study, to analyze changes in the water content and matric suction of cracked soil, the cracks (Figure 3.13a) are modelled as head boundaries (Figure 3.13b and c). An analysis is then performed by applying Eq. (3.43) or Eq. (3.44) in a numerical analysis. The idealized crack network (Figure 3.4d) is used in the analysis. In addition, a crack is assumed to have the same depth extending from the top to the bottom of the soil layer (Figure 3.10).

Figure 3.13 Modelling a crack network as boundary conditions: (a) 3D view of a crack network; (b) 3D view of a crack network modelled as head boundary conditions; (c) Plan view of a crack network modelled as head boundary conditions

3.5 Proposed Method to Analyze the Effect of Variation in Crack Network on the Water Content and Matric Suction of Cracked Soil

3.5.1 Proposed Averaging Technique of Water Content and Matric Suction of Cracked Soil

When water flows through a crack network in soil, the water content and matric suction of the soil matrix vary in a horizontal plane of cracked soil (Figure 3.14). In addition, the crack network may vary in soil. A crack network is characterized using a distribution function for crack length and crack orientation with a corresponding mean and standard deviation (e.g., Li and Zhang, 2007; Long et al., 1982). The mean and standard deviation of crack length and crack orientation can be obtained from measurements of the cracked soil specimen. However, more than one crack network can have the same mean and standard deviation. This condition results in different patterns of variation in water content and matric suction in cracked soil.

(d)

Figure 3.14 Variation in water content and matric suction of cracked soil: (a) 3D view of variation in water content; (b) 3D view of variation in matric suction; (c) Plan view of hypothetical variation in water content in Plane A; (d) Plan view of hypothetical variation in water content in Plane A

In this study, the average water content and matric suction of a plane is proposed as a method to represent the water content and matric suction values of a plane in cracked soil. The average water content is calculated by considering the cracked soil as a single soil element. First, the three-dimensional contours of water content and matric suction are obtained from the numerical analysis results. The average water content is then calculated as the volume of contour of water content (V_{wc}) above plane B (Figure 3.15a) divided by the area of plane B. Plane B is the plane where water content is equal to zero. The same method is used for obtaining the representative value of matric suction of cracked soil. The average matric suction is calculated as the volume of contour of matric suction ($V_{(ua-uw)}$) above plane C (Figure 3.15b). Plane C is the plane where matric suction is equal to zero.

Figure 3.15 3D contour for obtaining the average water content and matric suction of cracked soil from the contour of water content and matric suction: (a) 3D contour of water content; (b) 3D contour of matric suction

The variation in average water content and matric suction of soil models with different crack networks is then obtained through numerical analyses. The crack networks have the same mean and standard deviation of crack length and orientation. A range of variation of changes in water content and matric suction is obtained for cracked soil. This method is proposed to quantify the effect of variation in crack networks on the water content and matric suction of cracked soil.

3.5.2 Proposed Method to Generate a Crack Network

To quantify the effect of variation in crack networks on the water content and matric suction of cracked soil, various crack networks with the same mean and standard deviation of crack length and orientation need to be generated. Therefore, this study proposes a method to generate crack networks. In this method, the connections among crack endpoints are incorporated in the generation of crack networks. The method is explained in the following steps:

- The statistical parameters of the crack network are obtained from a cracked soil specimen. These parameters include the number of cracks, distribution function for crack length, orientation, and crack midpoint coordinates with the corresponding mean and standard deviation. In this proposed method, the crack length is modelled using a lognormal distribution, the crack orientation is modelled using a uniform distribution, and the crack midpoint coordinates are modelled using a uniform distribution. These statistical parameters serve as a target crack network. A number of crack networks are generated to achieve the target crack network.
- Crack network generation consists of two stages, namely the initial stage of crack network generation and the final stage of crack network generation.
- In the initial stage of crack network generation, A trial number cracks which is lower than the number of cracks in the target crack network is generated.
- Random crack numbers with a uniform distribution between 0 and 1 are generated. The inverse of the cumulative probability density function is then used to calculate random crack numbers with uniform and lognormal distributions (Ang and Tang, 1984). The random crack numbers with a uniform distribution are generated for crack orientation and crack midpoint coordinates,

while the random crack numbers with a lognormal distribution are generated for crack length.

- Each crack is then extended until it intersects another crack or the soil sample boundary. An example of generation of three trial numbers of cracks is shown in Figure 3.16. The sequence of crack extension runs from the first crack until the third crack, as shown in Figure 3.16a-d.
- In the final stage of crack network generation, the number of cracks, crack length, and crack orientation are recalculated and renumbered. The crack intersection points are considered as crack endpoints and the cracks between two intersection points are considered as one crack (Figure 3.16e). Therefore, the number of crack in the final stage will be equal or larger than the number of cracks in the initial stage. By performing this step, connections between cracks are incorporated into the crack network.
- The mean and standard orientation of the crack length, crack orientation, and crack midpoint coordinates are calculated. In addition, the distribution function of the crack midpoint coordinate, crack length, and crack orientation are verified using the R^2 of the distribution plot (Montgomery and Runger, 2007).
- A crack network is repeatedly generated by varying random numbers for crack length, orientation and midpoint coordinates. Trial number of cracks in the initial stage of crack network generation is also varied. The generation is performed repeatedly until the number of cracks in the target crack network is achieved. The mean and standard deviation of the crack midpoint coordinate, crack length, and crack orientation of the target crack should also be achieved. In addition, the criterion of the distribution function should be achieved.

(a)

(b)

(c)

(d)

Figure 3.16 Proposed method of generation of crack network: (a) Generation of first stage crack midpoint and orientation; (b) Crack no. 1 of the first stage crack network; (c) Crack no. 2 of the first stage crack network; (d) Crack no. 3 of the first stage crack network; (e) Final stage crack network

3.6 Summary

This chapter presents a framework to analyze lateral flow through cracked soil. The framework concentrates on two aspects of lateral flow through cracked soil: i) the flow rate through the crack network in the soil; and ii) changes in the water content and matric suction of cracked soil. The crack network in the soil is idealized as a series of linear cracks. A model to predict the lateral flow rate through cracked soil and a method to analyze changes in the water content and matric suction of cracked soil are developed utilizing the idealized crack network.

In this study, the flow into the soil matrix is assumed to be small. Therefore, flow through cracked soil is represented by flow through the crack network. The flow through a single crack is modelled as a flow through parallel plates. Cubic law (Taylor, 1948; Snow, 1968; Snow, 1969) is used to calculate the flow through parallel plates. Additional head losses due to changes in crack aperture are

incorporated in the calculation of the hydraulic gradient between two crack endpoints. The head values at each crack intersection point are then calculated using the conservation of mass principle. The flow rate through the crack network in the soil specimen is then calculated as a summation of the flows through cracks that intersect with the outflow boundary.

Changes in the water content and matric suction of cracked soil are quantified by modelling the crack network as head boundary conditions. An analysis of changes in the water content and matric suction of cracked soil is then performed by applying Eq. (3.43) or Eq. (3.44). In addition, the average water content and average matric suction are used to represent the water content and matric suction in a plane of cracked soil.

The effect of variation in crack networks on the water content and matric suction of cracked soil is quantified by analyzing the average water content and matric suction obtained from models with different crack networks. A range of variation of changes in water content and matric suction can then be obtained for cracked soil. A method is proposed to generate crack networks from a particular distribution function, mean and orientation of the crack length, crack orientation, and crack midpoint coordinates. The connection among crack endpoints is incorporated in crack network generation.

4 CHAPTER 4

RESEARCH PROGRAMME

4.1 Introduction

In this chapter, the research programme is presented. First, the outline of the research programme is presented in Section 4.2. In the following section (Section 4.3), soil characterization is described. The design of the large-scale lateral flow test apparatus is described in Section 4.4. Laboratory tests to investigate performance of the proposed method to analyze flow through cracked soil are described in Section 4.5. Subsequently, Section 4.6 describes the application of the proposed model to predict lateral flow rate through cracked soil. The laboratory tests are also then analyzed numerically, as described in Section 4.7. Lastly, Section 4.8 presents the parametric study of the effect of variation in crack network on the average values of water content and matric suction of a cracked soil.

4.2 Outline of Research Programme

The research programme consisted of six parts:

Soil characterization

The soil used in the laboratory tests was characterized. Basic soil property tests were performed. In addition, small-scale desiccation tests, a compaction test, and a trial compaction test on a small tray were performed to determine the initial conditions used in the lateral flow test. Soil-water characteristic curve (SWCC) tests were also performed using the initial conditions obtained from these tests.

Design of large-scale lateral flow test apparatus

A large-scale lateral flow test apparatus was developed. The design process consisted of performing small-scale desiccation tests, developing a small-scale lateral flow test apparatus, performing large-scale desiccation tests, and developing a large-scale lateral flow apparatus.

Laboratory experiments

Laboratory experiments were performed to verify the proposed method of analysis of lateral flow through cracked soil. The laboratory experiments consisted of small-scale lateral flow tests and large-scale lateral flow tests.

Application of the proposed model to predict lateral flow rate through cracked soil

The proposed method to predict lateral flow rate through cracked soil, which was presented in Chapter 3, was used to predict lateral flow rate through soil specimens. In addition, numerical analyses were performed to further investigate the performance of the proposed model.

Numerical analyses to investigate performance of the method of analysis of change in water content of cracked soil

Numerical analyses were performed to investigate the proposed method of analysis of lateral flow through cracked soil. The analyses included numerical analyses of flow rate through cracked soil and numerical analyses of changes in water content of cracked soil.

Parametric study of the effect of variation in crack network on the average values of water content and matric suction in cracked soil

A parametric study was performed to study the effect of variation in crack network on the average values of water content and matric suction in cracked soil. The numerical analyses, as well as the proposed method of crack network generation, were incorporated into this study. A computer code was developed to implement the proposed method of crack network generation.

4.3 Soil Characterization

Kaolin was selected as the material for the experiment because it is relatively homogeneous. Two conditions of kaolin were used in the experiment: slurried and compacted conditions. The slurried condition was selected for the small-scale test since shrinkage is greatest when the soil dries starting from a slurry condition. It is expected that the largest possible number of cracks will be formed in the small-

scale lateral flow test apparatus under the largest shrinkage condition. Compacted soil was selected to simulate actual soil conditions in the field.

4.3.1 Basic Soil Properties Tests

The basic properties of the soil used in the research were obtained. These include grain size distribution, Atterberg limits, and specific gravity. The tests were performed following the testing standards shown in Table 4.1.

Table 4.1 Tests and references for basic properties of soils

Soil Properties	Standard
Grainsize distribution	ASTM D422 (90)
Liquid Limit	BS 1377:1975
Plastic Limit	ASTM D4318 (95)
Shrinkage Limit	BS 1377
Specific Gravity	ASTM D854(92)
Soil Classification (Unified Soil Classification System)	ASTM D2487(93)

4.3.2 Small-Scale Desiccation Tests and Compaction Tests for Selection of Initial Conditions of the Specimens

Cracked soil specimens were required to investigate the performance of the proposed framework to analyze lateral flow through cracked soil. The cracked soil specimens were obtained from a desiccation process of soil specimens. To obtain cracked soil specimens during desiccation, the initial water content of the slurried and compacted soil had to be determined.

The initial water content of the slurried soil was determined in order to form the specimen into a flat surface and produce the largest number of cracks in the dry condition. Small scale desiccation tests were performed to determine the initial water content of slurried specimens used in the saturated permeability tests, soil-water characteristics curve tests, and lateral flow tests. Three slurried soil specimens

were placed in 25 cm x 25 cm aluminum trays with varying initial water contents (Table 4.2):

- 100% of liquid limit (LL),
- 150% of LL, and
- 200% of LL.

Figure 4.1 Small tray for small-scale desiccation test

The slurried soil specimens were dried at room conditions ($24^{\circ}\text{C} \pm 2^{\circ}\text{C}$ temperature and $78\% \pm 1\%$ relative humidity). The gravimetric water content of the specimens was measured periodically by weighing the specimens and calculating the change in water content. 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 4.4). The number of cracks at a water content level equal to 43.4% was counted using the definition of a single crack as explained in Section 3.2.

Table 4.2 Summary of small-scale desiccation tests

No.	Name of Test	Initial Condition of the Soil	Initial Gravimetric Water Content, w
1	Small-scale desiccation test 1	Slurried soil	100% LL
2	Small-scale desiccation test 2	Slurried soil	150% LL
3	Small-scale desiccation test 3	Slurried soil	200% LL

The initial water content of the compacted soil was determined to obtain a large amount of shrinkage. Shrinkage is obtained if the specimen is compacted at wet of optimum (Holtz et al., 2011). However, the water content should be lower than the plastic limit in order to have workability in soil mixing. Seed and Chan (1959) performed compaction tests on kaolin specimens as shown in Figure 4.2. An initial gravimetric water content equal to 21.8% will result in a large amount of shrinkage as indicated in Figure 4.2. This gravimetric water content equals to 125% of the optimum water content. Therefore, in this study initial water content equal to 125% of the optimum water content was selected as the initial condition for the compacted soil specimens. A compaction test was performed to obtain the optimum water content. The compaction test follows the standard Proctor test (ASTM D698).

Figure 4.2 Shrinkage as a function of water content and type of compaction (after Seed and Chan, 1959)

4.3.3 Trial Compaction Test on Small Tray

A trial compaction test was performed to investigate the density that can be achieved using a hand compactor (Figure 4.3) on the soil in a small tray (Figure 4.1). A soil-water characteristic curve (SWCC) test was then performed using this density. The trial compaction test was performed by compacting the soil at a water content equal to the initial water content determined by the compaction test.

Figure 4.3 Hand compactor

4.3.4 Saturated Permeability Tests

Two saturated permeability tests were performed: one test was performed on a specimen dried from slurried condition and one test was performed on a compacted soil specimen. The first 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%, which is equal to the gravimetric water content at the initial condition of the lateral flow test (Table 4.4). Gravimetric water content of the soil specimen at different times was measured periodically by weighing the specimen and calculating the change in 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.

The second test was performed on a compacted soil specimen. The compacted soil specimen was prepared using static compaction mold. 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.

4.3.5 Soil-water Characteristic Curves of Soils

Two soil-water characteristic curve (SWCC) tests were performed on the intact soil matrix. The first SWCC test was performed on an initially slurried soil and the second test was performed on a compacted soil. In the first test, a drying SWCC test on a slurried specimen was performed. The initial water contents of the initially slurried soil specimen was established by the results of the desiccation tests. The test was performed using a Tempe cell (Figure 4.4) and a 5-bar pressure plate (Figure 4.5). The Tempe cell could have pressures applied up to 100 kPa and the pressure plate apparatus could apply pressures up to 500 kPa of matric suction.

Tempe cells with two sizes were used in the experiments: large-size Tempe cell and small-size Tempe cell. The large size Tempe cell has 8.6 cm inner diameter and 6 cm in height; and the small-size Tempe cell has 5.4 cm inner diameter and 3 cm height. The large-size Tempe cell was used to measure SWCC of the initially slurried soil specimen; whereas the small-size Tempe cell was used to measure SWCC of the compacted soil specimen.

(a)

(b)

Figure 4.4 Tempe cell apparatus: (a) Large-size Tempe cell; (b) Small-size Tempe cell

Figure 4.5 Pressure plate apparatus

Derivation to obtain relationship between gravimetric water content, w and volumetric water content, θ_w , measurement and calculation to obtain both values are explained as follows.

Derivation

The volumetric water content, θ_w is defined as the ratio between the volume of water V_w and the volume of the soil, V as follows:

$$\theta_w = \frac{V_w}{V} \quad (4.1)$$

The degree of saturation, S is defined as the ratio between the volume of water V_w and the volume of voids in the soil, V_v as follows:

$$S = \frac{V_w}{V_v} \quad (4.2)$$

Eq. (4-2) can be written as:

$$V_w = SV_v \quad (4.3)$$

Substituting Eq. (4.3) into Eq. (4.1) gives:

$$\theta_w = \frac{SV_v}{V} \quad (4.4)$$

Porosity, n is defined as the ratio between the volume of voids, V_v and the volume of soil, V :

$$n = \frac{V_v}{V} \quad (4.5)$$

Then, substituting Eq. (4.5) into Eq. (4.4) gives:

$$\theta_w = Sn \quad (4.6)$$

The relationship between porosity, n and void ratio, e is as follows:

$$n = \frac{e}{1 + e} \quad (4.7)$$

Then, substituting Eq. (4.7) into Eq. (4.6) gives:

$$\theta_w = \frac{Se}{1 + e} \quad (4.8)$$

From the basic volume-mass relationship for soils:

$$Se = wG_s \quad (4.9)$$

where:

w = gravimetric water content

G_s = specific gravity

Substituting Eq. (4.9) into (4.8) gives:

$$\theta_w = \frac{wG_s}{1 + e} \quad (4.10)$$

Eq. (4.10) describes the relationship between gravimetric water content and volumetric water content. Degree of saturation, S and specific gravity, G_s are also used in the relationship.

Measurement of Gravimetric Water Content, w

In the beginning of SWCC test, soil was mixed with water to achieve a particular gravimetric water content, w and the following relationships apply:

$$w = \frac{M_w}{M_s} \quad (4.11)$$

$$M_w = wM_s \quad (4.12)$$

Mass of the specimen was then measured and the following relationship applies:

$$M = M_s + M_w \quad (4.13)$$

where:

M = mass of the soil specimen

M_s = mass of solids

M_w = mass of water

Substituting Eq. (4.12) into Eq. (4.13) gives:

$$M = M_s + wM_s \quad (4.14)$$

$$M = M_s(1 + w) \quad (4.15)$$

$$M_s = \frac{M}{(1 + w)} \quad (4.16)$$

Since mass of the specimen, M and gravimetric water content, w were known, then mass of solids, M_s can be calculated using Eq. (4.16). Mass of solids was constant throughout the test. At the end of test, the specimen was placed in the oven at 105°C for 24 hours to obtain the mass of solids. The measured mass of solids served as a check for the calculation of gravimetric water content performed during SWCC test.

The specimen was then saturated. Mass of the saturated specimen, M was measured and mass of water, M_w can be calculated using Eq. (4.13) since mass of solids M_s was constant throughout the test. Gravimetric water content, w at saturation was calculated using Eq. (4.11). Mass of specimen was measured by weighing the soil at each equilibrium of matric suction. Mass of water was calculated by subtracting mass of water at saturation with the reduction of mass due to the increase of matric suction. Gravimetric water content, w at each equilibrium of matric suction was calculated using Eq. (4.11).

Measurement of Specific Gravity, G_s

Specific gravity, G_s was measured before performing SWCC test.

Calculation of Void Ratio, e

Volume of soil solid can be calculated using the following relationships:

$$\rho_s = \frac{M_s}{V_s} \quad (4.17)$$

$$V_s = \frac{M_s}{\rho_s} \quad (4.18)$$

$$V_s = \frac{M_s}{G_s \rho_w} \quad (4.19)$$

where:

ρ_s = density of solids

V_s = volume of solids

ρ_w = density of water

Volume of the specimen, V was measured at each matric suction. In addition, the volume of the specimen, V at a particular water content was also calculated from the shrinkage curve obtained from the experiment in this study (Figure A.1 in Appendix A). The volume of soil calculated from the shrinkage curve served as a checking for the measurement of the volume of soil during SWCC test.

Volume of void was calculated as:

$$V = V_v + V_s \quad (4.20)$$

Therefore:

$$V_v = V - V_s \quad (4.21)$$

Void ratio can be calculated by substituting Volume of solid, V_s and volume of voids, V_v into the following relationship:

$$e = \frac{V_v}{V_s} \quad (4.22)$$

Calculation of Volumetric Water Content, θ_w

Volumetric water content, θ_w at each equilibrium of matric suction was calculated using Eq. (4.10) by incorporating the values of gravimetric water content, w , void ratio, e , and specific gravity, G_s .

The initially slurried soil specimen for the SWCC test was prepared 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 is called the initial drying SWCC (Pham et al., 2005). The other two curves of SWCC are the main drying SWCC and the main wetting SWCC (Pham et al., 2005). The main wetting SWCC was used in the numerical analysis of the small-scale lateral flow test. The main wetting SWCC was predicted from the main drying SWCC. The 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 of the drying SWCC and keeping the other parameters the same. This factor was based on the recommendation by Pham et al., (2005). The main wetting SWCC was predicted by dividing the slope of the main drying curve by 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.

In the second SWCC test, the initial water content for the compacted soil was set equal to 125% of the optimum water content. A drying-wetting SWCC test was performed. The compacted soil specimen for the SWCC test was prepared using the static compaction mold. The soil was then trimmed and inserted into the Tempe cell ring. In the lateral flow tests, the wetting process occurs. However, the wetting process that occurred did not follow the boundary wetting curve. Therefore, a scanning wetting curve was predicted. The scanning curve was predicted using the method proposed by Mualem (1974) as suggested by Pham et al. (2005) because of the simplicity and the accuracy of the method. The scanning curve starts from the

point where the water content is equal to the water content at the start of the large-scale lateral flow test (Table 4.5).

4.3.6 Permeability Functions of Soils

The permeability functions of soils were calculated using the indirect method (Fredlund and Rahardjo, 1993). The permeability function was calculated for the predicted wetting SWCC of the initially slurried soil specimen and the scanning wetting SWCC of the compacted soil specimen. Saturated permeability measured in the laboratory as described in Section 4.3.4 was incorporated in the calculation. In this study, 40 divisions of water content were used in the calculation of permeability function.

4.4 Design of the Large-Scale Lateral Flow Test Apparatus

The design of the large-scale lateral flow apparatus includes developing the small-scale lateral flow apparatus, performing small-scale desiccation tests, performing large-scale desiccation tests, and finally developing the large-scale lateral flow apparatus.

A small-scale lateral flow apparatus was designed as an initial stage of the design of the large-scale lateral flow apparatus. The mechanism of the small-scale lateral flow apparatus was used as a basis in the design of the large-scale lateral flow apparatus. In addition, the performance of the small-scale lateral flow apparatus was observed to improve the design of the large-scale lateral flow apparatus.

Large-scale desiccation tests were performed to investigate the cracks that were formed in the specimen. A cracked soil specimen was created to investigate the performance of the proposed seepage model. In addition, the number of cracks is influenced by the thickness of the soil and interface between the soil materials (Kodikara et al., 2000; Corte and Higashi, 1960). Therefore, the effect of thickness on the number of cracks should be incorporated into the design of the apparatus.

The large-scale lateral flow apparatus was designed following the mechanism of the small-scale lateral flow apparatus. The size of the soil specimen in the large-scale lateral flow should meet the following conditions:

- The soil specimen in the large-scale lateral flow test apparatus should have a number of cracks
- A high number of cracks is preferred because it will provide an opportunity to prove the performance of the proposed framework for analyzing flow through cracked soil.
- There should be connectivity between the cracks and connectivity between the cracks and inflow and outflow boundaries to ensure there is a lateral flow through the crack network in the soil.
- The size of the large-scale lateral flow test apparatus should be such that it can be placed in the laboratory. A size of 1 m x 1 m was initially planned. This size was verified using large-scale desiccation tests to achieve the above criteria.

Therefore, the large-scale desiccation tests were performed to investigate:

- The number of cracks that will be formed in a particular area
- The connectivity of the crack network.
- The formation of cracks

The size of the specimen in the large-scale lateral flow apparatus was determined in accordance with the results of the large-scale desiccation test.

4.4.1 Small-Scale Lateral Flow Apparatus

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. A schematic diagram of the 1-D lateral flow apparatus is shown in Figure 4.6. It consisted of a box with three compartments:

- The first compartment is the upstream water compartment.
- The second compartment contains the cracked soil specimen.
- The third compartment is the downstream water compartment.

Holes 0.5 cm x 2.5 cm with a spacing of 0.5 cm were constructed on the wall between the first and second compartments and on the wall between the second and 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.

(a)

(b)

Figure 4.6 Small-scale lateral flow apparatus: (a) 3-D view of the lateral flow apparatus; (b) Plan view of the lateral flow apparatus; (c) Section A-A; (d) Section B-B (Krisnanto et al., 2014)

4.4.2 Large-Scale Desiccation Tests

Large-scale lateral flow tests were performed on a large-scale tray, as shown in Figure 4.7. Six large-scale desiccation tests were performed. Three tests were performed on slurried soil and three tests were performed on compacted soil. The base and sides of the tray was covered by grease to simulate the boundary conditions of the large-scale lateral flow test. The same boundary conditions of the base were applied for all desiccation tests. The tests were performed at a room temperature of 25°C and the temperature and relative humidity were measured throughout the tests. In addition, the potential evaporation was measured by

providing a container near the soil specimen. The weight of the container containing water was measured regularly to measure the potential evaporation.

The slurried soil was prepared by mixing the soil at 150%LL and then pouring into the tray to a particular initial thickness for each test (Table 4.3). The compacted soil was prepared by compacting the soil in the tray at water content equal to 125% of the optimum water content. The soil specimen in each test was then allowed to desiccate. Changes in water content of the soil specimen were measured by weighing the tray containing the soil. The test was performed until the shrinkage limit was achieved. Some photos were obtained throughout the test to capture crack development. At the end of desiccation process, the cracked soil specimen was scanned to obtain a file that can be digitized to obtain a digitized crack network. At the end of the test, gravimetric water content samplings were carried out. Details of the tests are shown in Table 4.3.

Figure 4.7 Large tray for large-scale desiccation tests

Table 4.3 Summary of large-scale desiccation tests

No.	Name of Test	Initial Soil Condition	Measurement	Initial Thickness (cm)
1	Large-scale desiccation test 1	Slurried soil	Gravimetric water content sampling at end of test	2.5
2	Large-scale desiccation test 2	Slurried soil	Gravimetric water content sampling at end of test	1.23
3	Large-scale desiccation test 3	Slurried soil	Gravimetric water content sampling at end of test	1.23
4	Large-scale desiccation test 4	Compacted soil	Gravimetric water content sampling at end of test	2.01
5	Large-scale desiccation test 5	Compacted soil	Gravimetric water content sampling at end of test	1.47
6	Large-scale desiccation test 6	Compacted soil	Gravimetric water content sampling at end of test	1.47

4.4.3 Description of the Large-Scale Lateral Flow Apparatus

The large-scale lateral flow apparatus is shown in Figure 4.8. Basically, the large-scale lateral flow test apparatus is similar to the small-scale lateral flow test apparatus. The apparatus consists of three compartments:

- The first compartment is the upstream water compartment.
- The second compartment contains the cracked soil specimen.
- The third compartment is the downstream water compartment.

Some provisions for water outflow at the upstream and downstream compartments are provided so that the height of the water level in these compartments could be adjusted. The soil specimen compartment size is 1 m x 1 m in the plan view. The soil specimen compartment is enclosed by a wall 50 cm in height. A gap and pipe were provided on the wall between the first and second compartments and on the wall between the second and 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 (Figure 4.8c, d).

(a)

(b)

(c)

(d)

Figure 4.8 Large-scale lateral flow apparatus: (a) Plan view; (b) 3-D view; (c) Gap for water to flow; (d) Pipe connection for water flow into and from the cracked soil compartment

In addition, instruments were provided including a flow meter, ICT sensor, and standpipe. The flow meter was used to measure inflow into the upstream water compartment, the ICT sensor was used to measure the volumetric water content at several locations in the specimen, and the standpipe was used to measure the head at some crack intersection points. Instrumentation of the large-scale lateral flow apparatus is shown in Figure 4.9.

(a)

(b)

(c)

(d)

Figure 4.9 Instrumentation of the large scale lateral flow apparatus: (a) Flow meter; (b) ICT sensor; (c) ICT data recording equipment; (d) Standpipe

Calibration was performed on the ICT sensor. Since the length of the rod was larger than the planned thickness of soil, during the test a piece of Styrofoam was inserted in the rod so that the part of the rod that was not in contact with the soil specimen was covered by the Styrofoam (Figure 4.9b). This condition was incorporated in the calibration process. Calibration was performed by compacting soil specimens with a certain water content. The ICT sensor was then inserted and the measured volumetric water content was recorded (Figure 4.10). This process was repeated until the calibration chart was obtained. The calibration chart is shown in Appendix B.

Figure 4.10 Calibration of ICT

4.5 Laboratory Tests

4.5.1 Small-Scale Lateral Flow Tests

Two small-scale lateral flow tests were performed. Small-scale lateral flow tests were performed using the apparatus shown in Figure 4.6. Slurried soil was allowed to desiccate until the designated gravimetric water content (Table 4.4). A crack network formed during the desiccation process. At the end of the desiccation process, the crack network in the soil was scanned. A laser scanner was used to produce the plan view of the network of cracks. The laser scanner scanned the cracked soil specimen to result in a file that contains groups of points that describe the crack network. The finest resolution of the laser scanner was 1 mm. The data were then digitized using AutoCAD (Autodesk, 2004). 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 results of digitizing from the laser scanner and photograph were then combined as one digitized map plan view of the network of cracks.

In addition, a photo of the cracked soil was obtained. The results from scanning and the photo were then digitized to obtain a digitized crack network. From the digitized crack network, the skeleton crack network and idealized crack network were obtained.

During the lateral tests, water in the upstream compartment was maintained at a constant head value that was greater than the head at the downstream water compartment (third compartment). Water was directed to flow laterally through the network of cracks in the soil specimen (in the second compartment). Since the model was developed for lateral flow through cracked soil, lateral flow between the edge of the soil and box wall and lateral flow on top of the specimen were prevented from occurring. Therefore, the edge of the soil specimen was sealed to

the box wall and a layer of plastic sheet was put on top of the cracked soil. The edge of the plastic sheet was sealed to the box using silicon glue to avoid water leakage. The surface of the soil specimen was sealed to the plastic sheet using silicon glue to minimize leakage. Water was then poured on top of the plastic sheet to produce a pressure head on the plastic sheet that 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 water in the downstream compartment (the third compartment) was maintained at a constant head during the tests. In the small-scale lateral flow tests, only the outflow rate was measured.

Two small-scale lateral flow tests were performed. Details of the small-scale lateral flow tests are shown in Table 4.4.

Table 4.4 Details of the small-scale laboratory lateral flow tests

Test :	Small-Scale Lateral Flow Test 1	Small-Scale Lateral Flow 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, w (%) :	43.4	43.4

4.5.2 Large-Scale Lateral Flow Tests

Three aspects were investigated in the large-scale lateral flow tests:

- The statistical parameters of the crack network in the soil
- The lateral flow rate through the cracked soil
- Variation in the water content of the cracked soil

The large-scale lateral flow tests were performed similarly to the small-scale lateral flow tests. Large-scale lateral flow tests were performed using the apparatus shown in Figure 4.8. However, in these tests, sand was used on top of the plastic sheet above the cracked soil specimen to produce pressure on the plastic sheet.

The soil was compacted in the cracked soil compartment (Figure 4.8). Grease was applied at the base of the cracked soil compartment before the soil was compacted to minimize the lateral flow through base of the soil during lateral flow test. The compacted soil specimen was saturated by pouring water. The specimen was then covered with plastic sheet for 24 hours to ensure the equalization of water content throughout the specimen. A saturated water content equal to 54% was achieved. The saturated water content was calculated utilizing the water content at compaction and the total mass of soil that was compacted. The soil specimen was allowed to desiccate until the designated gravimetric water content 34% was reached (Table 4.5). During the desiccation of the specimen, thickness measurement was performed at a grid with distance of 20 cm over the specimens. Thickness measurement was performed by subtracting the height of second compartment without soil with height of second compartment with soil as shown in Figure 4.11. Soil volume was then calculated incorporating the soil thickness and plan area of soil specimen. Gravimetric water content was then back calculated using the shrinkage curve obtained from the shrinkage test. Thickness measurement was performed at several times during the desiccation process. As a results, values of gravimetric water content during desiccation could be obtained. A crack network formed during the desiccation process. After reaching the designated water content, the crack network in the soil was scanned. In addition, a photo of the cracked soil was obtained. The specimen was covered with plastic sheet for 24 hours to ensure equalization of water content in the specimen before the large-scale lateral flow tests were started.

The results from scanning and the photo were then digitized to obtain a digitized crack network. From the digitized crack network, the skeleton crack network and idealized crack network were obtained. Statistical analysis was then performed on

the idealized crack network. The mean and standard deviation of the crack length, orientation, and midpoint coordinates were calculated. In addition, the R^2 values of the probability plot for the crack length, orientation, and midpoint coordinates were calculated. Three probability plots were performed: uniform distribution, normal, and lognormal distribution.

Figure 4.11 Method of thickness measurement of the cracked soil specimen

To maintain a constant inflow rate of water, water was supplied into the upstream water compartment. Some amount of water will then overflow from the upstream water compartment through the pipe (Figure 4.8b). The inflow rate of the water supply into the upstream water compartment was measured using the flow meter (Figure 4.9a). Excess water flow rate from the upstream water compartment was measured by weighing the excess water every 1 minute interval. The inflow rate of water into the cracked soil specimen was computed by subtracting the flow rate from the water supply with the water overflow rate from the upstream water compartment. As a result, the inflow rates to the soil were obtained for every 1 minute interval. In addition, the outflow rate from the cracked soil specimen was measured by weighing the outflow water from the downstream water compartment every 1 minute interval.

Two large-scale lateral flow tests were performed. In the first test, only the flow rate and water content at the end of test were measured. Measurement of the water content at the end of the test was performed by obtaining samples of water content from the cracked soil specimen. Two types of samples were obtained: gravimetric water content samples and volumetric water content samples. In the gravimetric water content samples, only the mass of the soil was measured. In the volumetric water content samples, in addition to the mass, the volume of the soil was measured. Volumetric water content samples were obtained by inserting a steel tube into the soil (Figure 4.12). The soil was then extracted from the tube. The volume and mass of the soil sample was measured.

Figure 4.12 Tube for volumetric water content sampling

In the second test, in addition to these measurements, ICT sensors and standpipes were used. ICTs were installed at five locations in the cracked soil specimen. The locations were selected so that some ICTs were located near cracks and some ICTs were located at the centre of crack cells. ICTs measured the volumetric water content at one minute intervals. Standpipes were installed at four crack intersection points to verify the calculated head values. Details of the large-scale lateral flow tests are shown in Table 4.5 and details of the measurements of the large-scale lateral flow tests are shown in Table 4.6.

Table 4.5 Details of the large-scale laboratory lateral flow tests

Test :	Large-Scale Lateral Flow Test 1	Large-Scale Lateral Flow Test 2
Type of test :	Constant head	Constant head
Upstream head (m) :	0.122	0.122
Downstream head (m) :	0.10	0.10
Thickness of soil (m) :	0.025	0.025
Initial gravimetric water content of soil matrix, w (%) :	34	34

Table 4.6 Summary of the type of water content measurements: (a) Large-scale lateral flow test 1; (b) Large-scale lateral flow test 2

(a)

Location	X (m)	Y (m)	Type and Method of Water Content Measurement	
			Gravimetric water content, w (sampling method)	Volumetric water content, θ_w (sampling method)
1	0.05	0.94	√	
2	0.05	0.74	√	
3	0.05	0.54	√	
4	0.05	0.34	√	
5	0.05	0.14	√	
6	0.05	0.04	√	
7	0.25	0.86	√	
8	0.25	0.79	√	√
9	0.25	0.61	√	
10	0.25	0.49	√	√
11	0.25	0.36	√	
12	0.25	0.24	√	√
13	0.25	0.11	√	

Location	X (m)	Y (m)	Type and Method of Water Content Measurement	
			Gravimetric water content, w (sampling method)	Volumetric water content, θ_w (sampling method)
14	0.38	0.74	√	
15	0.38	0.49	√	
16	0.38	0.24	√	
17	0.50	0.86	√	
18	0.50	0.74	√	√
19	0.50	0.61	√	
20	0.50	0.49	√	√
21	0.50	0.24	√	√
22	0.50	0.11	√	
23	0.60	0.49	√	√
24	0.63	0.74	√	
25	0.63	0.24	√	
26	0.75	0.86	√	
27	0.75	0.74	√	√
28	0.75	0.61	√	
29	0.75	0.49	√	√
30	0.75	0.36	√	
31	0.75	0.24	√	√
32	0.75	0.11	√	
33	0.88	0.74	√	
34	0.88	0.49	√	
35	0.88	0.24	√	

(b)

Location	X (m)	Y (m)	Type and Method of Water Content Measurement		
			Gravimetric water content, w (sampling method)	Volumetric water content, θ_w (sampling method)	Volumetric water content, θ_w (instrumentation method)
1	0.53	0.48	√	√	√
2	0.75	0.49	√		
3	0.76	0.79	√	√	√
4	0.78	0.27	√	√	√
5	0.10	0.49	√		
6	0.50	0.74	√		
7	0.25	0.74	√		
8	0.29	0.49	√	√	√
9	0.25	0.24	√		
10	0.52	0.29	√	√	√

A Summary of the small- and large-scale lateral flow tests is presented in Table 4.7.

Table 4.7 Summary of the lateral flow tests

No.	Name of Test	Description of Test	Measurement
1	SLF-1	Small-scale lateral flow test 1	<ul style="list-style-type: none">• Lateral outflow rate• Gravimetric water content sampling at end of test
2	SLF-1	Small-scale lateral flow test 2	<ul style="list-style-type: none">• Lateral outflow rate• Gravimetric water content sampling at end of test
3	LLF-1	Large-scale lateral flow test 1	<ul style="list-style-type: none">• Lateral inflow rate• Lateral outflow rate• Gravimetric water content sampling at end of test• Volumetric water content sampling at end of test
4	LLF-2	Large-scale lateral flow test 2	<ul style="list-style-type: none">• Lateral inflow rate• Lateral outflow rate• Volumetric water content measurement during the test• Gravimetric water content sampling at end of test• Volumetric water content sampling at end of test

4.6 Prediction of Lateral Flow Rate through a Crack Network and Comparison of Flow through a Crack Network with Flow through Cracked Soils

The proposed model to predict lateral flow (Eqs. (3.38) and (3.18)) was used to predict lateral flow through a crack network in soil. The model was applied to the small-scale lateral flow tests and large-scale lateral flow tests. The idealization process described in Section 3.2 was used to obtain the idealized crack network.

4.7 Numerical Analyses of Laboratory Tests

The numerical analyses consist of numerical analyses to quantify lateral flow rates through cracked soils and numerical analyses to model changes in the water content and matric suction of cracked soils.

4.7.1 Numerical Analyses to Quantify Lateral Flow Rates through Cracked Soils

To analyze the seepage rate into the soil matrix, numerical analyses of the laboratory test were performed using SVFlux (Soil Vision, 2009). These analyses were performed to provide an additional verification to the laboratory tests on the assumption used in the proposed model of flow rate through the cracked soil that seepage rate into the soil matrix is relatively small compared to the flow through the crack network. The same boundary conditions as in the laboratory test were assigned to the finite element model. The SWCC and permeability function of the soil matrix were used as inputs in the numerical analyses. The crack network was modelled as a saturated material while incorporating the permeability calculated using Eq. (3.34). However, the additional head loss calculated using Eq. (3.17) could not be incorporated into 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:

$$q = q' \quad (4.23)$$

where:

q = the flow rate calculated from the proposed model

q' = the flow rate through a single crack in the numerical simulation.

From Eq. (3.2), incorporating the head values of two crack intersection points results in:

$$\frac{gb^3}{12\nu} \frac{(H_j - H_k - h_l)}{L} = \frac{gb^3}{12\nu} \frac{(H_j - H_k)}{L} \quad (4.24)$$

$$b' = \sqrt[3]{\frac{H_j - H_k - h_l}{H_j - H_k}} b^3 \quad (4.25)$$

where:

b = the crack aperture calculated using the proposed model (Eq. (3.38))

b' = the crack aperture used in the numerical model

H_j = the heads at crack intersection point j

H_k = the heads at crack intersection point k

h_l = the additional head loss (Eq. (3.17))

L = the length of the corresponding crack

The aperture of each crack was calculated using Eq. (4.25). The calculated value was used in the numerical model.

The model is applied to the small-scale lateral flow tests and large scale lateral flow tests. A summary of the numerical analyses to quantify lateral flow rates through cracked soils is shown in Table 4.8 (analyses 1-1, 1-5, 1-9, and 1-13).

Table 4.8 Summary of the numerical analyses

Analysis No.	Name of Numerical Analysis	Laboratory Test to be Simulated	Description of the Analysis	Computed Parameters
1-1	SmallLF1-SatCr	Small-scale lateral flow test 1	<ul style="list-style-type: none"> • The soil matrix and the crack network were modelled as different materials. • The crack cells were modelled as unsaturated materials. • The crack network was modelled as saturated materials. 	<ul style="list-style-type: none"> • Lateral inflow rate through the cracked soil model at 30 second intervals. • Lateral out flow rate through the cracked soil model at 30 second intervals.
1-2	SmallLF1-BC	Small-scale lateral flow test 1	<ul style="list-style-type: none"> • The crack network was modelled as head boundary conditions (the proposed method). 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at end of test.
1-3	SmallLF1-C1	Small-scale lateral flow test 1	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Fredlund et al. (2010) method was used in the 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at end of test.
1-4	SmallLF1-C2	Small-scale lateral flow test 1	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Li et al. (2011) method was used in the analysis. 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at end of test.

Analysis No.	Name of Numerical Analysis	Laboratory Test to be Simulated	Description of the Analysis	Computed Parameters
1-5	SmallILF2-SatCr	Small-scale lateral flow test 2	<ul style="list-style-type: none"> • The soil matrix and the crack network were modelled as different materials. • The crack cells were modelled as unsaturated materials. • The crack network was modelled as saturated materials. 	<ul style="list-style-type: none"> • Lateral inflow rate through the cracked soil model at 30 second intervals. • Lateral out flow rate through the cracked soil model at 30 second intervals.
1-6	SmallILF2-BC	Small-scale lateral flow test 2	<ul style="list-style-type: none"> • The crack network was modelled as head boundary conditions (the proposed method). 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at end of test.
1-7	SmallILF2-C1	Small-scale lateral flow test 2	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Fredlund et al. (2010) method was used in the 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at end of test.
1-8	SmallILF2-C2	Small-scale lateral flow test 2	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Li et al. (2011) method was used in the analysis. 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at end of test.

Analysis No.	Name of Numerical Analysis	Laboratory Test to be Simulated	Description of the Analysis	Computed Parameters
1-9	LargeLF1-SatCr	Large-scale lateral flow test I	<ul style="list-style-type: none"> • The soil matrix and the crack network were modelled as different materials. • The crack cells were modelled as unsaturated materials. • The crack network was modelled as saturated materials. 	<ul style="list-style-type: none"> • Lateral inflow rate through the cracked soil model at 1 minute intervals. • Lateral out flow rate through the cracked soil model at 1 minute intervals.
1-10	LargeLF1-BC	Large-scale lateral flow test I	<ul style="list-style-type: none"> • The crack network was modelled as head boundary conditions (the proposed method). 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at sampling locations at end of test. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
1-11	LargeLF1-C1	Large-scale lateral flow test I	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Fredlund et al. (2010) method was used in the analysis. 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at sampling locations at end of test. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.

Analysis No.	Name of Numerical Analysis	Laboratory Test to be Simulated	Description of the Analysis	Computed Parameters
1-12	LargeLF1-C2	Large-scale lateral flow test 1	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Li et al. (2011) method was used in the analysis. 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations at end of test. • Volumetric water content at sampling locations at end of test. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
1-13	LargeLF2-SatCr	Large-scale lateral flow test 2	<ul style="list-style-type: none"> • The soil matrix and the crack network were modelled as different materials. • The crack cells were modelled as unsaturated materials. • The crack network was modelled as saturated materials. 	<ul style="list-style-type: none"> • Lateral inflow rate through the cracked soil model at 1 minute intervals. • Lateral out flow rate through the cracked soil model at 1 minute intervals.
1-14	LargeLF2-BC	Large-scale lateral flow test 2	<ul style="list-style-type: none"> • The crack network was modelled as head boundary conditions (the proposed method). 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations end of test. • Volumetric water content at sampling locations at time: 0, 25 min, 50 min, 75 min. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.

Analysis No.	Name of Numerical Analysis	Laboratory Test to be Simulated	Description of the Analysis	Computed Parameters
1-15	LargeLF2-C1	Large-scale lateral flow test 2	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Fredlund et al. (2010) method was used in the analysis. 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations end of test. • Volumetric water content at sampling locations at time: 0, 25 min, 50 min, 75 min. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
1-16	LargeLF2-C2	Large-scale lateral flow test 2	<ul style="list-style-type: none"> • The cracked soil specimen was modelled as a continuum. • The Li et al. (2011) method was used in the analysis. 	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations end of test. • Volumetric water content at sampling locations at time: 0, 25 min, 50 min, 75 min. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.

4.7.2 Numerical Analyses of Change in Water Content and Matric Suction in Cracked Soils using the Proposed Method

Numerical analyses were performed to investigate the performance of the proposed method for analyzing changes in the water content and matric suction of cracked soils. The proposed method (Section 3.4) was used to model changes in water content and matric suction of cracked soils. The results were then compared with the water content values obtained from the laboratory tests. Numerical analyses were performed using SVFlux software (Soil Vision, 2009).

Numerical analyses were performed to simulate changes in the water content and matric suction of cracked soils. To obtain the head boundaries of each crack cell, the heads between two crack intersection points were calculated through linear interpolation from the head of the two crack intersection points. The heads at the intersection points were obtained from the calculation of the prediction of lateral flow rate through the cracked soil specimen (Section 4.6). A summary of the analyses of changes in water content and matric suction along cracked soils using the proposed method are shown in Table 4.8 (analyses 1-2, 1-6, 1-10, and 1-14).

4.7.3 Numerical Analyses of Lateral Flow Tests by Modelling Cracked Soil as a Continuum Material

In addition, numerical analyses by modelling the cracked soils as continuums were performed. The analyses were performed as a comparison with the proposed method for analyzing changes in the water content and matric suction of cracked soils. Numerical analyses were performed to simulate lateral flow tests using representations of the cracked soils as continuum materials to verify that modelling a cracked soil as a continuum material will result in water content values that are different from those obtained from laboratory tests. Two methods were implemented in the analyses: the method proposed by Fredlund et al. (2010) and the method proposed by Li et al. (2011).

In the Fredlund et al. (2010) method, the SWCC and permeability function of the continuum that represented the cracked soil were obtained. The SWCC of the

cracked soil has two air entry values (AEVs): one AEV corresponds to the crack network and one AEV corresponds to the soil matrix. In this study, the mean crack aperture was used in the calculation of the AEV of the crack network, whereas the AEV of the soil matrix was obtained from the laboratory tests. The saturated permeability of the cracked soil was then calculated, combining the saturated permeability of the crack network and the saturated permeability of the soil matrix. The saturated permeability of the crack network was computed using Kozeny and Carman's method (Kozeny, 1927; Carman, 1939). In this study, the permeability of the soil matrix was obtained using the indirect calculation method as presented in Section 4.3.6. The permeability function was then computed, incorporating Irmay's (1971) method and Leong and Rahardjo's (1997) method. The SWCC and permeability function of the cracked soil were incorporated in the crack soil model in the numerical analysis.

In the Li et al. (2011) method, the SWCC was calculated based on the pore size distribution of the cracked soil. The volumetric water content of the cracked soil at a matric suction was calculated as a summation of the volumetric water content of the soil matrix and the volumetric water content of the crack network. Both were weighed by each porosity. The permeability function was calculated by superimposing the permeability of the crack network and the permeability of the soil matrix multiplied by a volumetric weighing factor. The permeability of the crack network was calculated using cubic law (Taylor, 1948; Snow, 1968; Snow, 1969), as used in Eq. (3.2). The SWCC and permeability function of the cracked soil was incorporated in the crack soil model in the numerical analysis.

A summary of the analyses of lateral flow modelling the cracked soil as a continuum material are shown in Table 4.8 (analyses 1-3, 1-4, 1-7, 1-8, , 1-11, 1-12, 1-15, and 1-16).

4.8 Parametric Study of the Effect of Variation in Crack Network on the Average Values of Water Content and Matric Suction of a Cracked Soil

A parametric study was performed to quantify the effect of variation in crack network on the average values of water content and matric suction of cracked soil. Some models of cracked soils were developed for each large-scale lateral flow test. The crack network of each large-scale lateral flow test was characterized to obtain the distribution function, mean and standard deviation of crack length, crack orientation, and crack midpoint coordinates. Crack networks were generated by incorporating the statistical parameters obtained from the cracked soil specimens. Based on these crack networks, soil models were developed. Changes in water content and matric suction were analyzed using numerical analyses of these models.

4.8.1 Characterization of the Crack Network in Soils

Three distribution functions were used to characterize the crack network in the soil: uniform distribution, normal distribution, and lognormal distribution. Three functions were used to characterize the crack network in the soil because they were previously used to characterize the crack network in the soil in as presented Chapter 2.

In addition, the performance of each distribution function used to characterize the distribution of the crack midpoint coordinate, crack length, and crack orientation was verified using the R^2 of the distribution plot (Montgomery and Runger, 2007).

4.8.2 Numerical Generation of Crack Network

Crack networks were generated based on the statistical parameters of the crack networks of the laboratory specimens in the large-scale lateral flow tests. The method proposed in Chapter 3 was used in crack network generation to obtain variation in the crack network in the soil model. A computer code to generate random crack networks was developed. FORTRAN 77 was implemented in the code. The flow chart of the computer code is shown in Figure 4.13. The method presented in Section 3.5.2 was applied in the development of the computer code. A random number generator algorithm proposed by Etter (1990) was used in the

computer code. Three seed numbers were used as input for random number generation: one seed number was for the X midpoint coordinate generation, one seed number was for the Y midpoint coordinate generation, and one seed number was for crack orientation generation. In addition, the performance of the final stage crack network as compared to the target crack network was assessed using the following parameters:

- Error of number of cracks
- Error of mean of crack length
- Error of standard deviation of crack length
- Error of mean of crack orientation
- Error of standard deviation of crack length
- Error of mean of crack midpoint X coordinates
- Error of standard deviation of crack midpoint X coordinates
- Error of mean of crack midpoint Y coordinates
- Error of standard deviation of crack midpoint Y coordinates
- R^2 of lognormal frequency distribution plot of crack length
- R^2 of uniform frequency distribution plot of crack orientation
- R^2 of uniform frequency distribution plot of crack midpoints X coordinates
- R^2 of uniform frequency distribution plot of crack midpoints Y coordinates

Error of number of cracks is defined as the difference between the number of cracks of the final stage crack network and the target number of cracks:

$$ErrNum = NI - N \quad (4.26)$$

where:

$ErrNum$ = error of number of cracks

NI = number of generated cracks at the final stage crack network

N = target number of cracks

Error of number of cracks should be equal or greater than the selected error of number of cracks criterion.

Figure 4.13 Flow chart of computer code for crack network generation

Error of mean of crack length is defined as the difference between the mean length of the final stage crack network and the target mean length of crack network divided by the target mean length of crack network:

$$ErrMLength = \frac{MLengthl - MLength}{MLength} \quad (4.27)$$

where:

$ErrMLength$ = error of mean of crack length

$MLengthl$ = mean of crack length of the final stage crack network

$MLength$ = target mean of crack length of crack network

Error of mean of crack length should be equal or greater than the selected error of mean of crack length criterion.

Error of standard deviation of crack length is defined as the difference between the standard deviation of crack length of the final stage crack network and the target standard deviation of crack length of crack network divided by the target standard deviation of crack length of crack network:

$$ErrStdvLength = \frac{StdvLength1 - StdvLength}{StdvLength} \quad (4.28)$$

where:

$ErrStdvLength$ = error of standard deviation of crack length

$StdvLength1$ = standard deviation of crack length of the final stage crack network

$StdvLength$ = target standard deviation of crack length of crack network

Error of standard deviation of crack length should be equal or greater than the selected error of standard deviation of crack length criterion.

Error of mean crack orientation is defined as the difference between mean of crack orientation of the final stage crack network and the target mean of orientation of crack network divided by the target mean of orientation of crack network:

$$ErrMOrient = \frac{MOrient1 - MOrient}{MOrient} \quad (4.29)$$

where:

$ErrMOrient$ = error of mean of crack orientation

$MOrient1$ = mean of crack orientation of the final stage crack network

$MOrient$ = target mean of orientation of crack network

Error of mean crack orientation should be equal or greater than the selected error of mean of crack orientation criterion.

Error of standard deviation of crack orientation is defined as the difference between the standard deviation of crack orientation of the final stage crack network and the

target standard deviation of crack orientation of crack network divided by the target standard deviation of crack orientation of crack network:

$$ErrStdvOrient = \frac{StdvOrient1 - StdvOrient}{StdvOrient} \quad (4.30)$$

where:

ErrStdvOrient = error of standard deviation of crack orientation

StdvOrient1 = standard deviation of crack orientation of the final stage crack network

StdvOrient = target standard deviation of crack orientation of crack network

Error of standard deviation of crack orientation should be equal or greater than the selected error of standard deviation of crack orientation criterion.

Error of mean of crack midpoint X coordinates is defined as the difference between the mean of crack midpoint X coordinates of the final stage crack network and the target mean of crack midpoint X coordinates network of crack network divided by the target mean of crack midpoint X coordinates network of crack network:

$$ErrMXmid = \frac{MXmid1 - MXmid}{MXmid} \quad (4.31)$$

where:

ErrMXmid = error of mean of crack midpoint X coordinates

MXmid1 = mean of crack midpoint X coordinates of the final stage crack network

MXmid = target mean of crack midpoint X coordinates network of crack network

Error of mean of crack midpoint X coordinates should be equal or greater than the selected error of mean of crack midpoint X coordinates criterion.

Error of standard deviation of crack midpoint X coordinates is defined as the difference between standard deviation of crack midpoint X coordinates of the final stage crack network and the target standard deviation of crack midpoint X coordinates network of crack network divided by the target standard deviation of crack midpoint X coordinates network of crack network:

$$ErrStdvXmid = \frac{StdvXmid1 - StdvXmid}{StdvXmid} \quad (4.32)$$

where:

ErrStdvXmid = error of standard deviation of crack midpoint X coordinates

StdvXmid1 = standard deviation of crack midpoint X coordinates of the final stage crack network

StdvXmid = target standard deviation of crack midpoint X coordinates network of crack network

Error of standard deviation of crack midpoint X coordinates should be equal or greater than the selected criteria error of standard deviation of crack midpoint X coordinates criterion.

Error of mean of crack midpoint Y coordinates is defined as the difference between mean of crack midpoint Y coordinates of the final stage generated crack network and the target mean of crack midpoint Y coordinates network of crack network divided by the target mean of crack midpoint Y coordinates network of crack network:

$$ErrMYmid = \frac{MYmid1 - MYmid}{MYmid} \quad (4.33)$$

where:

ErrMYmid = error of mean of crack midpoint Y coordinates

MYmid1 = mean length of crack midpoint Y coordinates of the final stage crack network

MYmid = target mean of crack midpoint Y coordinates network of crack network

Error of mean of crack midpoint Y coordinates should be equal or greater than the selected error of mean of crack midpoint Y coordinates criterion.

Error of standard deviation of crack midpoint Y coordinates is defined as the difference between standard deviation of crack midpoint Y coordinates of the final stage crack network and the target standard deviation of crack midpoint Y

coordinates network of crack network divided the by target standard deviation of crack midpoint Y coordinates network of crack network:

$$ErrStdvYmid = \frac{StdvYmid1 - StdvYmid}{StdvYmid} \quad (4.34)$$

where:

- ErrStdvYmid* = error of standard deviation of crack midpoint Y coordinates
StdvYmid1 = standard deviation of crack midpoint Y coordinates of the final stage crack network
StdvYmid = target standard deviation of crack midpoint Y coordinates network of crack network

Error of standard deviation of crack midpoint Y coordinates should be equal or greater than the selected error of standard deviation of crack midpoint Y coordinates criterion.

R^2 of frequency distribution plot were calculated after plotting the data in the corresponding distribution plot:

- Lognormal distribution plot for crack lengths
- Uniform distribution plot for the crack orientations, crack midpoint X coordinates, and crack midpoint Y coordinates

R^2 should be equal or greater than the selected criteria for the crack network generation.

The scripts of the computer code developed to generate the crack networks and an example of input and output files are presented in Appendix C.

In this study, three crack networks were generated for each lateral flow test. The criteria used for crack network generation is shown in Table 4.9.

Table 4.9 Criteria for the crack network generation

Name of crack network :	Network 1-1	Network 1-2	Network 1-3	Network 2-1	Network 2-2	Network 2-3
Source of statistical parameters of the crack network :	Large-scale lateral flow test 1	Large-scale lateral flow test 1	Large-scale lateral flow test 1	Large-scale lateral flow test 2	Large-scale lateral flow test 2	Large-scale lateral flow test 2
<i>ErrNum</i> :	2	2	2	2	2	2
<i>ErrMLength</i> (m) :	0.1	0.1	0.1	0.1	0.1	0.1
<i>ErrStdvLength</i> (m) :	0.5	0.5	0.5	0.5	0.5	0.5
<i>ErrMOrient</i> (deg) :	0.1	0.1	0.1	0.1	0.1	0.1
<i>ErrStdvOrient</i> (deg) :	1	1	1	1	1	1
<i>ErrMXmid</i> (m) :	0.1	0.1	0.1	0.1	0.1	0.1
<i>ErrStdvXmid</i> (m) :	0.5	0.5	0.5	0.5	0.5	0.5
<i>ErrMYmid</i> (m) :	0.1	0.1	0.1	0.1	0.1	0.1
<i>ErrStdvYmid</i> (m) :	0.5	0.5	0.5	0.5	0.5	0.5
R^2 of crack length :	0.90	0.90	0.90	0.90	0.90	0.90
R^2 of crack orientation :	0.95	0.95	0.95	0.95	0.95	0.95
R^2 of X midpoint coordinate :	0.95	0.95	0.95	0.95	0.95	0.95
R^2 of Y midpoint coordinate :	0.95	0.95	0.95	0.95	0.95	0.95

4.8.3 Numerical Analyses of Changes in the Water Content and Matric Suction of Cracked Soils Based on a Numerically Generated Crack Network

Numerical analyses were performed to quantify changes in the water content and matric suction of the cracked soil model with the generated crack network. The average water content and matric suction values obtained from the model with the generated crack network were then compared to the model with the crack network obtained from the laboratory test. A plot of variation in water content and matric suction over time was obtained for each lateral flow test. The analyses were performed for each of the two large-scale lateral flow tests.

To obtain the head boundaries of each crack cell, the head between two crack intersection points was calculated by linear interpolation from the head of the two crack intersection points. For the calculations of head, the representative crack aperture, b , was needed. In this parametric study, the value of b was back-calculated to obtain the same flow rate through the crack network in the soil specimen, Q , as that obtained in the laboratory test. In addition, b was the same for all cracks. Head values were then calculated using the proposed method in Section 3.3. The head values were used as the head boundary in the numerical model.

Three cracked soil models were analyzed for each large-scale lateral flow test. Each crack network from the three crack networks that were generated using the developed computer code (Section 4.8.2) was applied in these models. Details of the numerical analyses that were performed are shown in Table 4.10.

Table 4.10 Summary of the parametric study

Analysis No.	Name of Parametric Analysis	Crack Network in the Model	Computed Parameters
2-1	Param LargeLF1-Netw1-1	Network 1-1	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations, at end of the large-scale lateral flow test 1. • Volumetric water content at sampling locations, at end of the large-scale lateral flow test 1. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
2-2	Param LargeLF1-Netw1-2	Network 1-2	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations, at end of the large-scale lateral flow test 1. • Volumetric water content at sampling locations, at end of the large-scale lateral flow test 1. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
2-3	Param LargeLF1-Netw1-3	Network 1-3	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations, at end of the large-scale lateral flow test 1. • Volumetric water content at sampling locations, at end of the large-scale lateral flow test 1. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.

Analysis No.	Name of Parametric Analysis	Crack Network in the Model	Computed Parameters
2-4	Param LargeLF1-Netw2-1	Network 2-1	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations, at end of the large-scale lateral flow test 2. • Volumetric water content at sampling locations, at end of the large-scale lateral flow test 2. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
2-5	Param LargeLF1-Netw2-2	Network 2-2	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations, at end of the large-scale lateral flow test 2. • Volumetric water content at sampling locations, at end of the large-scale lateral flow test 2. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.
2-6	Param LargeLF1-Netw2-3	Network 2-3	<ul style="list-style-type: none"> • Gravimetric water content at sampling locations, at end of the large-scale lateral flow test 2. • Volumetric water content at sampling locations, at end of the large-scale lateral flow test 2. • Grid of volumetric water content at 5 minute intervals. • Grid of matric suction at 5 minute intervals.

5 CHAPTER 5

PRESENTATION OF RESULTS

5.1 Introduction

This chapter presents the results of the experiments, numerical analyses and the parametric study. The characterization and basic properties of soils are presented first in Section 5.2. The results of laboratory testing for the design of large-scale lateral flow test apparatus are then presented in Section 5.3. This includes the results of trial compaction on small trays and the results of large-scale lateral flow tests. The results of lateral flow tests are then presented in Section 5.4. This includes the results of small-scale and large-scale lateral flow tests. The results of predictions of lateral flow rates through cracked soil samples obtained from the laboratory tests are presented in Section 5.5. Numerical analyses of the laboratory tests are then presented in Section 5.6. Finally, the results of the parametric study are presented in Section 5.7.

5.2 Characterization and Basic Properties of Soil

5.2.1 Basic Properties of Soil

Coarse grade kaolin soil produced by Kaolin Malaysia Sdn Bhd (Malaysia) was used in the experiment. The basic properties of the soil are shown in Table 5.1. The soil is characterized as silt with high plasticity.

Table 5.1 Basic properties of soil

Specific gravity, G_s :	2.65
Silt (%) :	70
Clay (%) :	30
Liquid Limit, LL (%) :	67.9
Plastic Limit, PL (%) :	38.5
Shrinkage Limit, SL (%) :	32
Plasticity Index, PI (%) :	29.4
Soil Classification according to Unified Classification System (USCS) :	MH (silt with high plasticity)
Optimum water content, w_{opt} (%) :	25.7
Maximum dry density, ρ_d (Mg/m ³) :	1.42
Saturated permeability of slurried soil, k_{s1} (m/s) :	8.0×10^{-12}
Saturated permeability of compacted soil, k_{s2} (m/s) :	2.5×10^{-7}

5.2.2 Results of Small-Scale Desiccation Tests and Compaction Test for Selection of Initial Condition of the Specimens

Results of Desiccation Tests on Slurried Soil

The results of the small-scale desiccation tests are shown in Figure 5.1. The test is summarized in Table 4.2. Each crack in each specimen was numbered. The crack number in the specimen was indicated by the largest number in the specimen. Specimen 1 (initial water content equal to 100% of LL) had 14 cracks. This was the largest number of cracks among the three specimens (Figure 5.1a). 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 (Figure 5.1c). At the initial water content equal to 200% of LL, the surface of the specimen could easily be maintained as flat. Specimen 2 had an initial water content equal to 150% of LL and 6 cracks were formed (Figure 5.1b). The surface of the soil was maintained flat at the initial water content equal to 150% of LL. In addition, there were some continuous paths in the

crack network from one side of the tray to the other side, indicating that lateral flow through cracked soil specimens could be expected in the lateral flow tests. An initial water content of 150% of LL (Figure 5.1b) was selected as the initial water content of the specimens for the lateral flow tests.

Figure 5.1 Results of small-scale desiccation tests on slurried soil: (a) Specimen 1 with an initial water content equal to 100% of LL; (b) Specimen 2 with an initial water content equal to 150% of LL; (c) Specimen 3 with an initial water content equal to 200% of LL

Compaction Test Results

From the standard Proctor compaction test results (Figure 5.2), the optimum water content, w_{opt} , was found to be equal to 25.7% and the maximum dry density, ρ_d , was equal to 1.42 Mg/m³. Based on Figure 4.2, a water content equal to $1.25w_{opt}$ (equal to 32%) is expected to give large shrinkage. Therefore, a water content equal to 32% was selected as the initial water content for the desiccation process to obtain cracked soil specimens.

Figure 5.2 Compaction test results using the standard Proctor method

5.2.3 SWCCs of Soils

The SWCC of the slurried soil is shown in Figure 5.3. The measured data were then fitted using the Fredlund and Xing (1994) equation. The fitting parameter for the SWCC of the slurried soil is shown in Table 5.2.

(a)

(b)

(c)

Figure 5.3 SWCC of the slurried soil: (a) SWCC of the slurried soil in terms of gravimetric water content; (b) SWCC of the slurried soil in terms of volumetric water content; (c) SWCC of the slurried soil in terms of degree of saturation (from Krisnanto et al., 2014)

Table 5.2 Fitting parameters of the SWCC of the slurried soil: (a) SWCC of the slurried soil in terms of gravimetric water content; (b) SWCC of the slurried soil in terms of volumetric water content; (c) SWCC of the slurried soil in terms of degree of saturation

(a)

Fitting Parameters	Initial Drying (Fitted Curve)	Main Drying (Predicted Curve)	Main Wetting (Predicted Curve)
a_f (kPa)	27.1	27.1	8.56
n_f (kPa)	0.55	0.55	0.37
m_f (kPa)	1.30	1.30	1.31

(b)

Fitting Parameters	Initial Drying (Fitted Curve)	Main Drying (Predicted Curve)	Main Wetting (Predicted Curve)
a_f (kPa)	38.2	38.2	12.1
n_f (kPa)	1.13	1.13	0.77
m_f (kPa)	0.49	0.49	0.51

(c)

Fitting Parameters	Initial Drying (Fitted Curve)	Main Drying (Predicted Curve)	Main Wetting (Predicted Curve)
a_f (kPa)	69.8	69.8	22.1
n_f (kPa)	1.34	1.34	0.90
m_f (kPa)	0.37	0.4	0.39

The SWCC of the compacted soil is shown in Figure 5.4. The measured data were then fitted using the Fredlund and Xing (1994) equation. The fitting parameter for the SWCC of the slurried soil is shown in Table 5.3.

(a)

(b)

(c)

Figure 5.4 SWCC of the compacted soil: (a) SWCC of the compacted soil in terms of gravimetric water content; (b) SWCC of the compacted soil in terms of volumetric water content; (c) SWCC of the compacted soil in terms of degree of saturation

Table 5.3 Fitting parameters of the SWCC of the compacted soil: (a) SWCC of the compacted soil in terms of gravimetric water content; (b) SWCC of the compacted soil in terms of volumetric water content; (c) SWCC of the compacted soil in terms of degree of saturation

(a)

Fitting Parameters	Drying (Fitted Curve)	Wetting (Fitted Curve)
a_f (kPa)	100	22.1
n_f (kPa)	0.61	0.60
m_f (kPa)	1.93	1.50

(b)

Fitting Parameters	Initial Drying (Fitted Curve)	Main Wetting (Fitted Curve)
a_f (kPa)	100.0	22.1
n_f (kPa)	0.73	0.60
m_f (kPa)	1.41	1.50

(c)

Fitting Parameters	Initial Drying (Fitted Curve)	Main Wetting (Fitted Curve)
a_f (kPa)	214.1	22.1
n_f (kPa)	0.67	0.60
m_f (kPa)	1.77	1.50

5.2.4 Permeability Functions of Soils

The permeability function of the slurried soil is shown in Figure 5.5. The wetting permeability function was calculated indirectly from the main wetting SWCC in terms of degree of saturation against matric suction (Figure 5.3c).

Figure 5.5 Permeability function of the slurried soil (from Krisnanto et al., 2014)

The permeability function of the compacted soil is shown in Figure 5.6. The wetting permeability function was calculated indirectly from the scanning wetting SWCC in terms of degree of saturation against matric suction (Figure 5.4c).

Figure 5.6 Permeability function of the compacted soil

5.3 Results of Laboratory Tests for the Design of Large-scale Lateral Flow Test Apparatus

5.3.1 Results of Trial Compaction on a Small Tray

Implementation of the trial compaction on a small tray is shown in Figure 5.7. From the test, it was recognized that the achieved dry density, ρ_d , is 1.2 Mg/m^3 . The maximum dry density, ρ_d , obtained from the standard Proctor test performed in this study was 1.42 Mg/m^3 (Figure 5.2). Therefore, the relative compaction for the large-scale lateral flow tests performed in this study was 85% with respect to the standard Proctor test.

Figure 5.7 Implementation of the trial compaction test

5.3.2 Results of Large-scale Desiccation Tests

The results of large-scale desiccation tests 1 to 3 performed on slurried soil and large-scale desiccation tests 4 to 6 performed on compacted soil are presented in this section.

5.3.2.1 Results of Large-scale Desiccation Test 1 (Slurried Soil Specimen)

The temperature and relative humidity during the large-scale desiccation test 1 are shown in Figure 5.8. Temperature varied from 24.2°C to 26.2°C with an average

value of 25.2°C. Relative humidity varied from 54.3% to 71.1% with an average value of 66.0 %.

Figure 5.8 Temperature and relative humidity at the specimen location of large-scale desiccation tests 1 and 2 (from Krisnanto et al., 2011)

The development of the crack network during the desiccation test is shown in Figure 5.9. In desiccation test 1, after the initial crack network formed, no additional cracks were formed. The aperture of the cracks became wider as time increased.

Figure 5.9 Cracked soil specimen at the end of large-scale desiccation test 1 (at 333 hours) (from Krisnanto et al., 2011)

Water content and matric suction changes during the test considering the cracked soil as a single soil element are shown in Figure 5.10. Cracks started to develop at 211 hours.

The matric suction change of the cracked soil specimen considering cracked soil as a single soil element was obtained by back-calculating each water content value observed in the desiccation test (Figure 5.10a) using the SWCC (Figure 5.3). Changes in the matric suction of the cracked soil specimen are shown in Figure 5.10b. The initial crack occurred at a water content equal to 0.50, which corresponds to matric suction equal to 34.9 kPa. This matric suction value is near the air entry value of SWCC, as indicated by parameter a_f in Table 5.2. In this test, after the initial crack formed, there were significant changes in the rate of increase in matric suction (Figure 5.10b). However, no significant changes in the rate of decrease in water content were observed in the desiccation tests (Figure 5.10a).

(a)

(b)

Figure 5.10 Changes in water content and matric suction of the specimen in large-scale desiccation test 1: (a) Change in water content; (b) Change in matric suction (from Krisnanto et al., 2011)

Seven cracks were formed at the end of large-scale desiccation test 1 as shown in Figure 5.12. An example of the calculation of number of crack at time 211 hours is shown in Figure 5.11. The cracks were connected to each other (Figure 5.9). In addition, there were connections between the crack network and the sides of the tray. The development of the number of cracks with decreasing gravimetric water content and increasing matric suction are shown in Figure 5.12a and Figure 5.12b, respectively.

Figure 5.11 Calculation of the number of cracks in large-scale desiccation test 1 at time 211 hours

(a)

(b)

Figure 5.12 Number of cracks in large-scale desiccation test 1: (a) Number of cracks vs. gravimetric water content; (b) Number of cracks vs. matric suction

At the end of large-scale desiccation test 1, gravimetric samplings were obtained from the soil specimen. The locations of the sampling are illustrated in Figure 5.13. The gravimetric water contents at the end of large-scale desiccation test 1 are shown in Appendix A.2.1.

Figure 5.13 Location of gravimetric water content sampling in large-scale desiccation test 1

5.3.2.2 Results of Large-scale Desiccation Test 2 (Slurried Soil Specimen)

The temperature and relative humidity during the large-scale desiccation test 2 are shown in Figure 5.8. The development of the crack network during the desiccation test is shown in Figure 5.14. After the initial cracks formed (Figure 5.14a), additional cracks formed until the final condition was reached, as shown in Figure 5.14b.

(a)

(b)

Figure 5.14 Development of the crack network during large-scale desiccation test 2:

(a) Crack network in large-scale desiccation test 2 (at 76.5 hours); (b) Final crack network in desiccation test 2 (at 259.5 hours) (from Krisnanto et al., 2011)

Water content and matric suction changes during the test considering cracked soil as a single soil element are shown in Figure 5.15. Cracks started to develop at 67.5 hours.

(a)

(b)

Figure 5.15 Changes in water content and matric suction of the specimen during large-scale desiccation test 2: (a) Change in water content; (b) Change in matric suction (from Krisnanto et al., 2011)

An example of the calculation of number of crack at time 72 hours is shown in Figure 5.16. A total of 77 cracks were formed at the end of large-scale desiccation

test 2 as shown in Figure 5.17. The cracks were relatively unconnected to each other (Figure 5.14b). There were connections between the crack network and the sides of the tray. The development of the number of cracks with decreasing gravimetric water content and increasing matric suction are shown in Figure 5.17a and Figure 5.17b, respectively.

Figure 5.16 Calculation of the number of cracks in large-scale desiccation test 2 at time 30 hours

(a)

(b)

Figure 5.17 Number of cracks in large-scale desiccation test 2: (a) Number of cracks vs. gravimetric water content; (b) Number of cracks vs. matric suction

At the end of large-scale desiccation test 2, gravimetric samplings were obtained from the soil specimen. The gravimetric water contents at the end of large-scale desiccation test 2 are shown in Appendix A.2.2.

5.3.2.3 Results of Large-scale Desiccation Test 3 (Slurried Soil Specimen)

The temperature and relative humidity during the large-scale desiccation test 3 are shown in Figure 5.18.

Figure 5.18 Temperature and relative humidity at the specimen location of large-scale desiccation test 3

Figure 5.19 Cracked soil specimen at the end of large-scale desiccation test 3 (180 hours)

Water content and matric suction changes during the test considering cracked soil as a single soil element are shown in Figure 5.20. Cracks started to develop at 75 hours.

(a)

(b)

Figure 5.20 Changes in water content and matric suction in the specimen during large-scale desiccation test 3: (a) Change in water content; (b) Change in matric suction

A total of 190 cracks were formed at the end of large-scale desiccation test 3 as shown in Figure 5.21. The cracks were relatively connected to each other (Figure 5.19). There were connections between the crack network and the sides of the tray. The development of the number of cracks with decreasing gravimetric water content and increasing matric suction are shown in Figure 5.21a and Figure 5.21b, respectively.

(a)

(b)

Figure 5.21 Number of cracks in large-scale desiccation test 3: (a) Number of cracks vs. gravimetric water content; (b) Number of cracks vs. matric suction

5.3.2.4 Results of Large-scale Desiccation Test 4 (Compacted Soil Specimen)

The temperature and relative humidity during the large-scale desiccation test 4 are shown in Figure 5.22. The development of the crack network during the desiccation test is shown in Figure 5.23. After the initial cracks formed (Figure 5.23a), additional cracks formed until the final condition was reached, as shown in Figure 5.23e.

Figure 5.22 Temperature and relative humidity at the specimen location of large-scale desiccation test 4

(a)

(b)

(c)

(d)

(e)

Figure 5.23 Development of the crack network during large-scale desiccation test 4:
(a) Initial; (b) At 64 hours; (c) At 272 hours; (d) At 331 hours; (e) At the end of the
test (343 hours)

Water content and matric suction changes during the test considering cracked soil as a single soil element are shown in Figure 5.24. Cracks started to develop at 49 hours.

(a)

(b)

Figure 5.24 Changes in water content and matric suction of the specimen during large-scale desiccation test 4: (a) Change in water content; (b) Change in matric suction

A total of 50 cracks were formed in large-scale desiccation test 4, as shown in Figure 5.25. The cracks were relatively connected to each other (Figure 5.23e). There were connections between the crack network and the sides of the tray. The

development of the number of cracks with decreasing gravimetric water content and increasing matric suction are shown in Figure 5.25a and Figure 5.25b, respectively.

(a)

(b)

Figure 5.25 Number of cracks in large-scale desiccation test 4: (a) Number of cracks vs. gravimetric water content; (b) Number of cracks vs. matric suction

5.3.2.5 Results of Large-scale Desiccation Test 5 (Compacted Soil Specimen)

The temperature and relative humidity during the large-scale desiccation test are shown in Figure 5.26. Development of the crack network during the desiccation test is shown in Figure 5.27. After the initial cracks formed (Figure 5.27a), additional cracks formed until the final condition was reached, as shown in Figure 5.27b to Figure 5.27d.

Figure 5.26 Temperature and relative humidity at the specimen location of large-scale desiccation test 5

(a)

(b)

(c)

(d)

Figure 5.27 Development of the crack network during large-scale desiccation test 5:

(a) Initial; (b) At 46 hours; (c) At 95 hours; (d) At the end of the test (235 hours)

Water content and matric suction changes during the test considering cracked soil as a single soil element are shown in Figure 5.28. Cracks started to develop at 49 hours.

(a)

(b)

Figure 5.28 Changes in water content and matric suction of the specimen during large-scale desiccation test 5: (a) Change in water content; (b) Change in matric suction

A total of 130 cracks were formed in large-scale desiccation test 5, as shown in Figure 5.29. The cracks were relatively connected to each other (Figure 5.27d). There were connections between the crack network and the sides of the tray. The development of the number of cracks with decreasing gravimetric water content and increasing matric suction are shown in Figure 5.29a and Figure 5.29b, respectively.

(a)

(b)

Figure 5.29 Number of cracks in large-scale desiccation test 5: (a) Number of cracks vs. gravimetric water content; (b) Number of cracks vs. matric suction

5.3.2.6 Results of Large-scale Desiccation Test 6 (Compacted Soil Specimen)

The temperature and relative humidity during the large-scale desiccation test are shown in Figure 5.30. The development of the crack network during the desiccation test is shown in Figure 5.31. After the initial cracks formed (Figure 5.31a), additional cracks formed until the final condition was reached, as shown in Figure 5.31b.

Figure 5.30 Temperature and relative humidity at the specimen location of large-scale desiccation test 6

(a)

(b)

Figure 5.31 Development of the crack network during large-scale desiccation test 6:

(a) At 46.5 hours; (b) At the end of the test (96 hours)

Water content and matric suction changes during the test considering cracked soil as a single soil element are shown in Figure 5.32. Cracks started to develop at 43 hours.

(a)

(b)

Figure 5.32 Changes in water content and matric suction of the specimen during large-scale desiccation test 6: (a) Change in water content; (b) Change in matric suction

A total of 40 cracks were formed in large-scale desiccation test 6, as shown in Figure 5.33. The cracks were relatively connected to each other (Figure 5.31b). There were connections between the crack network and the sides of the tray. The development of the number of cracks with decreasing gravimetric water content and increasing matric suction are shown in Figure 5.33a and Figure 5.33b, respectively.

(a)

(b)

Figure 5.33 Number of cracks in desiccation large-scale test 6: (a) Number of cracks vs. gravimetric water content; (b) Number of cracks vs. matric suction

5.3.3 Concluding Remarks

From the small-scale and large-scale desiccation tests, the following points were concluded:

- Compacted soil resulted in cracks propagating in all directions, whereas slurried soil results in cracks that did not always propagate in all directions.
- A plan area of 75 cm x 75 cm was sufficient when using an initial thickness ranging from 1 cm to 2.5 cm. However, to incorporate more cracks, a plan area of 1 m x 1 m was used in the large-scale lateral flow test.

Therefore, compacted soil with 2.5 cm thickness was selected for the large-scale lateral flow test. This combination was expected to provide a sufficient number of cracks, connectivity between the cracks, and connectivity between the inflow and outflow boundaries.

Slurried soil was used for the small-scale lateral flow test because it gives the highest amount of shrinkage. Cracks that were continuous from the inflow and outflow boundaries were expected to form.

5.4 Results of Lateral Flow Tests

5.4.1 Results of Small-Scale Lateral Flow Tests

The results of small-scale lateral flow tests 1 and 2 are presented in this section.

5.4.1.1 Results of Small-Scale Lateral Flow Test 1

The specimen for small-scale lateral flow test 1 was prepared at an initial water content equal to 150% of LL. The specimen was desiccated from the initial water content until it reached the designated water content of 43.4% as shown in Table 4.4. The cracked soil specimen for small-scale lateral flow test 1 is shown in Figure 5.34.

Figure 5.34 Cracked soil specimen for small-scale lateral flow test 1

The results of the water outflow measurement are shown in Figure 5.35. 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 approximately 2 minutes and became constant at a value of $1.05 \times 10^{-4} \text{ m}^3/\text{s}$ after 4 minutes.

Figure 5.35 Measured lateral out flow rate of small-scale lateral flow test 1

The results of the water content measurement after the lateral flow tests are shown in Table 5.4. The sampling number shown in Table 5.4 corresponds to the location of water content measurement in Figure 5.48c.

Table 5.4 Water content at the end of small-scale lateral flow test 1

Specimen No.	Gravimetric Water Content, w (%)
1	50.9
2	47.6
3	49.2
4	50.1
5	46.3

5.4.1.2 Results of Small-Scale Lateral Flow Test 2

The cracked soil specimen for small-scale lateral flow test 2 is shown in Figure 5.36. The specimen was prepared at an initial water content equal to 150% of LL.

The specimens were desiccated the initial water content until it reached the designated water contents of 43.4% as shown in Table 4.4.

Figure 5.36 Cracked soil specimen for small-scale lateral flow test 2: (a) Cracked soil specimen; (b) Sealing the side gap of the specimen

The results of the water outflow measurement are shown in Figure 5.37. 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 approximately 0.4 minutes and to $1.2 \times 10^{-4} \text{ m}^3/\text{s}$ at about 1 minute. Fluctuation of the water flow rate occurred from 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.

Figure 5.37 Measured lateral out flow rate of small-scale lateral flow test 2

The results of the water content measurement after the lateral flow tests are shown in Table 5.5. The sampling number shown in Table 5.5 corresponds to the location of water content measurement in Figure 5.50b.

Table 5.5 Water content at the end of small-scale lateral flow test 2

Specimen No.	Gravimetric Water Content, w (%)
1	50.5
2	47.8
3	53.6
4	47.0
5	46.3

5.4.2 Results of Large-scale Lateral Flow Tests

Results of large-scale lateral flow tests 1 and 2 are presented in this section.

5.4.2.1 Results of Large-scale Lateral Flow Test 1

Temperature and relative humidity during the large-scale desiccation test 1 are shown in Figure 5.38. Changes in the water content of the specimen for large-scale lateral flow test 1 is shown in Figure 5.39. The development of the crack network during large-scale desiccation test 1 is shown in Figure 5.40. After the initial cracks

formed (Figure 5.40a), additional cracks formed until the final condition was reached, as shown in Figure 5.40b to Figure 5.40c.

Figure 5.38 Temperature and relative humidity at the specimen location of large-scale lateral flow test 1 during desiccation

Figure 5.39 Changes in the water content of the specimen of large-scale lateral flow test 1 during desiccation

(a)

(b)

(c)

Figure 5.40 Development of the crack network in the soil specimen of the large-scale lateral flow test 1: (a) Initiation of cracks in the specimen (at 63 hours); (b) Cracks in the specimen at 71 hours; (c) Cracks in the specimen at the end of the desiccation test (at 95 hours)

The results of the water outflow measurement are shown in Figure 5.41. The water flow rate increased from zero at the beginning of the test to $6.0 \times 10^{-6} \text{ m}^3/\text{s}$ at approximately 7.5 minutes.

Figure 5.41 Measured outflow rate through the cracked soil specimen of large-scale lateral flow test 1

At the end of large-scale lateral flow test 1, gravimetric and volumetric water content sampling were obtained from the soil specimen. Gravimetric and volumetric water contents at the end of large-scale lateral flow test 1 are shown in Appendix A.3.1

5.4.2.2 Results of Large-scale Lateral Flow Test 2

The temperature and relative humidity during the large-scale desiccation test are shown in Figure 5.42. Changes in the water content of the specimen of large-scale lateral flow test 2 is shown in Figure 5.43. The development of the crack network during the desiccation test is shown in Figure 5.44. After the initial cracks formed (Figure 5.44a), additional cracks formed until the final condition was reached, as shown in Figure 5.44b to Figure 5.44c.

Figure 5.42 Temperature and relative humidity at the specimen location of large-scale lateral flow test 2 during desiccation

Figure 5.43 Change in water content and matric suction of the specimen during desiccation of large-scale lateral flow test 2

(a)

(b)

Figure 5.44 Development of the crack network in the soil specimen of large-scale lateral flow test 2: (a) Specimen at $t = 47$ hours; (b) Specimen at the end of desiccation ($t = 93$ hours)

The laboratory setting for large-scale lateral flow test 2 is shown in Figure 5.45.

(a)

(b)

Figure 5.45 Experimental setup for large-scale lateral flow test 2: (a) Overview; (b) ICTs and standpipes; (c) Sand layer on top of the specimen

The results of the water outflow measurement are shown in Figure 5.46. The water flow rate increased from zero at the beginning of the test to $60 \times 10^{-6} \text{ m}^3/\text{s}$ at approximately 25 minutes.

Figure 5.46 Measured lateral inflow and outflow rate through the cracked soil specimen of large-scale lateral flow test 2

The instrumentation data for volumetric water content are shown in Figure 5.47.

Figure 5.47 Change in water content during the large-scale lateral flow test 2

At the end of large-scale lateral flow test 2, gravimetric and volumetric water content sampling were obtained from the soil specimen. Gravimetric and volumetric water contents at the end of large-scale lateral flow test 2 are shown in Appendix A.3.2.

5.5 Results of Prediction of Lateral Flow Rates through the Crack Network and Comparison of Flow through the Crack Network with Flow through Cracked Soils

5.5.1 Small-scale Lateral Flow Tests

5.5.1.1 Small-scale Lateral Flow Test 1

The proposed model was used to predict the lateral flow rate of the specimen in small-scale lateral flow test 1. The first step for making a prediction of lateral flow rate was to represent crack network in the cracked soil obtained from scanning and photo of a digitized crack network, as shown in Figure 5.48a and Figure 5.48b. The digitized crack network was then converted to a skeleton of the crack network and

converted to an idealized crack network using the principles explained in Chapter 3. The skeleton of the crack network is shown in Figure 5.48d, whereas the idealized crack network is shown in Figure 5.48e.

After representing the actual crack network as an idealized crack network, Eqs. (3.1) and (3.2) were applied to predict the lateral flow rate through the crack network. Equations (3.18) and (3.38) were incorporated into Eq. (3.2) to calculate the lateral flow. The head values (Table 4.4) were assigned to the upstream and downstream boundaries, respectively, and the head values at each crack intersection point 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. The results of the prediction of the lateral flow rate through the crack network of small-scale lateral flow test 1 are shown in Figure 5.49.

(a)

(b)

(c)

(d)

Figure 5.48 Idealization of cracked soil specimen of small-scale lateral flow test 1:
 (a) Cracked soil specimen; (b) Digitized crack network; (c) Locations of water content measurement; (d) Skeleton of crack network; (e) Idealized crack network

Figure 5.49 Comparison of flow obtained from small-scale lateral flow test 1 and prediction using the proposed mode

5.5.1.2 Small-scale Lateral Flow Test 2

The proposed model was used to predict the lateral flow rate of the specimens in small-scale lateral flow test 2. The digitized crack network is shown in Figure 5.50a. The locations of water content measurement are shown in Figure 5.50b. The skeleton of the crack network is shown in Figure 5.50c, whereas the idealized crack network is shown in Figure 5.50d. The results of prediction of the lateral flow rate through the crack network of small-scale lateral flow test 2 are shown in Figure 5.51.

(b)

(c)

Figure 5.50 Cracked soil specimen of small-scale lateral flow test 2: (a) Digitized crack network; (b) Locations of water content measurement; (c) Skeleton of crack network; (d) Idealized crack network

Figure 5.51 Comparison of flow obtained from small-scale lateral flow test 2 and prediction using the proposed mode

5.5.2 Large-scale Lateral Flow Tests

5.5.2.1 Large-scale Lateral Flow Test 1

The proposed model was used to predict the lateral flow rate of the specimens in large-scale lateral flow test 1. A cracked soil specimen is shown in Figure 5.52a. The digitized crack network is shown in Figure 5.52b. The skeleton of the crack network is shown in Figure 5.52c, whereas the idealized crack network is shown in Figure 5.52d. The numbers in Figure 5.52b, Figure 5.52c, and Figure 5.52d correspond to the location numbers in Table 4.6a. The results of prediction of the lateral flow rate through the crack network of large-scale lateral flow test 1 are shown in Figure 5.53.

(a)

(b)

(c)

(d)

Figure 5.52 Idealization of cracked soil specimen of large-scale lateral flow test 1:

(a) Cracked soil specimen; (b) Digitized crack network; (c) Skeleton of crack network; (d) Idealized crack network

Figure 5.53 Comparison of flow obtained from large-scale lateral flow test 1 and prediction using the proposed mode

5.5.2.2 Large-scale Lateral Flow Test 2

The proposed model was used to predict the lateral flow rate of the specimens in large-scale lateral flow test 2. A cracked soil specimen is shown in Figure 5.54a. The digitized crack network is shown in Figure 5.54b. The skeleton of the crack network is shown in Figure 5.54c, whereas the idealized crack network is shown in Figure 5.54d. The numbers in Figure 5.54b, Figure 5.54c, and Figure 5.54d correspond to the location numbers in Table 4.6b. The results of prediction of the lateral flow rate through the crack network of large-scale lateral flow test 2 are shown in Figure 5.55.

(a)

(b)

(c)

(d)

Figure 5.54 Idealization of cracked soil specimen of large-scale lateral flow test 2:
 (a) Cracked soil specimen; (b) Digitized crack network; (c) Skeleton of crack network; (d) Idealized crack network

Figure 5.55 Comparison of flow obtained from large-scale lateral flow test 2 and prediction using the proposed mode

5.6 Results of Numerical Analyses of Laboratory Tests

The results of numerical analyses of the laboratory tests are presented in this section. The numerical analyses consist of numerical analyses to quantify lateral flow rates through cracked soils and numerical analyses to model changes in the water content and matric suction of cracked soils.

5.6.1 Results of Numerical Analyses to Quantify Lateral Flow Rates through Cracked Soils

5.6.1.1 Small-scale Lateral Flow Test 1

A finite element model for the numerical analysis of small-scale lateral flow test 1 is shown in Figure 5.56. The results of numerical analyses to quantify the lateral flow rate through the cracked soil specimen of small-scale lateral flow test 1 is shown in Figure 5.57.

Figure 5.56 Finite element model for numerical simulation of small-scale lateral flow test 1

Figure 5.57 Comparison of flow obtained from small-scale lateral flow test 1 and prediction using the proposed model

5.6.1.2 Small-scale Lateral Flow Test 2

A finite element model for the numerical analysis of small-scale lateral flow test 2 is shown in Figure 5.58. The results of numerical analyses to quantify the lateral flow rate through the cracked soil specimen of small-scale lateral flow test 2 is shown in Figure 5.59.

Figure 5.58 Finite element model for numerical simulation of small-scale lateral flow test 2

Figure 5.59 Comparison of flow obtained from small-scale lateral flow test 2 and prediction using the proposed model

5.6.1.3 Large-scale Lateral Flow Test 1

A finite element model for the numerical analysis of large-scale lateral flow test 1 is shown in Figure 5.60. The results of numerical analyses to quantify the lateral flow rate through the cracked soil specimen of large-scale lateral flow test 1 is shown in Figure 5.61.

Figure 5.60 Finite element model for numerical simulation of large-scale lateral flow test 1

Figure 5.61 Comparison of flow obtained from large-scale lateral flow test 1 and prediction using the proposed model

5.6.1.4 Large-scale Lateral Flow Test 2

A finite element model for the numerical analysis of large-scale lateral flow test 2 is shown in Figure 5.62. The results of numerical analyses to quantify the lateral flow rate through the cracked soil specimen of large-scale lateral flow test 2 is shown in Figure 5.63.

Figure 5.62 Finite element model for numerical analysis of large-scale lateral flow test 2

Figure 5.63 Comparison of flow obtained from large-scale lateral flow test 2 and numerical analysis

5.6.2 Results of Numerical Analyses to Model Changes in Water Content and Matric Suction of Cracked Soils

5.6.2.1 Results of Numerical Analyses of Lateral Flow Test by Modelling the Crack Network as Head Boundary Conditions

5.6.2.1.1 Results of Numerical Analyses of Large-Scale Lateral Flow Test 1

The model for large-scale lateral flow test 1 is shown in Figure 5.64a and Figure 5.64b. The model is a 3D model consisted of several regions. Shapes of the regions were made to resemble the crack network in the cracked soil specimen. Different regions are indicated by different colour in the numerical model (Figure 5.64b and Figure 5.64c). The crack network was modelled as head boundaries, as shown by bold lines along the boundaries (Figure 5.64a). Points of the locations of water content sampling are also allocated in the model, as shown in Figure 5.64a. These points correspond to the points listed in Table 4.6a. The mesh of the model is shown in Figure 5.64b and Figure 5.64c.

(a)

(b)

(c)

Figure 5.64 Finite element model of large-scale lateral flow test 1: (a) Crack network model; (b) Plan view of the finite element mesh; (c) 3D view of the finite element mesh

Comparisons between the measured values, sampling values, and computed values from the numerical analyses of large-scale lateral flow test 1 are shown in Figure 5.65a and Figure 5.65b for gravimetric and volumetric water content values, respectively. The numbers in Figure 5.65 correspond to the location numbers in Figure 5.52 and Table 4.6a. The plot in Figure 5.65 shows that the computed values of water content and measured and sampling values only differ by about 10%.

(a)

(b)

Figure 5.65 Comparison of water content obtained from sampling at the end of large-scale lateral flow test 1 and water content obtained from the numerical analysis: (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

5.6.2.1.2 Results of Numerical Analyses of Large-scale Lateral Flow Test 2

The model for large-scale lateral flow test 2 is shown in Figure 5.66a and Figure 5.66b. The model is a 3D model consisted of several regions. Shapes of the regions were made to resemble the crack network in the cracked soil specimen. Different regions are indicated by different colour in the numerical model (Figure 5.66c and Figure 5.66d). The crack network was modelled as head boundaries, as shown by bold lines along the boundaries (Figure 5.66a and Figure 5.66b). Points of the locations of ICT sensors, water content sampling, and standpipes are also allocated in the model, as shown in Figure 5.66a. These points correspond to the points listed in Table 4.6b. The mesh of the model is shown in Figure 5.66c and Figure 5.66d.

(a)

(b)

(c)

(d)

Figure 5.66 Finite element model of the large-scale lateral flow test 2: (a) Plan view of the cracked soil model; (b) 3D view of the boundary conditions of the cracked soil model; (c) Plan view of the finite element mesh; (d) 3D view of the finite element mesh

The volumetric water content computed from the numerical analyses was then plotted together with the data obtained from the ICT sensors (Figure 5.47). The plots are shown in Figure 5.67. The plots indicate that the measured values are close to the computed values from the numerical analyses. This similarity proves the reasonableness of the proposed method for analyzing changes in water content in cracked soil. This measurement also strengthens the results obtained from large-scale lateral flow test 1 where only the results at the end of test were obtained. The plots show that the numerical values are quite similar with the measured values. This indicates that the use of head boundaries is better than the representation of cracks as a continuum for analyzing changes in water content.

(a)

(b)

(c)

(d)

(e)

Figure 5.67 Numerical simulation and instrumentation results of changes in volumetric water content during large-scale lateral flow test 2: (a) At ICT-1 location; (b) At ICT-3 location; (c) At ICT-4 location; (d) At ICT-8 location; (e) At ICT-10 location

Comparisons between the measured values, sampling values, and computed values from numerical analyses of large-scale lateral flow test 2 are shown in Figure 5.68 and Figure 5.69. Figure 5.68 is a replot of Figure 5.67 for several time measurements (0, 25 min, 50 min, and 75 min) and a plot of the sampling values against the computed values from the numerical analysis (Figure 5.68d). The numbers in Figure 5.68 and Figure 5.69 correspond to the location numbers in Figure 5.54 and Table 4.6b. The plot in Figure 5.68 and Figure 5.69 show that the computed values of water content and measured and sampling values only differ by about 10%.

(a)

(b)

(c)

Figure 5.68 Comparison of volumetric water content obtained from instrumentation, sampling, and numerical analysis of large-scale lateral flow test 2: (a) At time = 0; (b) At time = 25 minute; (c) At time = 50 minute; (d) At time = 75 min (the end of the lateral flow test)

Figure 5.69 Comparison of gravimetric water content obtained from water content sampling at the end of large-scale lateral flow test 2 ($t = 75$ min)

5.6.2.2 Results of Numerical Analyses of Lateral Flow Tests by Modeling the Cracked Soil as a Continuum Material

As mentioned in Section 4.7.3, to assess the performance of the proposed method presented in Section 5.6.2.1, numerical analyses were also performed by modelling the cracked soil as a continuum material. The results are presented in this section. Two methods are presented:

- Fredlund et al. (2010)
- Li et al. (2011)

5.6.2.2.1 Results of Numerical Simulation of Large-scale Lateral Flow Test 1

For each method, a numerical analysis was performed. The SWCC and permeability function computed using each method were input into the numerical analyses. Finite element model for numerical analysis of the large-scale lateral flow test 1 is shown in Figure 5.70.

(a)

(b)

Figure 5.70 Finite element model of large-scale lateral flow test 1: (a) Cracked soil model; (b) 3D view of boundary conditions of the model; (c) Plan view of the finite element mesh; (d) 3D view of the finite element mesh

The results obtained from both methods are shown in Figure 5.71 and Figure 5.72. The plots show a comparison of the gravimetric and volumetric water contents obtained from the numerical analysis and from sampling at the end of test. The plots show that the numerical values are quite different from the measured values. This indicates that the use of head boundaries is better than the representation of cracks as a continuum for analyzing changes in water content.

(a)

(b)

Figure 5.71 Comparison of water content obtained from sampling and numerical analysis incorporating the Fredlund et al. (2010) method at the end of large-scale lateral flow test 1: (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

(a)

(b)

Figure 5.72 Comparison of water content obtained from sampling and numerical analysis incorporating the Li et al. (2011) method at the end of large-scale lateral flow test 1: (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

5.6.2.2.2 Results of Numerical Simulation of Large-scale Lateral Flow Test 2

For each method, a numerical analysis was performed. The SWCC and permeability function computed using each method were input into the numerical analyses. Finite element model for numerical analysis of the large-scale lateral flow test 2 is shown in Figure 5.73.

(a)

(b)

(c)

(d)

Figure 5.73 Finite element model of large-scale lateral flow test 2: (a) Cracked soil model; (b) 3D view of boundary conditions of the model; (c) Plan view of the finite element mesh; (d) 3D view of the finite element mesh

The results obtained from both methods are shown in Figure 5.74, Figure 5.75, Figure 5.76, and Figure 5.77. Figure 5.74 and Figure 5.76 show plots of the volumetric water content computed from the numerical analyses vs. the values of volumetric water content obtained from the ICT sensors. Figure 5.75 and Figure 5.77 show plots of gravimetric water content computed from numerical analyses vs. the values of gravimetric water content obtained from sampling. The plots show that the numerical values are quite different from the measured values. This indicates that the use of head boundaries is better than the representation of cracks as a continuum for analyzing changes in water content.

(a)

(b)

(c)

Figure 5.74 Comparison of volumetric water content obtained from instrumentation, sampling, and numerical analysis of large-scale lateral flow test 2 using Fredlund et al. (2010) method: (a) At time = 0; (b) At time = 25 minute; (c) At time = 50 minute; (d) At time = 75 min (the end of the lateral flow test)

Figure 5.75 Comparison of gravimetric water content obtained from water content sampling using Fredlund et al. (2010) method at the end of large-scale lateral flow test 2 ($t = 75$ min)

(a)

(b)

(c)

(d)

Figure 5.76 Comparison of volumetric water content obtained from instrumentation, sampling, and numerical analysis of large-scale lateral flow test 2 using Li et al. (2011) method: (a) At time = 0; (b) At time = 25 minute; (c) At time = 50 minute; (d) At time = 75 min (the end of the lateral flow test)

Figure 5.77 Comparison of gravimetric water content obtained from water content sampling using Li et al. (2011) method at the end of large-scale lateral flow test 2 ($t = 75$ min)

5.7 Results of the Parametric Study of the Effect of Variation in Crack Network on Average Values of Water Content and Matric Suction of Cracked Soils

Figure 5.65 to Figure 5.69 show that the locations near cracks had higher water contents than those far from cracks. Crack networks influence variation in water content and matric suction in the soil. Soils with different crack networks can have different average values of water content and matric suction. Therefore, the effect of variation in crack network on the average values of water content and matric suction of cracked soils needs to be investigated.

5.7.1 Characterization of the Crack Network in the Soil

The crack networks were generated using the same statistical parameters (mean, standard deviation, and distribution function for crack length, crack orientation, and X and Y coordinate of crack midpoints) as those obtained from the laboratory tests. The statistical parameters for each laboratory test are presented as follows. The

crack networks generated using the developed computer code (Appendix C) are also presented.

5.7.1.1 Large-scale Lateral Flow Test 1

The statistical parameters of the crack network obtained from large-scale lateral flow test 1 are shown in Figure 5.78 to Figure 5.81. There were 44 cracks in the specimen. The crack length has a mean and distribution 0.144 m and 0.107 m, respectively. The crack orientation has a mean and distribution of 87.5° and 52.5°, respectively. The X coordinate of the crack midpoints has a mean and distribution of 0.528 m and 0.267 m, respectively. The Y coordinate of the crack midpoints has a mean and distribution of 0.508 m and 0.268 m, respectively. The R^2 obtained from the probability plot of crack length (Figure 5.78) shows that crack length can be characterized using a lognormal distribution. The R^2 obtained from the probability plot of crack orientation (Figure 5.79) shows that crack orientation can be characterized using a uniform distribution. The R^2 obtained from the probability plot of the X coordinate of the crack midpoint (Figure 5.80) shows that the X coordinate of the crack midpoint can be characterized using a uniform distribution. The R^2 obtained from the probability plot of the Y coordinate of the crack midpoint (Figure 5.81) shows that the Y coordinate of the crack midpoint can be characterized using a uniform distribution. Li and Zhang (2010) also found similar behaviour. A summary of the statistical parameters of the crack network obtained from large-scale lateral flow test 1 is shown Table 5.6.

(a)

(b)

(c)

(d)

Figure 5.78 Statistical analysis of the crack length of the crack network of large-scale lateral flow test 1: (a) Histogram of crack length; (b) Uniform probability plot of crack length; (c) Normal probability plot of crack length; (d) Lognormal probability plot of crack length

(a)

(b)

(c)

(d)

Figure 5.79 Statistical analysis of the crack orientation of the crack network of large-scale lateral flow test 1: (a) Histogram of crack orientation; (b) Uniform probability plot of crack orientation; (c) Normal probability plot of crack orientation; (d) Lognormal probability plot of crack orientation

(a)

(b)

(c)

(d)

Figure 5.80 Statistical analysis of the X coordinate of the crack midpoint of the crack network of large-scale lateral flow test 1: (a) Histogram of X coordinate of crack midpoint; (b) Uniform probability plot of X coordinate of crack midpoint; (c) Normal probability plot of X coordinate of crack midpoint; (d) Lognormal probability plot of X coordinate of crack midpoint

(a)

(b)

(c)

(d)

Figure 5.81 Statistical analysis of the Y coordinate the of crack midpoint of the crack network of large-scale lateral flow test 1: (a) Histogram of Y coordinate of crack midpoint; (b) Uniform probability plot of Y coordinate of crack midpoint; (c) Normal probability plot of Y coordinate of crack midpoint; (d) Lognormal probability plot of Y coordinate of crack midpoint

Table 5.6 Summary of the statistical parameters of the crack network of large-scale lateral flow test 1: (a) Mean and standard deviation; (b) R^2 of uniform, normal, and lognormal distribution

(a)

Crack Parameter	Mean	Standard Deviation
Length (m)	0.144	0.107
Orientation (deg)	87.5	52.5
X-coordinate of crack midpoints	0.528	0.267
Y-coordinate of crack midpoints	0.508	0.268

(b)

Crack Parameter	R^2 of Uniform Distribution	R^2 of Normal Distribution	R^2 of Lognormal Distribution
Length	0.82	0.87	0.97
Orientation	0.96	0.95	0.76
X-coordinate of crack midpoints	0.98	0.96	0.90
Y-coordinate of crack midpoints	0.98	0.96	0.92

5.7.1.2 Large-scale Lateral Flow Test 2

The statistical parameters of the crack network obtained from large-scale lateral flow test 2 are shown in Figure 5.82 to Figure 5.85. There were 40 cracks in the specimen. The crack length has a mean and distribution of 0.121 m and 0.093 m, respectively. The crack orientation has a mean and distribution of 87.3° and 52.9°, respectively. The X coordinate of the crack midpoints has a mean and distribution of 0.515 m and 0.212 m, respectively. The Y coordinate of the crack midpoints has a mean and distribution of 0.563 m and 0.277 m, respectively. The R^2 obtained from the probability plot of crack length (Figure 5.82) shows that crack length can be characterized using a lognormal distribution. The R^2 obtained from the probability plot of crack orientation (Figure 5.83) shows that crack orientation can be characterized using a uniform distribution. The R^2 obtained from the probability plot of the X coordinate of the crack midpoint (Figure 5.84) shows that the X coordinate of the crack midpoint can be characterized using a uniform distribution. The R^2 obtained from the probability plot of the Y coordinate of the crack midpoint (Figure 5.85) shows that the Y coordinate of the crack midpoint can be characterized using a uniform distribution. Li and Zhang (2010) also found similar behaviour. A summary of the statistical parameters of the crack network obtained from large-scale lateral flow test 2 is shown Table 5.7.

(a)

(b)

(c)

(d)

Figure 5.82 Statistical analysis the crack length of the crack network of large-scale lateral flow test 2: (a) Histogram of crack length; (b) Uniform probability plot of crack length; (c) Normal probability plot of crack length; (d) Lognormal probability plot of crack length

(a)

(b)

(c)

(d)

Figure 5.83 Statistical analysis of crack orientation of the crack network of large-scale lateral flow test 2: (a) Histogram of crack orientation; (b) Uniform probability plot of crack orientation; (c) Normal probability plot of crack orientation; (d) Lognormal probability plot of crack orientation

(a)

(b)

(c)

(d)

Figure 5.84 Statistical analysis of the X coordinate of the crack midpoint of the crack network of large-scale lateral flow test 2: (a) Histogram of X coordinate of crack midpoint; (b) Uniform probability plot of X coordinate of crack midpoint; (c) Normal probability plot of X coordinate of crack midpoint; (d) Lognormal probability plot of X coordinate of crack midpoint

(a)

(b)

(c)

(d)

Figure 5.85 Statistical analysis of the Y coordinate of the crack midpoint of the crack network of large-scale lateral flow test 2: (a) Histogram of Y coordinate of crack midpoint; (b) Uniform probability plot of Y coordinate of crack midpoint; (c) Normal probability plot of Y coordinate of crack midpoint; (d) Lognormal probability plot of Y coordinate of crack midpoint

Table 5.7 Summary of the statistical parameters of the crack network of large-scale lateral flow test 2: (a) Mean and standard deviation; (b) R^2 of uniform, normal, and lognormal distribution

(a)

Crack Parameter	Mean	Standard Deviation
Length (m)	0.121	0.093
Orientation (deg)	87.3	52.9
X-coordinate of crack midpoints	0.515	0.212
Y-coordinate of crack midpoints	0.563	0.277

(b)

Crack Parameter	R^2 of Uniform Distribution	R^2 of Normal Distribution	R^2 of Lognormal Distribution
Length	0.88	0.89	0.98
Orientation	0.99	0.95	0.86
X-coordinate of crack midpoints	0.98	0.95	0.96
Y-coordinate of crack midpoints	0.98	0.95	0.81

5.7.2 Results of Numerical Generation of Crack Network

5.7.2.1 Crack Network Generated Based on Statistical Parameters of the Crack Network of Large-scale Lateral Flow Test 1

From the statistical parameters shown in Table 5.6, three crack networks were generated as shown in Figure 5.86. The crack networks were generated incorporating the method described in Section 3.5.2 and Section 4.8.2. The crack networks were used in the analysis of change in water content and matric suction of cracked soil.

(a)

(b)

(c)

Figure 5.86 Crack networks generated numerically based on large-scale lateral flow test 1: (a) Crack network 1-1; (b) Crack network 1-2; (c) Crack network 1-3

5.7.2.2 Crack Network Generated Based on Statistical Parameters of the Crack Network of Large-scale Lateral Flow Test 2

From the statistical parameters shown in Table 5.7, three crack networks were generated as shown in Figure 5.87. The crack networks were generated incorporating the method described in Section 3.5.2 and Section 4.8.2. The crack networks were used in the analysis of change in water content and matric suction of cracked soil.

(a)

(b)

(c)

Figure 5.87 Crack networks generated numerically based on large-scale lateral flow test 2: (a) Crack network 2-1; (b) Crack network 2-2; (c) Crack network 2-3

5.7.3 Results of Numerical Analyses of Change in Water Content and Matric Suction of Cracked Soils Based on Numerically Generated Crack Networks

The numerically generated crack networks (Figure 5.86 and Figure 5.87) were incorporated in crack soil models. Numerical analyses were then performed to analyze change in water content of cracked soil with varying crack networks. Averaging techniques were applied to the analysis to obtain the water content and matric suction of cracked soil. The average water content was applied to the numerical analysis of the laboratory specimens of cracked soil and the model of cracked soils with the generated crack network. The results are presented as follows.

5.7.3.1 Results of Numerical Analyses Utilizing Crack Networks Generated Based on Statistical Parameters Obtained from Large-scale Lateral Flow Test 1

The results of numerical analyses of cracked soil models incorporating crack network generated based on the statistical parameters obtained from large-scale lateral flow test 1 are shown in Figure 5.88, Figure 5.89, and Figure 5.90.

(a)

(b)

Figure 5.88 Comparison of water content obtained from sampling at the end of large-scale lateral flow test 1 and water content obtained from numerical analysis of the cracked soil model incorporating network 1-1 (Analysis no. 2-1) : (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

(a)

(b)

Figure 5.89 Comparison of water content obtained from sampling at the end of large-scale lateral flow test 1 and water content obtained from numerical analysis of the cracked soil model incorporating network 1-2 (Analysis no. 2-2): (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

(a)

(b)

Figure 5.90 Comparison of water content obtained from sampling at the end of large-scale lateral flow test 1 and water content obtained from numerical analysis of the cracked soil model incorporating network 1-3 (Analysis no. 2-3): (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

Three-dimensional (3D) contours of water content and matric suction for several time during the lateral flow were then obtained. Examples of 3D contours of water content and matric suction with time at the end of large-scale desiccation test 1 are shown in Figure 5.91 to Figure 5.94.

(a)

(b)

Figure 5.91 3D contours of water content and matric suction at the end of large-scale lateral flow test 1 obtained from laboratory specimen: (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

(a)

(b)

Figure 5.92 3D contours of water content and matric suction at the end of large-scale lateral flow test 1 obtained from crack network 1-1 (Analysis no. 2-1): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

(a)

(b)

Figure 5.93 3D contours of water content and matric suction at the end of large-scale lateral flow test 1 obtained from crack network 1-2 (Analysis no. 2-2): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

(a)

(b)

Figure 5.94 3D contours of water content and matric suction at the end of large-scale lateral flow test 1 obtained from crack network 1-3 (Analysis no. 2-3): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

Average values of water content and matric suction were then calculated at several times during the lateral flow. The results of the analyses are shown in Figure 5.95. The variation of the average water content and matric suction of the cracked soil models with four different crack networks is relatively small.

(a)

(b)

Figure 5.95 Comparison of average water content and average matric suction of cracked soil models of large-scale lateral flow test 1: (a) Average water content; (b) Average matric suction

5.7.3.2 Results of Numerical Analyses Utilizing Crack Networks Generated Based on Statistical Parameters Obtained from Large-scale Lateral Flow Test 2

The results of numerical analyses cracked soil models incorporating crack network generated based on the statistical parameters obtained from large-scale lateral flow test 2 are shown in Figure 5.96 to Figure 5.101.

(a)

(b)

(c)

(d)

Figure 5.96 Comparison of volumetric water content obtained from instrumentation and sampling of large-scale lateral flow test 2 and water content obtained from numerical analysis of the cracked soil model incorporating network 2-1 (Analysis no. 2-4): (a) At time = 0; (b) At time = 25 minutes; (c) At time = 50 minutes; (d) At time = 75 minutes (the end of lateral flow test)

Figure 5.97 Comparison of gravimetric water content obtained from water content sampling at the end of large-scale lateral flow test 2 ($t = 75$ min) and water content obtained from numerical analysis of the cracked soil model incorporating network 2-1 (Analysis no. 2-4)

(a)

(b)

(c)

(d)

Figure 5.98 Comparison of volumetric water content obtained from instrumentation and sampling of large-scale lateral flow test 2 and water content obtained from numerical analysis of the cracked soil model incorporating network 2-2 (Analysis no. 2-5): (a) At time = 0; (b) At time = 25 minutes; (c) At time = 50 minutes; (d) At time = 75 minutes (the end of the lateral flow test)

Figure 5.99 Comparison of gravimetric water content obtained from water content sampling at the end of large-scale lateral flow test 2 ($t = 75$ minutes) and water content obtained from numerical analysis of the cracked soil model incorporating network 2-2 (Analysis no. 2-5)

(a)

(b)

(c)

(d)

Figure 5.100 Comparison of volumetric water content obtained from instrumentation and sampling of large-scale lateral flow test 2 and water content obtained from numerical analysis of the cracked soil model incorporating network 2-3 (Analysis no. 2-6): (a) At time = 0; (b) At time = 25 minutes; (c) At time = 50 minutes; (d) At time = 75 minutes (the end of the lateral flow test)

Figure 5.101 Comparison of gravimetric water content obtained from water content sampling at the end of large-scale lateral flow test 2 ($t = 75$ minutes) and water content obtained from numerical analysis of the cracked soil model network 2-3 (Analysis no. 2-6)

Three-dimensional (3D) contours of water content and matric suction for several time during the lateral flow were then obtained. Examples of 3D contours of water content and matric suction with time at the end of large-scale desiccation test 2 are shown in Figure 5.102 to Figure 5.105.

(a)

(b)

Figure 5.102 3D contours of water content and matric suction at end of large-scale lateral flow test 2 obtained from laboratory specimen ($t=75$ minutes) (Analysis no. 2-5): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

(a)

(b)

Figure 5.103 3D contours of water content and matric suction at the end of large-scale lateral flow test 2 ($t=75$ min) obtained from crack network 2-1 (Analysis no. 2-5): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

(a)

(b)

Figure 5.104 3D contours of water content and matric suction at the end of large-scale lateral flow test 2 ($t=75$ minutes) obtained from crack network 2-2 (Analysis no. 2-6): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

(a)

(b)

Figure 5.105 3D contours of water content and matric suction at the end of large-scale lateral flow test 2 ($t=75$ minutes) obtained from crack network 2-3 (Analysis no. 2-6): (a) 3D contour of volumetric water content; (b) 3D contour of matric suction

Average values of water content and matric suction were then calculated at several times during the lateral flow. The results of the analyses are shown in Figure 5.106. The variation of the average water content and matric suction of the cracked soil models with four different crack networks is relatively small.

(a)

(b)

Figure 5.106 Comparison of average water content and average matrix suction of cracked soil models of large-scale lateral flow test 2: (a) Average water content; (b) Average matrix suction

6 CHAPTER 6

DISCUSSIONS

6.1 Introduction

In this chapter, the results obtained in Chapter 5 are discussed. Formation of the crack network and spatial variation in water content and matric suction of cracked soil is discussed first in Section 6.2. The performance of the proposed model to quantify lateral flow rate through the crack network is then discussed in Section 6.3. The performance of the proposed method to quantify change in water content and matric suction of cracked soils is presented in Section 6.4. The performance of the proposed averaging technique to quantify change in water content and matric suction of cracked soils is then discussed in Section 6.5. Each of Section 6.2 to Section 6.5 is ended with concluding remarks on what can be learned from the discussion. Finally, the implications of the proposed method in the numerical analysis of water flow in cracked soil are discussed in Section 6.6.

6.2 Formation of the Crack Network and Spatial Variation in Water Content and Matric Suction of Cracked Soil

6.2.1 Formation of Crack Network in Soil

Based on the large-scale desiccation test results (Figure 5.14, Figure 5.23, and Figure 5.27), desiccation cracks occurred in two stages. These stages are described in Figure 6.1. In the first stage, some cracks formed at random location in the specimen. The first stage cracks formed and propagated until they intersected other cracks or intersected the specimen boundary (Figure 6.1a, b, c). In the second stage cracks initiated from a location at a primary crack (Figure 6.1d). The cracks formed and propagated until they intersected other cracks or intersected the specimen boundary (Figure 6.1e). Some previous studies also indicated almost the same stages during the crack development (e.g. Li and Zhang, 2010; Atique et al., 2010;

Kodikara et al., 2000; Konrad and Ayad, 1997; Morris et al., 1992). In addition, from this study it was observed that there were two types of secondary cracks:

- Secondary cracks that started to develop from a linear portion of a primary crack (cracks started from points 1 and 2 in Figure 6.1d). The cracks oriented relatively orthogonal with respect to the corresponding crack.
- A secondary crack started to develop from an intersection point that makes an angle (cracks started from points 3 and 4 in Figure 6.1d).

(a)

(b)

(c)

(d)

(e)

Figure 6.1 Schematics of the formation of a crack network: (a) Initiation of the first stage cracks; (b) Development of the first cracks; (c) Fully developed of the first stage cracks; (d) Initiation and development of the second stage cracks; (e) Fully developed of the second stage cracks

Several previous studies indicated that cracks occurred predominantly in orthogonal patterns (e.g. Morris et al., 1992; Atique and Sanchez, 2011). However, several previous studies also indicated that cracks with non-orthogonal patterns also occurred (e.g. Kodikara et al., 2000). The phenomenon that a large number of cracks intersect orthogonally together with several number of cracks intersect at an angle lower than 90° was also observed in this study as can be seen in Figure 5.9, Figure 5.14, Figure 5.19, Figure 5.23, Figure 5.27, and Figure 5.31. The orthogonal crack intersection occurred simultaneously with a curvature near the crack intersection point. This is shown schematically by crack AB in Figure 6.2a. For the idealized crack proposed in this study, crack AB is represented by a straight line connecting two crack intersection points A and B (Figure 6.2b). This causes the intersection point B to be not orthogonal in the idealized crack network. The numerically generated crack network was developed to simulate the idealized crack network (Figure 3.4). In spite of this idealization in numerically generated crack network, the effect of curvature of cracks to the prediction of lateral flow and to the

changes in water content of cracked soil specimens are small, as discussed in Section 6.3.3 and Section 6.4.3. Therefore, the developed method for numerically generating the crack network is still applicable in the prediction of flow rate through crack network and the analysis of the changes in water content of cracked soils.

Figure 6.2 Schematic diagram: (a) Curved crack portion near crack intersection point; (b) Idealized crack

Several attempts to predict crack network based on mechanical properties of soil have been performed in previous studies (e.g. Lachenbruch, 1961; Lee et al., 1988; Abu Hejleh et al., 1995; Konrad and Ayyad, 1997; Kodikara and Choi, 2006). However, these studies only dealt with limited aspects of crack network (e.g. crack spacing and crack depth). Prediction of a crack network based on the mechanical properties of soil has not been fully developed and is difficult to be incorporated in the numerically generated crack network. Therefore, in this study the mechanical aspect has not been incorporated in the numerically generated crack network. In spite of that, some aspects of the crack network generation have been incorporated such as the primary and secondary stages in crack formation and the connectivity among cracks.

6.2.2 Formation of the Initial Cracks in Soil

In large-scale desiccation test 1, the initial crack occurred at a water content equal to 0.50 (Figure 5.10a) corresponding to matric suction equal to 34.9 kPa (Figure 5.10b); whereas in large-scale desiccation test 2, the initial crack occurred at a water

content equal to 0.59 (Figure 5.15a) corresponding to matric suction equal to 10.1 kPa (Figure 5.15b). These two matric suction values are near the air entry value of SWCC as indicated by parameter a in Table 5.2. In both tests after the initial crack formed, there was a significant change in the rate of increase in matric suction (Figure 5.10b and Figure 5.15b). However, no significant change in the rate of decrease in water content was observed in either desiccation test (Figure 5.10a and Figure 5.15a).

The reason for a significant change in matric suction although there was no significant change in water content (Figure 5.10 and Figure 5.15) can be investigated by observing the corresponding SWCC in Figure 5.3. The relationship between matric suction and water content is not linear. Therefore, if there was a linear change in water content as in the large-scale desiccation tests, the change of matric suction was not correspondingly linear.

6.2.3 Spatial Variation of Water Content in Cracked Soil and Formation of Cracks in Soil during Desiccation

Figure 6.3 to Figure 6.6 show that the water content and matric suction vary in a plane of a cracked soil specimen.

Figure 6.3 Contour of water content of cracked soil in large-scale desiccation test 1
(Krisnanto et al., 2011)

Figure 6.4 Contour of water content of cracked soil in large-scale desiccation test 2

(Krisnanto et al., 2011)

Figure 6.5 Contour of matric suction of cracked soil in large-scale desiccation test 1

(Krisnanto et al., 2011)

Figure 6.6 Contour of matric suction of cracked soil in large-scale desiccation test 2
(Krisnanto et al., 2011)

The variations in water content in the cracked soil specimens along sections X-X (large-scale desiccation test 1, see Figure 6.3) and Y-Y (large scale desiccation test 2, see Figure 6.4) are shown in Figure 6.7. It can be seen that a crack occurred at a location between two local points of lowest water content. At these two locations of local points of lowest water content, the amount of soil shrinkage is the highest. These two locations acted as a static point from where the soil was pulled. Observations at other cross sections showed similar results.

Figure 6.7 Gravimetric water content at section X-X (large-scale desiccation test 1) and section Y-Y (large-scale desiccation test 2) (Krisnanto et al., 2011)

Observations of variations in matric suction along several cross sections in the cracked soil specimens showed that a crack occurred at a location between the two local points of highest matric suction. Examples of variation in matric suction in specimens of large-scale desiccation test 1 along section X-X (Figure 6.5) and large-scale desiccation test 2 along section Y-Y (Figure 6.6) are shown Figure 6.8.

Figure 6.8 Matric suction at section X-X (large-scale desiccation test 1) and section Y-Y (large-scale desiccation test 2) (Krisnanto et al., 2011)

6.2.4 Concluding Remarks

From the above discussion, the following conclusions can be drawn:

1. Cracks formed in two stages. In the first stage, some cracks formed at random locations in the specimen. The first stage cracks formed and propagated until they intersected other cracks or intersected the specimen boundary. In the second stage, cracks initiated from a location at a primary crack. The cracks formed and propagated until they intersected other cracks or intersected the specimen boundary.
2. It was observed that, after the initial cracks formed in large-scale desiccation test 1 and large-scale desiccation test 2, there was a significant change in the rate of increase in matric suction. However, there was no significant change in the rate of decrease in water content.
3. During large-scale desiccation test 1 and large-scale desiccation test 2, a crack formed at a location between two local points with the lowest water content values. These two locations acted as static points from where the soil was pulled.

6.3 Performance of the Proposed Method to Quantify Lateral Flow Rate through Cracked Soil using Lateral Flow through the Crack Network

6.3.1 The Use of Lateral Flow Rate through a Crack Network to Represent Lateral Flow Rate through Cracked Soil

The laboratory test results showed that the measured lateral flow rate was relatively constant with time (Figure 5.35, Figure 5.37, Figure 5.41, and Figure 5.46), 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 5.4, Table 5.5, Table A.5 and Table A.6) with those of the corresponding wetting SWCC in Figure 5.3c and Figure 5.4c 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 reflected a transient flow. These observations 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
- The water seepage through soil matrix which was a transient flow.

The results of the laboratory measurement of lateral flow rate that are plotted together with the numerical analyses (Figure 5.57; Figure 5.59; Figure 5.61, and Figure 5.63) show that the inflow and outflow rates calculated from the numerical simulation are quite similar, indicating that the seepage rate into the soil matrix was small as compared to the flow rate through the crack network. In addition, the close values between the inflow and outflow measurements of large-scale lateral flow test 2 (Figure 5.63) provide a fact that the seepage rate into the soil matrix was small as compared to the flow through the network of cracks. Therefore, the lateral flow rate through cracked soil can be quantified from the lateral flow through the crack network.

6.3.2 Incorporating Additional Head Loss in the Hydraulic Gradient between Crack Endpoints

Comparisons between the measured and predicted lateral flow rates using the proposed model (Figure 5.49, Figure 5.51, Figure 5.53, and Figure 5.55) show that the predicted lateral flow rates through the network of cracks are relatively close to the measured results. This indicated that the incorporation of the additional head loss due to changes in crack aperture in the calculation of hydraulic gradient (Eq. (3.18)) and the use of the representative crack aperture b (Eq. (3.38)) provide a satisfactory method to predict the lateral flow rate through the network of cracks. The representative crack aperture can then provide a means to calculate the aperture that should be used in the cubic law to accurately predict flow in a crack.

6.3.3 Additional Head Loss due to the Curvature of Cracks

The assumption that additional head loss due to the curved shape of cracks is minimum is confirmed by the close values between the results of laboratory experiments and the predicted lateral flow rates using the proposed model. The close values indicated that the additional head loss due to curvature of cracks is small. Therefore, the idealization of the actual cracks using linear cracks are sufficient in the proposed model to predict lateral flow rate through cracked soil. In addition, results from previous studies indicate that most of the cracks in soil are linear (e.g. Atique et al., 2010; Kodikara et al., 2000; Corte and Higashi, 1960). Therefore, the assumption of linear cracks in the idealized crack network can be used to analyze flow through cracked soil.

6.3.4 Incorporating Additional Head Loss in Numerical Analyses to Compute Lateral Flow Rate through Cracked Soil

The results of the numerical simulation are shown in Figure 5.57, Figure 5.59, Figure 5.61, and Figure 5.63 together with the 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 rates from the proposed model. These results indicate that in the numerical analysis, the crack aperture should be calculated to

incorporate the effect of additional head loss due to change in crack aperture (Eq. (4.25)). The head loss is obtained from the proposed model (Eq. (3.17)).

6.3.5 The Use of Constant Aperture from Top to the Bottom of Cracked Soil Layer

The model to predict lateral flow through the crack network was developed based on the assumption that the cracks extend from the top to the bottom of the soil layer with a constant aperture (Section 3.3). However, the actual crack aperture may vary with depth as shown in Figure 3.9. Although there is a difference in terms of the crack aperture, the model can still be used by considering the crack consists of several sub cracks with constant apertures as shown in Figure 6.9. Flow rate through the crack is then calculated as a summation of all the sub cracks that constitute the crack.

The assumption of constant aperture serves as a starting point for analyzing actual cracks with decreasing aperture with depth. Further study is needed to provide a method to represent the varying crack aperture from top to the bottom of crack soil layer (Figure 6.9a) with series of sub cracks of constant aperture (Figure 6.9b).

Figure 6.9 Division of a crack into several sub cracks

6.3.6 Change in the Crack Aperture due to Wetting of the Soil Matrix

During lateral flow, soil matrix experienced wetting. Soil then swelled due to an increase in water content. However, Figure 5.65, Figure 5.68, and Figure 5.69 indicate that the increase of water content only occurred at locations near the cracks. The soil matrix in the centre of crack cells were still at water contents close to the water content before the start of lateral flow tests. It can be inferred that large swelling occurred only at locations near crack walls. A large portion of soil matrix experienced very little swelling. The crack aperture was not closed at this condition. Therefore, the assumption that crack aperture remains constant during the lateral flow (Section 3.3) is still acceptable.

6.3.7 Possibility of the Lateral Flow through Lateral Cracks and Curling Edges in the Specimen

In a real soil system, horizontal cracks will occur due to the development of tensile stress caused by a difference in lateral shrinkage with depth as observed by Konrad and Ayyad (1997). The observed soil was silty clay with liquid limit, LL and plastic limit, PL were 50% and 25%, respectively. The temperature during desiccation varied between 15°C to 30°C. Water table was at 70 cm depth below the ground surface. The soil desiccated from a gravimetric water content around 100%. This initial water content was relatively uniform from the ground surface to 70 cm depth. Desiccation cracks initiated at the gravimetric water content equal to 94%. This value of water content was relatively uniform from the ground surface to 10 cm depth. Lateral cracks initiated at a condition when there is a variation of gravimetric water content around 40% at ground surface to 60% at depth of 10 cm. Lateral cracks occurred at depth 6 to 8 cm below ground surface.

The specimens used in the large-scale lateral flow tests in this study were 2.5 cm in thickness (Table 4.5). This thickness was smaller than the depth where the lateral cracks occurred in the observation by Konrad and Ayyad (1997). The decrease in gravimetric water content during desiccation of the specimen in this study was from 54% to 34% which was less than that as observation by Konrad and Ayyad (1997). Large variation in water content, along the depth of soil, was less probable to occur.

Therefore, it can be expected that lateral cracks did not occur between the top and the bottom of the soil specimen. In addition to this, grease was applied at the base of the cracked soil compartment (Figure 4.8) before the soil was compacted and sand was provided on top of the plastic sheet above the cracked soil specimen to produce pressure on top of the cracked soil specimen. Using this effort, it was expected that the lateral flows below and on top of the cracked soil were minimized.

A model to predict the soil deformation due to curling of desiccating clay has been developed (Kodikara et al., 2004). However, the model was only developed for small specimens. In this study which incorporated large-size specimens, the gap between the soil specimen and the wall of the lateral flow apparatus was sealed using silicon filler to minimize the flow to occur through this gap. Therefore, the possibility of water flow under the curling edges of the specimen had already been minimized

6.3.8 Concluding Remarks

From the above discussion, the following conclusions can be drawn:

1. The seepage rate into the soil matrix was small as compared to the flow through the crack network. Therefore, the lateral flow rate through cracked soil can be quantified from the lateral flow through the crack network.
2. Additional head loss due to the curvature of cracks was small since the cracks were mostly linear.
3. Additional head loss due to changes in crack aperture can be used in the model to predict lateral flow through the crack network. The representative crack aperture can then be used in the cubic law that was used in the model.
4. In the numerical analyses to compute lateral flow rate through cracked soil, crack aperture should be calculated to incorporate the effect of additional head loss due to the change in crack aperture.

6.4 Performance of the Proposed Method to Quantify Change in Water Content and Matric Suction of Cracked Soil by Modelling the Crack Network as Head Boundary Conditions

6.4.1 Summary of the Results of Analyses of Changes in Water Content and Matric Suction of Cracked Soil

Results of the analyses of changes in water content of cracked soil using head boundary condition presented in Chapter 5 are summarized in Figure 6.10. The summary includes results obtained from large-scale lateral flow test 1 (Figure 5.65) and results obtained from large-scale lateral flow test 2 (Figure 5.68 and Figure 5.69).

Figure 5.65 Comparison of water content obtained from sampling at the end of large-scale lateral flow test 1 and water content obtained from the numerical analysis: (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

Figure 5.68 Comparison of volumetric water content obtained from instrumentation, sampling, and numerical analysis of large-scale lateral flow test 2: (a) At time = 0; (b) At time = 25 minute; (c) At time = 50 minute; (d) At time = 75 min (the end of the lateral flow test)

Figure 5.69 Comparison of gravimetric water content obtained from water content sampling at the end of large-scale lateral flow test 2 ($t = 75$ min)

Figure 6.10 Summary of results of analyses of change in water content of cracked soil by modelling cracks as head boundary conditions

Results of the analyses of change in water content of cracked soil by modelling cracked soil as a continuum as presented in Chapter 5 are summarized in Figure 6.11.

Figure 5.71 Comparison of water content obtained from sampling and numerical analysis incorporating the Fredlund et al. (2010) method at the end of large-scale lateral flow test 1: (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

Figure 5.72 Comparison of water content obtained from sampling and numerical analysis incorporating the Li et al. (2011) method at the end of large-scale lateral flow test 1: (a) Comparison of gravimetric water content; (b) Comparison of volumetric water content

Figure 5.74 Comparison of volumetric water content obtained from instrumentation, sampling, and numerical analysis of large-scale lateral flow test 2 using Fredlund et al. (2010) method: (a) At time = 0; (b) At time = 25 minute; (c) At time = 50 minute; (d) At time = 75 min (the end of the lateral flow test)

Figure 5.75 Comparison of gravimetric water content obtained from water content sampling using Fredlund et al. (2010) method at the end of large-scale lateral flow test 2 ($t = 75$ min)

Figure 5.76 Comparison of volumetric water content obtained from instrumentation, sampling, and numerical analysis of large-scale lateral flow test 2 using Li et al. (2011) method: (a) At time = 0; (b) At time = 25 minute; (c) At time = 50 minute; (d) At time = 75 min (the end of the lateral flow test)

Figure 5.77 Comparison of gravimetric water content obtained from water content sampling using Li et al. (2011) method at the end of large-scale lateral flow test 2 ($t = 75$ min)

Figure 6.11 Summary of results of analyses of change in water content by modelling cracked soil as a continuum

6.4.2 Mechanisms of Change in Water Content of Cracked Soil during Lateral Flow

A comparison between the measurements and numerical analyses (Figure 5.65, Figure 5.68, and Figure 5.69) gives good agreement. This agreement indicates that the use of head boundary conditions to model the changes in water content of cracked soil is appropriate. On the other hand, the results from the model of cracked soil using the continuum approach did not provide satisfactory agreement with the measured results (Figure 5.71, Figure 5.72, Figure 5.74, Figure 5.75, Figure 5.76, and Figure 5.77).

The cause of the different performances for the two approaches can be investigated by comparing cracked soil and intact soil. In intact soil, the location of pores with different sizes is randomly distributed, as described in Figure 2.3. In cracked soil, the macropores (cracks) are located such that the macropores are continuous and form vertical cracks, as shown in Figure 3.9. The cracks resemble the connected macropores which have the same water entry value and are connected continuously in vertical direction. This difference results in different mechanisms when water infiltrates the soil. In intact soil, during wetting water enters the soil starting from the small pores as they have a low water entry value. Subsequently, water enters the bigger pores. In cracked soil, a different phenomenon occurs. Water enters the crack first, then the soil matrix (e.g., van Dam, 2000; Novak et al., 2000). In other words, in cracked soil during infiltration, water fills the macropores first and then seeps to the soil matrix. The mechanism of water filling the soil matrix is the same as that of intact soil, and is supported by analyses performed by Zhan et al. (2007), van Dam (2000), and Bronswijk et al. (1995).

Some soils with large pores can be considered as a continuum, such as gravel-sized soil with large pores like granite chips (e.g. Rahardjo et al., 2012) and recycled concrete aggregate (RCA) (e.g. Rahardjo et al., 2013). These soils still behave as a continuum and analyses incorporating their SWCC and permeability function show good agreement as indicated by the similar results between the numerical analyses and instrumentation. The compaction causes soil particles to fill the voids and, as a

result, the soil particle comes in contact with other particles. This results in a single grain (Craig, 2004; Harr, 1977), as shown in Figure 6.12. This arrangement is different than that of cracked soil where the cracks resemble connected macropores with the same water entry value and are connected continuously in vertical direction (Figure 3.9).

The difference between gravel-sized soil and cracked soil is in gravel-sized soil, pores with relatively similar water entry values are not connected continuously in vertical direction as in cracked soil. It can be concluded that this difference causes the different changes in water content in cracked soil and intact soil.

Figure 6.12 Single grain structure (from Craig, 2004)

Petters and Klavetters (1988) proposed a continuum method for cracked soil. In this method, macropores that have relatively similar water entry values are connected to each other. However, this method was intended for slowly-changing water movement. The water that fills the crack network in the ground surface comes from infiltration. During infiltration, water fills the cracks relatively fast. Therefore, the method proposed in this study should be used to model changes in water content of cracked soil in the ground surface.

6.4.3 Deviation from Measurements due to the Nonlinear Shape of Cracks

Figure 5.65 shows that there are some differences between the results from numerical analysis and the results from laboratory measurements. The differences occur at location no. 16, 21, and 29 in large-scale lateral flow test 1 (Figure 5.65).

These locations are near the cracks that have a curved shape (Figure 5.52). However, at locations where the actual cracks are relatively linear, the differences are small, as shown in Figure 5.65, Figure 5.68, and Figure 5.69. Therefore, it can be inferred that this difference is caused by modelling curved cracks as linear cracks. However, most of the results are within a 10% difference. The proposed method works well for analyzing changes in water content of cracked soil. In the literature, most cracks are linear (e.g. Atique et al., 2010; Kodikara et al., 2000; Corte and Higashi, 1960). Therefore, the use of linear cracks to idealize a crack network in soil will yield results that are close to the actual values. In addition, the use of linear cracks to idealize a crack network in soil has been used in previous studies (e.g. Long et al., 1982; Li and Zhang, 2010). Thus, the method proposed in this study can be incorporated with the existing framework to characterize crack networks in soil.

6.4.4 Concluding Remarks

From the above discussion, the following conclusions can be drawn:

1. The proposed method that use head boundary conditions to quantify change in water content and matric suction of cracked soil can be used for the following conditions:
 - Soil with macropores with relatively similar water entry values that are connected; and
 - Fast water movement filling up cracks.For soil with macropores with relatively similar water entry values that are connected but the water movement is relatively slow (e.g., cracked soil located far below the ground surface), the continuum approach is still appropriate.
2. The existing method that use continuum approach to quantify change in water content and matric suction of cracked soil can be used for the following conditions:
 - Soil with macropores with similar water entry values that are not connected; or
 - Soil with macropores with relatively similar water entry values that are connected, but with a slow water movement.

3. The use of linear cracks to idealize actual cracks gives good results for modelling changes in water content in cracked soil. This occurs because most cracks are linear. The use of linear cracks is compatible with previous studies characterizing crack networks in soil.

6.5 Performance of the Proposed Method to Quantify Change in Water Content along Cracked Soils Using an Averaging Technique

6.5.1 Incorporating the Findings of Formation of Crack Networks in the Numerical Generation of Crack Networks

Six examples of crack network were generated following the method proposed by Long et al. (1982) and Li and Zhang (2007) as shown in Figure 6.13 and Figure 6.14. Three crack networks were generated incorporating statistical parameters obtained from each large-scale lateral flow tests 1 and 2. Random numbers between 0 and 1 were generated for crack midpoint X coordinate, crack midpoint Y coordinate, crack length, and crack orientation. These random numbers were then used to generate other random numbers with uniform and lognormal distributions. The inverse of the cumulative probability density functions (Ang and Tang, 1984) was used to calculate random crack numbers with uniform and lognormal distributions. Crack midpoint X coordinate, crack midpoint Y coordinate, and crack orientation were generated based on uniform distribution and crack length was generated based on lognormal distribution.

(a)

(b)

Figure 6.13 Three examples of numerically-generated crack networks based on the statistical parameters of large-scale lateral flow test 1 following the method proposed by Long et al. (1982) and Li and Zhang (2007): (a) Network 1-1b; (b) Network 1-2b; (c) Network 1-3b

Figure 6.14 Three examples of numerically-generated crack networks based on the statistical parameters of large-scale lateral flow test 2 following the method proposed by Long et al. (1982) and Li and Zhang (2007): (a) Network 2-1b; (b) Network 2-2b; (c) Network 2-3b

Six examples of the crack networks generated using this method exhibit poor performance in terms of the connections among cracks. Only few cracks connected to each other as shown in Figure 6.13 and Figure 6.14. In the desiccated crack network in ground surface, cracks are relatively connected to each other (e.g. Li and Zhang, 2010; Atique et al., 2010; Tang et al., 2008; Kodikara et al., 2000; Konrad and Ayad, 1997; McKay et al., 1993; Morris et al., 1992; Ruland et al., 1991; D'Astous et al., 1989; Fleming, 1973). The crack networks in Figure 6.13 and Figure 6.14 did not work well to replicate the crack network in the soil.

The numerically generated crack network in Li and Zhang (2007) and Long et al. (1982) still had connections among cracks. However, there is a significant difference in the number of cracks reported in those studies with the number of cracks presented in this study. The numerically generated crack network in Long et al. (1982) was 74 cracks per m^2 and in Li and Zhang (2007) were 2095 to 5447 cracks per m^2 . In this study, 44 cracks per m^2 were formed in the large-scale lateral flow tests 1 and 40 cracks were formed in the large-scale lateral flow tests 2. The number of cracks per square meter obtained from this study is much lower than those obtained in the previous studies. It can be concluded that the low number of cracks caused the poor connectivity among cracks.

Number of cracks per square meter from field observations in the previous studies is shown in Table 6.1. Some of the literature only provided data on spacing. Therefore, the number of cracks per square meter was back calculated assuming a square pattern of crack network. From Table 6.1 it is clear that the number of cracks per square meter varies. Some cracked soils have number of cracks per square meter lower than the number of cracks obtained in this study. The numerically generated crack networks incorporating number of cracks based on these cracked soils will exhibit poor performance in terms of the connection among cracks as shown in Figure 6.13 and Figure 6.14. Therefore, the proposed method can solve the problem of connectivity among cracks. Thus, the proposed method of crack generation has advantages, since it works well for the low and high crack density

Table 6.1 Field observation results of number of cracks per square meter

Soil Type	Number of Cracks per m ²	Reference
Silty clay	2098	Li and Zhang (2010)
Clay	20 to 48 (back calculated)	Konrad and Ayad (1997)
Clayey till	80 (back calculated)	McKay et al. (1993)
Mine tailing	1	Morris et al. (1992)
Clayey till	200 (back calculated)	Ruland et al. (1991)
Clay	100 (back calculated)	D'Astous et al. (1989)

The numerically generated crack network proposed in this study works well in terms of crack connectivity as shown in Figure 5.86 and Figure 5.87. However, in the crack generation, the primary and secondary cracks were not explicitly incorporated. This made the input data to be relatively simple since only total number of cracks that was needed as an input. In addition, the generated crack network still exhibits polygon shapes as indicated in the observation of the crack network in the field (e.g. Li and Zhang, 2010; Konrad and Ayad, 1997; McKay et al., 1993; Morris et al., 1992; Ruland et al., 1991; D'Astous et al., 1989; Fleming, 1973). Therefore, the proposed method of crack generation still works well to replicate desiccated crack network in soil.

6.5.2 Effect of Variation in the Crack Network on the Average Value of Water Content and Matric Suction of Cracked Soils

A comparison of the average water content obtained from the numerical analyses of the cracked soil model using the crack network obtained from the laboratory specimen and the cracked soil model using the numerically-generated crack network shows relatively similar results, as shown in Figure 5.95 for large-scale lateral flow test-1 and Figure 5.106 for large-scale lateral flow test-2. Even though the difference is small in the beginning of the test, the difference becomes larger as the duration of flow increases (Figure 5.95 and Figure 5.106). Figure 5.95 and Figure 5.106 are replotted in Figure 6.15 and Figure 6.16, respectively together with the maximum difference of water content or matric suction for each plot. For large-scale lateral flow test 1, the maximum difference of average water content was 1 %

(Figure 6.15a) and the maximum difference of average matric suction was 7% (Figure 6.15b). For large-scale lateral flow test 2, the maximum difference of average water content is 2% (Figure 6.16a) and the maximum difference of average matric suction is 30% (Figure 6.16b).

The above discussion indicates that the difference of average matric suction tends to be higher than the difference of average volumetric water content. However, this trend was only obtained for the models that incorporate the crack networks generated based on the statistical parameters obtained from the laboratory specimens used in this study. In addition, incorporating other crack networks can change the values of maximum difference of average water content and average matric suction of cracked soil model. In spite of that, the results obtained from this study provide a means to quantify the variation in average water content and average matric suction in cracked soil due to the variation of crack networks.

(a)

Figure 6.15 Maximum difference in average water content and average matric suction of cracked soil models of large-scale lateral flow test 1: (a) Average volumetric water; (b) Average matric suction

Figure 6.16 Maximum difference in average water content and average matric suction of cracked soil models of large-scale lateral flow test 2: (a) Average volumetric water; (b) Average matric suction

6.5.3 Differences in Patterns of Changes in Water Content between Cracked Soil and Intact Soil

Because the results of analysis using head boundary conditions are similar to the results from laboratory instrumentation and sampling (Figure 5.65, Figure 5.68, and Figure 5.69), it can be inferred that the flow condition described in Figure 3.10 did occur. Water filled directly into the bottom of the cracks and then seeped into the soil matrix. This condition was relatively similar to that described in Zhang and Zhang (2010), as shown in Figure 2.15. However, previous studies did not provided a method for incorporating the actual crack network to the cracked soil model for analysis of change in water content and matric suction. In this study, the actual crack network is incorporated in the analysis.

It can be concluded that the mechanism of water flow in cracked soil is not similar to that of intact soil with macropores. The water content distribution in cracked soil is different from that of the intact soil matrix.

6.5.4 Concluding Remarks

From the above discussion, the following conclusions can be drawn:

1. In this study, the previous method for the numerical generation of a crack network was improved by incorporating connectivity among cracks.
2. The difference between the average water content obtained from the analyses of the cracked soil model incorporating crack networks obtained from laboratory specimens and the cracked soil model incorporating numerically-generated crack networks becomes larger as the duration of flow increased. For large-scale lateral flow test 1, the maximum variation in average water content was 1 % and the maximum difference in average matric suction was 7%. For large-scale lateral flow test 2, the maximum difference in average water content was 2% and the maximum variation in average matric suction was 30%.
3. In lateral flow through cracked soil, water filled directly into the bottom of the cracks and then seeped into the soil matrix. Therefore, the use of head boundary conditions can model changes in water content and matric suction of cracked soil due to lateral flow through the crack network better than the use of a continuum to represent cracked soil.

6.6 Implications of the Proposed Method in the Analysis of Lateral Water Flow through Cracked Soil

From the proposed framework, lateral flow of water through cracked soil can be analysed as follows:

1. Lateral flow rate through cracked soil can be computed from lateral flow rate through the crack network. The lateral flow rate through the crack network is calculated by incorporating head losses due to change in crack aperture. The flow rate along the soil mass is then calculated for one REV.
2. To quantify changes in the water content and matric suction of cracked soil during lateral flow, the cracks can be modelled as head boundary conditions.

3. Effect of variation in the water content and matric suction of cracked soil can be quantified using an averaging technique. This study indicates that the maximum difference of average water content and matric suction due to the variation of crack network will be 2% and 30%, respectively. However, further study is needed to determine maximum difference of average water content and matric suction of cracked soil.

7CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The conclusions obtained from this study are presented in the following sections.

7.1.1 Formation of Cracks

The following conclusions can be drawn about the formation of cracks:

1. A large number of cracks intersect orthogonally together with several number of cracks intersect at an angle lower than 90° was observed in this study. The orthogonal crack intersection occurred simultaneously with a curvature near the crack intersection point.
2. Cracks formed in two stages. In the first stage, some cracks formed at random locations in the specimen. The first stage cracks formed and propagated until they intersected other cracks or intersected the specimen boundary. In the second stage, cracks initiated from a location at a primary crack. The cracks formed and propagated until they intersected other cracks or intersected the specimen boundary.
3. It was observed that, after the initial cracks formed in large-scale desiccation test 1 and large-scale desiccation test 2, there was a significant change in the rate of increase in matric suction. However, there was no significant change in the rate of decrease in water content.
4. During large-scale desiccation test 1 and large-scale desiccation test 2, a crack formed at a location between two local points with the lowest water content values. These two locations acted as static points from where the soil was pulled.

7.1.2 Development of Lateral Flow Test Apparatus

The following conclusions can be drawn from the development of the lateral flow test apparatus:

1. Large-scale and small-scale lateral flow apparatuses were developed in this study. The small-scale lateral flow test apparatus was designed as the pilot study for the development of the large-scale lateral flow test apparatus. By placing desiccated soil samples in the large-scale lateral flow test apparatus, the formation of cracks can be observed in a more controlled environment. In addition, crack networks in the soil can be obtained with help from scanning equipment. Finally, by using the large-scale lateral flow test apparatus, the lateral flow rate through cracked soil and the change in water content of cracked soil can be quantified.
2. Using the apparatus, it was identified that, during lateral flow into an unsaturated cracked soil specimen, two types of flow occurred simultaneously: water flow through the crack network, which is a steady state flow, and water seepage through the soil matrix, which is a transient flow.

7.1.3 Proposed Model to Quantify Lateral Flow Rate through Cracked Soil

The following conclusions can be drawn about the proposed model to predict the lateral flow rate through cracked soil:

1. The seepage rate into the soil matrix was small as compared to the flow through the crack network . Therefore, the lateral flow rate through cracked soil can be quantified from the lateral flow through the crack network.
2. Additional head loss due to the curvature of cracks was small since the cracks were mostly linear.
3. Additional head loss due to changes in crack aperture can be used in the model to predict lateral flow rate through the crack network. The representative crack aperture can then be used in the cubic law that was used in the model.
4. In the numerical analyses to compute the lateral flow rate through cracked soil, the crack aperture should be calculated to incorporate the effect of additional head loss due to the change in crack aperture.

7.1.4 Proposed Method to Quantify Change in Water Content and Matric Suction of Cracked Soil

The following conclusions can be drawn from the proposed method to quantify change in the water content and matric suction of cracked soil:

1. The proposed method that use head boundary conditions to quantify change in water content and matric suction of cracked soil can be used for the following conditions:

- Soil with macropores with relatively similar water entry values that are connected; and
- Fast water movement filling up cracks.

For soil with macropores with relatively similar water entry values that are connected but the water movement is relatively slow (e.g., cracked soil located far below the ground surface), the continuum approach is still appropriate.

2. The existing method that use continuum approach to quantify change in water content and matric suction of cracked soil can be used for the following conditions:

- Soil with macropores with similar water entry values that are not connected; or
- Soil with macropores with relatively similar water entry values that are connected, but with a slow water movement.

3. The use of linear cracks to idealize actual cracks gives good results for modelling changes in water content in cracked soil. This occurs because most cracks are linear. The use of linear cracks is compatible with previous studies characterizing crack networks in soil.

4. In this study, the existing method for the numerical generation of a crack network was improved by incorporating connectivity among cracks. Computer code was developed to implement the proposed method of crack network generation.

5. The difference between the average water content obtained from the analyses of the cracked soil model incorporating crack networks obtained from laboratory specimens and the cracked soil model incorporating numerically-generated crack networks became larger as the duration of the flow rate increased. For large-scale lateral flow test 1, the maximum variation in average water content was 1% and the maximum difference in average matric suction was 7%. For large-scale lateral flow test 2, the maximum variation in average water content was 2% and the maximum difference in average matric suction was 30%.

6. When there was lateral flow through cracked soil, water filled directly into the bottom of the cracks and then seeped into the soil matrix. Therefore, the use of head boundary conditions can model changes in the water content and matric suction of in the matrix of cracked soil due to lateral flow through the crack network of cracked soil better than the use of a continuum.

7.1.5 Implications of the Proposed Method in the Analysis of Lateral Water Flow through Cracked Soil

The results obtained from this study can be applied to the analysis of lateral water flow through cracked soil as follows:

1. The lateral flow rate through cracked soil can be computed from the lateral flow rate through the crack network. The lateral flow rate through the crack network is calculated by incorporating head losses due to changes in crack aperture. The flow rate along the soil mass is then calculated for one REV.
2. To quantify changes in the water content and matric suction of cracked soil during lateral flow, the cracks can be modelled as head boundary conditions.
3. The effect of variation in the water content and matric suction of cracked soil can be quantified using an averaging technique. This study indicates that the maximum difference in the average water content and matric suction due to variation in the crack network is 2% and 30%, respectively. However, further study is needed to determine the maximum difference in the average water content and matric suction of cracked soil.

7.2 Recommendations

Further study is needed relating to lateral flow rate and changes in the water content and matric suction of cracked soil in the following aspects:

1. The instrumentation setup of the large-scale lateral flow test apparatus can be improved. Improvements can be made by incorporating an instrument to measure changes in soil thickness during lateral flow, incorporating an instrument to measure changes in crack aperture during lateral flow, incorporating an instruments to measure matric suction in the soil specimens, or designing an

automatic and integrated measurement system of the inflow, outflow, and change in water content and matric suction of cracked soil specimens.

2. The model to predict lateral flow rates through cracked soil can be improved by incorporating changes in aperture due to wetting of the soil matrix.
3. Further research on the limiting value of the hydraulic gradient between slow and fast water movement is needed.

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A. APPENDIX A

DETAIL OF LABORATORY TEST RESULTS

A.1 Characterization and Properties of Soil

A.1.1 Shrinkage Test Results

Soil : L2 grade Kaolin

Shrinkage limit : 32%

Figure A.1 Result of shrinkage test

A.1.2 Saturated Permeability Results of Slurried Soil

Soil : L2 grade Kaolin

Table A.1 Results of saturated permeability test of initially slurried soil

Test	B Parameter	Back Pressure Difference (kPa)	Saturated Permeability, k_{sI} (m/s)
1	0.92	10	6.8×10^{-12}
2	0.92	20	7.3×10^{-12}
3	0.96	10	8.0×10^{-12}
4	0.96	30	8.0×10^{-12}
5	0.96	20	7.7×10^{-12}

A.1.3 Saturated Permeability Results of Compacted Soil

Soil : L2 grade Kaolin

Table A.2 Results of saturated permeability test of compacted soil

Test	B Parameter	Back Pressure Difference (kPa)	Saturated Permeability, k_{s2} (m/s)
1	0.91	40	1.9×10^{-7}
2	0.95	50	2.5×10^{-7}
3	0.95	100	2.5×10^{-7}
4	0.95	150	2.4×10^{-7}

A.2 Results of Large-Scale Desiccation Tests

A.2.1 Results of Large-Scale Desiccation Tests 1

Table A.3 Gravimetric water content at the end of large-scale desiccation test 1

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.00	0.00	29.8
0.05	0.00	29.5
0.10	0.00	30.6
0.15	0.00	30.8
0.20	0.00	31.7
0.25	0.00	32.3
0.30	0.00	32.5
0.35	0.00	32.2
0.40	0.00	32.3
0.45	0.00	30.7
0.50	0.00	30.7
0.55	0.00	32.5
0.60	0.00	34.2
0.65	0.00	33.0
0.70	0.00	34.4
0.75	0.00	32.3
0.00	0.05	29.6
0.05	0.05	32.7
0.10	0.05	32.9
0.15	0.05	33.0
0.20	0.05	33.0
0.25	0.05	32.6
0.30	0.05	32.9
0.35	0.05	32.3
0.40	0.05	32.5
0.45	0.05	33.3
0.50	0.05	32.0
0.55	0.05	33.4
0.60	0.05	37.8
0.65	0.05	36.5
0.70	0.05	36.3
0.75	0.05	34.3

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.00	0.10	31.5
0.10	0.10	32.3
0.20	0.10	32.8
0.30	0.10	33.8
0.40	0.10	32.2
0.50	0.10	32.9
0.60	0.10	36.9
0.70	0.10	35.8
0.00	0.20	31.1
0.10	0.20	34.0
0.20	0.20	32.3
0.30	0.20	32.8
0.40	0.20	32.8
0.50	0.20	35.3
0.60	0.20	36.7
0.70	0.20	36.9
0.00	0.30	33.5
0.10	0.30	35.6
0.20	0.30	33.2
0.30	0.30	32.9
0.40	0.30	35.6
0.50	0.30	35.5
0.60	0.30	35.2
0.70	0.30	35.2
0.00	0.40	33.7
0.10	0.40	35.5
0.20	0.40	34.9
0.30	0.40	36.2
0.40	0.40	34.4
0.50	0.40	32.8
0.60	0.40	34.5
0.70	0.40	46.6
0.00	0.50	35.1
0.10	0.50	34.8
0.20	0.50	35.6
0.30	0.50	33.8
0.40	0.50	35.7
0.50	0.50	35.7
0.60	0.50	34.8
0.70	0.50	35.6

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.00	0.60	35.1
0.10	0.60	36.0
0.20	0.60	34.5
0.30	0.60	34.6
0.40	0.60	33.2
0.50	0.60	32.7
0.60	0.60	34.7
0.70	0.60	35.3
0.00	0.70	35.3
0.10	0.70	35.9
0.20	0.70	36.8
0.30	0.70	34.4
0.40	0.70	34.2
0.50	0.70	34.1
0.60	0.70	33.8
0.70	0.70	33.7
0.00	0.75	32.7
0.10	0.75	35.7
0.20	0.75	34.9
0.30	0.75	34.0
0.40	0.75	33.5
0.50	0.75	33.2
0.60	0.75	33.0
0.70	0.75	32.9

A.2.2 Results of Large-Scale Desiccation Tests 2

Table A.4 Gravimetric water content at the end of large-scale desiccation test 2

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.00	0.00	14.6
0.10	0.00	60.4
0.20	0.00	48.4
0.30	0.00	30.4
0.40	0.00	50.0
0.50	0.00	29.9
0.60	0.00	21.9
0.76	0.00	37.6
0.00	0.10	40.3
0.10	0.10	18.5
0.20	0.10	37.9
0.30	0.10	28.9
0.40	0.10	38.8
0.50	0.10	52.9
0.60	0.10	29.9
0.76	0.10	58.4
0.00	0.20	35.3
0.10	0.20	53.0
0.20	0.20	37.9
0.30	0.20	21.1
0.40	0.20	42.5
0.50	0.20	38.8
0.60	0.20	56.1
0.76	0.20	65.4
0.00	0.30	31.2
0.10	0.30	27.3
0.20	0.30	28.7
0.30	0.30	50.9
0.40	0.30	49.3
0.50	0.30	48.2
0.60	0.30	20.8
0.76	0.30	41.0

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.00	0.40	49.0
0.10	0.40	37.8
0.20	0.40	57.7
0.30	0.40	31.5
0.40	0.40	72.6
0.50	0.40	54.9
0.60	0.40	37.5
0.76	0.40	48.6
0.00	0.50	69.3
0.10	0.50	51.2
0.20	0.50	73.2
0.30	0.50	82.8
0.40	0.50	63.0
0.50	0.50	59.3
0.60	0.50	52.2
0.76	0.50	64.6
0.00	0.60	59.0
0.10	0.60	84.4
0.20	0.60	71.1
0.30	0.60	71.7
0.40	0.60	61.5
0.50	0.60	94.7
0.60	0.60	69.7
0.76	0.60	70.7
0.00	0.76	57.7
0.10	0.76	83.5
0.20	0.76	83.4
0.30	0.76	65.2
0.40	0.76	35.8
0.50	0.76	28.5
0.60	0.76	64.7
0.76	0.76	15.1

A.3 Results of Large-Scale Lateral Flow Tests

A.3.1 Results of Large-Scale Lateral Flow Test 1

Table A.5 Water content at the end of large-scale lateral flow test 1: (a) Gravimetric water content; (b) Volumetric water content

(a)

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.05	0.94	38.5
0.05	0.74	35.1
0.05	0.54	38.1
0.05	0.34	34.3
0.05	0.14	31.3
0.05	0.04	40.1
0.25	0.86	37.0
0.25	0.79	41.2
0.25	0.61	31.6
0.25	0.49	48.5
0.25	0.36	48.5
0.25	0.24	44.1
0.25	0.11	48.5
0.38	0.74	49.5
0.38	0.49	47.8
0.38	0.24	40.0
0.50	0.86	36.2
0.50	0.74	43.7
0.50	0.61	42.2
0.50	0.49	30.3
0.50	0.24	41.0
0.50	0.11	37.4
0.60	0.49	47.0
0.63	0.74	43.5
0.63	0.24	38.4
0.75	0.86	45.9
0.75	0.74	42.6
0.75	0.61	51.0
0.75	0.49	41.0
0.75	0.36	44.1

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.75	0.24	42.3
0.75	0.11	35.1
0.88	0.74	36.5
0.88	0.49	52.1
0.88	0.24	32.8

(b)

X (m)	Y (m)	Volumetric Water Content, θ_w
0.25	0.79	0.42
0.25	0.49	0.50
0.25	0.24	0.45
0.50	0.74	0.46
0.50	0.49	0.43
0.50	0.24	0.49
0.60	0.49	0.53
0.75	0.74	0.51
0.75	0.49	0.43
0.75	0.24	0.52

A.3.2 Results of Large-Scale Lateral Flow Test 2

Table A.6 Water content at the end of large-scale lateral flow test 2: (a) Gravimetric water content; (b) Volumetric water content

(a)

X (m)	Y (m)	Gravimetric Water Content, w (%)
0.53	0.48	33.0
0.75	0.49	41.8
0.76	0.79	38.0
0.78	0.27	38.0
0.10	0.49	37.0
0.50	0.74	45.0
0.25	0.74	44.0
0.29	0.49	45.9
0.25	0.24	37.7
0.52	0.29	47.0

(b)

X (m)	Y (m)	Volumetric Water Content, θ_w
0.53	0.48	0.39
0.76	0.79	0.38
0.78	0.27	0.40
0.29	0.49	0.44
0.52	0.29	0.45

B. APPENDIX B

CALIBRATION CHART OF ICT INSTRUMENT USED IN LARGE-SCALE LATERAL FLOW TEST

Figure B.1 ICT calibration chart

C. APPENDIX C

COMPUTER CODE FOR NUMERICAL GENERATION OF CRACK NETWORK

C.1 Script of Computer Code for Numerical Generation of Crack Network

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*****
*
* A PROGRAM TO GENERATE RANDOM CRACK NETWORK
*
* THIS PROGRAM GENERATES A RANDOM CRACK NETWORK
* USING THE STATISTICAL PARAMETERS OF LENGTH AND ORIENTATION
* OF A CRACK NETWORK.
*
* CONNECTION AMONG CRACK ENDPOINTS IS INCORPORATED IN THIS PROGRAM
*
*****
*
* INPUT FILE:
*
* LINE 1: PRJCTNAME=NAME OF THE PROJECT (WITHOUT SPACINGS)
*
* LINE 2
*   COLUMN 1-3: N=NUMBER OF CRACKS (MAX: 150 CRACKS)
*
* LINE 3
*   COLUMN 1-5: MLENGTH(F5.3)=MEAN CRACKS LENGTH
*   COLUMN 6-8: BLANK
*   COLUMN 9-13: STDVLENGTH(F5.3)=STANDARD DEVIATION OF CRACKS LENGTH
*
* LINE 4
*   COLUMN 1-5 : MORIENT(F7.3)=MEAN CRACKS ORIENTATION
*   COLUMN 6-8 : BLANK
*   COLUMN 9-13: STDVORIENT(F7.3)=STANDARD DEVIATION OF CRACKS
ORIENTATION
*
* LINE 5
*   COLUMN 1-5: MXMID(F5.3)=MEAN OF CRACK MIDPOINT X COORDINATES
*   COLUMN 6-8: BLANK
*   COLUMN 9-13: STDVXMID (F5.3)=ERROR OF STANDARD DEVIATION OF CRACK
MIDPOINT X COORDINATES
*
* LINE 6
*   COLUMN 1-5: MYMID(F5.3)=MEAN OF CRACK MIDPOINT Y COORDINATES
*   COLUMN 6-8: BLANK
*   COLUMN 9-13: STDVYMID (F5.3)=ERROR OF STANDARD DEVIATION OF CRACK
MIDPOINT Y COORDINATES
*
```


Appendix C - Computer Code for Numerical Generation of Crack Network

```
* LINE 7
* COLUMN 1-10 : SEEDX0(I10)=SEED TO GENERATE MIDPOINT X COORDINATES
* COLUMN 11-13: BLANK
* COLUMN 14-24: SEEDY0(I10)=SEED TO GENERATE MIDPOINT Y COORDINATES
* COLUMN 25-27: BLANK
* COLUMN 28-38: SEEDORIENT(I10)=SEED TOGENERATE CRACK ORIENTATION
*
* LINE 8
* COLUMN 1-5 : X0A(1) (F5.3)=X ENDPOINT COORDINATE OF FIRST CRACK
NETWORK BOUNDARY
* COLUMN 6-8: BLANK
* COLUMN 9-13: Y0A(1) (F5.3)=Y ENDPOINT COORDINATE OF FIRST CRACK
NETWORK BOUNDARY
* COLUMN 14-6: BLANK
* COLUMN 17-21: X0B(1) (F5.3)=X ENDPOINT COORDINATE OF FIRST CRACK
NETWORK BOUNDARY
* COLUMN 22-24: BLANK
* COLUMN 25-29: Y0B(1) (F5.3)=Y ENDPOINT COORDINATE OF FIRST CRACK
NETWORK BOUNDARY
* COLUMN 30-32: BLANK
* COLUMN 33-37: ORIENT(1) (F5.2)=ORIENTATION ANGLE OF THE FIRST CRACK
NETWORK BOUNDARY
*
* LINE 9
* COLUMN 1-5 : X0A(2) (F5.3)=X ENDPOINT COORDINATE OF SECOND CRACK
NETWORK BOUNDARY
* COLUMN 6-8: BLANK
* COLUMN 9-13: Y0A(2) (F5.3)=Y ENDPOINT COORDINATE OF SECOND CRACK
NETWORK BOUNDARY
* COLUMN 14-6: BLANK
* COLUMN 17-21: X0B(2) (F5.3)=X ENDPOINT COORDINATE OF SECOND CRACK
NETWORK BOUNDARY
* COLUMN 22-24: BLANK
* COLUMN 25-29: Y0B(2) (F5.3)=Y ENDPOINT COORDINATE OF SECOND CRACK
NETWORK BOUNDARY
* COLUMN 30-32: BLANK
* COLUMN 33-37: ORIENT(2) (F5.2)=ORIENTATION ANGLE OF THE SECOND CRACK
NETWORK BOUNDARY
*
* LINE 10
* COLUMN 1-5 : X0A(3) (F5.3)=X ENDPOINT COORDINATE OF THIRD CRACK
NETWORK BOUNDARY
* COLUMN 6-8: BLANK
* COLUMN 9-13: Y0A(3) (F5.3)=Y ENDPOINT COORDINATE OF THIRD CRACK
NETWORK BOUNDARY
* COLUMN 14-6: BLANK
* COLUMN 17-21: X0B(3) (F5.3)=X ENDPOINT COORDINATE OF THIRD CRACK
NETWORK BOUNDARY
* COLUMN 22-24: BLANK
* COLUMN 25-29: Y0B(3) (F5.3)= ENDPOINT COORDINATE OF THIRD CRACK
NETWORK BOUNDARY
* COLUMN 30-32: BLANK
* COLUMN 33-37: ORIENT(3) (F5.2)=ORIENTATION ANGLE OF THE THIRD CRACK
NETWORK BOUNDARY
*
* LINE 11
```

```
* COLUMN 1-5 : X0A(4) (F5.3)=X ENDPOINT COORDINATE OF FOURTH CRACK
NETWORK BOUNDARY
* COLUMN 6-8: BLANK
* COLUMN 9-13: Y0A(4) (F5.3)=Y ENDPOINT COORDINATE OF FOURTH CRACK
NETWORK BOUNDARY
* COLUMN 14-6: BLANK
* COLUMN 17-21: X0B(4) (F5.3)=X ENDPOINT COORDINATE OF FOURTH CRACK
NETWORK BOUNDARY
* COLUMN 22-24: BLANK
* COLUMN 25-29: Y0B(4) (F5.3)=Y ENDPOINT COORDINATE OF FOURTH CRACK
NETWORK BOUNDARY
* COLUMN 30-32: BLANK
* COLUMN 33-37: ORIENT(4) (F5.2)=ORIENTATION ANGLE OF THE FOURTH CRACK
NETWORK BOUNDARY
*
* LINE 12
* COLUMN 1-10: NITER(I10)=NUMBER OF ITERATION
*
* LINE 13
* COLUMN 1-3:ERRNUM(I3)=ERROR NUMBER OF CRACKS
*
* LINE 14
* COLUMN 1-5: ERRMLENGTH(F5.3)=ERROR OF MEAN OF CRACK LENGTH
* COLUMN 6-8:BLANK
* COLUMN 9-13:ERRSTDVLENGTH(F5.3)=ERROR OF STANDARD DEVIATION OF CRACK
LENGTH
* COLUMN 14-16:BLANK
* COLUMN 17-21:ERRMORIENT(F5.3)=ERROR OF MEAN OF CRACK ORIENTATION
* COLUMN 22-24:BLANK
* COLUMN 25-29:ERRSTDVORIENT(F5.3)=ERROR OF STANDARD DEVIATION OF CRACK
ORIENTATION
*
* LINE 15
* COLUMN 1-5:ERRMXMID (F5.3)=ERROR OF MEAN OF CRACK MIDPOINT X
COORDINATES
* COLUMN 6-8:BLANK
* COLUMN 9-13:ERRSTDVXMID (F5.3)=ERROR OF STANDARD DEVIATION OF CRACK
MIDPOINT X COORDINATES
* COLUMN 14-16:BLANK
* COLUMN 17-21:ERRMYMID (F5.3)= ERROR OF MEAN OF CRACK MIDPOINT Y
COORDINATES
* COLUMN 22-24:BLANK
* COLUMN 25-29:ERRMYMID (F5.3)= ERROR OF STANDARD DEVIATION OF CRACK
MIDPOINT Y COORDINATES
*
* LINE 16
* COLUMN 1-5: R2X(F5.3)=MINIMUM RSQUARE OF FREQUENCY DISTRIBUTION PLOT
OF CRACK MIDPOINT X COORDINATES
* COLUMN 6-8:BLANK
* COLUMN 9-13:R2Y(F5.3)=MINIMUM RSQUARE OF FREQUENCY DISTRIBUTION PLOT
OF CRACK MIDPOINT Y COORDINATES
* COLUMN 14-16:BLANK
* COLUMN 17-21:R2LENGTH(F5.3)=MINIMUM RSQUARE OF FREQUENCY DISTRIBUTION
PLOT OF CRACK LENGTH
* COLUMN 22-24:BLANK
* COLUMN 25-29:R2ORIENT(F5.3)=MINIMUM RSQUARE OF FREQUENCY DISTRIBUTION
PLOT OF CRACK ORIENTATION
```

Appendix C - Computer Code for Numerical Generation of Crack Network

```
*
*****
*
* DEFINITION OF VARIABLES
*
*   VARIABLE NAMES FOR INPUT DATA
*   INTEGER N
*   REAL MLENGTH,STDVLENGTH
*   REAL MORIENT,STDVORIENT
*   INTEGER SEEDX0,SEEDY0,SEEDORIENT
*   REAL X0A(204),Y0A(204),X0B(204),Y0B(204),ORIENT0(204)
*   INTEGER NITER
*   INTEGER ERRNUM
*   REAL ERRMLENGTH,ERRSTDVLENGTH,ERRMORIENT,ERRSTDVORIENT
*   REAL R2X,R2Y,R2LENGTH,R2ORIENT
*
*   VARIABLE NAMES FOR RANDOM X0,Y0 COORDINATE GENERATION
*   INTEGER I,SEEDX01,SEEDY01,SEEDORIENT01
*   REAL RANDX0,RANDY0,X0(204),Y0(204)
*
*   VARIABLE NAMES FOR CRACK ORIENTATION (NORMAL DIST) GENERATION
*   REAL RANDORIENT0,Z
*
*   VARIABLE NAMES FOR DEVELOPMENT OF THE CRACKS
*   REAL LGTH,LGTH0,X0I,Y0I,X4,Y4,X5,Y5
*   REAL ORIENT0I,ORIENT0K,XA,YA
*   INTEGER J,K
*   INTEGER CN0
*
*   VARIABLE NAMES FOR ITERATION PROCESS TO OBTAIN FINAL CRACK NETWORK
*   INTEGER NMAXP,P,PMIN,PMAX,Q
*   INTEGER NITER1,CN
*   INTEGER VAL
*   REAL XAI,YAI
*   INTEGER NITSCT
*   REAL XITSCT(204),YITSCT(204),DITSCT(204),PIVOTD,PIVOTX,PIVOTY
*   REAL X1A(404),Y1A(404),X1B(404),Y1B(404)
*   REAL X1(404),Y1(404)
*   REAL LGTH1(404),ORIENT1(404)
*
*   VARIABLE NAMES FOR CALCULATION OF MEAN LENGTH AND MEAN ORIENTATION
*   REAL SUMLGTH1,SUMORIENT1,CN1,MLENGTH1,MORIENT1
*   VARIABLE NAMES FOR CALCULATION OF STD DEV LENGTH
*   AND STD DEV ORIENTATION
*   REAL SUMLGTH1DEV2,LGTH1DEV2,STDVLENGTH1
*   REAL SUMORIENT1DEV2,ORIENT1DEV2,STDVORIENT1
*   VARIABLES NAMES FOR CALCULATION ERROR OF CRACK NUMBER,
*   ERROR OF MEAN CRACK LENGTH, ERROR OF STD DEV CRACK LENGTH,
*   ERROR OF MEAN CRACK ORIENTATION, ERROR OF STD DEV CRACK ORIENTATION
*   INTEGER ERRNUM1
*   REAL ERRMLENGTH1,ERRSTDVLENGTH1
*   REAL ERRMORIENT1,ERRSTDVORIENT1
*
*   VARIABLES NAMES FOR CALCULATION OF RSQUARE
*   SORT DATA ASCENDING (STEP 1)
*   REAL PIVOT,ABSIS(404)
```

Appendix C - Computer Code for Numerical Generation of Crack Network

```
*      VARIABLE NAMES FOR CALCULATING CUMM DIST PROB (CDP) (STEP 2)
      REAL CDP(404)
*      VARIABLE NAMES FOR CALCULATING INVERSE CDP (STEP 3)
      REAL ZJI,ORDINATE(404)
*      VARIABLE NAMES FOR CALCULATING A AND B OF LINEAR REGRESSION (STEP
4)
      REAL SIGXY,SIGY,SIGXSQ,SUMABSI, SUMORDINATE,AVGX,AVGY,A1,A2,A,B
*      VARIABLE NAMES FOR CALCULATING R2 (STEP 5)
      REAL SST1,SSE1,YCAP(404)
      REAL R2X1,R2Y1,R2LENGTH1,R2ORIENT1

*      VARIABLES OF CALCULATED ERRORS
      REAL C1,D1,E1,F1,G1,H1,I1,J1,K1,GLOBALERR0,GLOBALERR1

*      VARIABLE FOR CONVERGENCE CHECK
      INTEGER CONV
      REAL GLOBALERR1PVT
      INTEGER CN0PVT
      REAL X0PVT(404),Y0PVT(404),ORIENT0PVT(404)
      REAL X0APVT(404),Y0APVT(404),X0BPVT(404),Y0BPVT(404)
      REAL X1APVT(404),Y1APVT(404),X1BPVT(404),Y1BPVT(404)
      REAL X1PVT(404),Y1PVT(404),LGTH1PVT(404),ORIENT1PVT(404)
      INTEGER CNPVT,ERRNUM1PVT
      REAL ERRMLENGTH1PVT,ERRSTDVLENGTH1PVT
      REAL ERRMORIENT1PVT,ERRSTDVORIENT1PVT
      INTEGER NITER1PVT
      REAL R2X1PVT,R2Y1PVT,R2LENGTH1PVT,R2ORIENT1PVT

      CHARACTER*70 INPUT,OUTPUT
      CHARACTER*70 PRJCTNAME

*      LOCATION OF THE INPUT AND OUTPUT FILES IN THE COMPUTER DIRECTORY
      INPUT ='E:\DEVELOP PROGRAM\RANDCRACK\INPUT2-9.txt'
      OUTPUT='E:\DEVELOP PROGRAM\RANDCRACK\OUTPUT2-9.txt'

      OPEN(UNIT=1,FILE=INPUT,status='OLD')
      OPEN(UNIT=2,FILE=OUTPUT,status='UNKNOWN')

*****
*      READ INPUT DATA

      READ(1,*)PRJCTNAME
      READ(1,7)N
7  FORMAT(I3)

      READ(1,15)MLENGTH,STDVLENGTH
15  FORMAT(F5.3,3X,F5.3)

      READ(1,20)MORIENT,STDVORIENT
20  FORMAT(F7.3,3X,F7.3)

      READ(1,25)SEEDX0,SEEDY0,SEEDORIENT
25  FORMAT(I10,3X,I10,3X,I10)

*      UPSTREAM(TOP) BOUNDARY
      READ(1,35)X0A(1),Y0A(1),X0B(1),Y0B(1),ORIENT0(1)
35  FORMAT(F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.2)
```

Appendix C - Computer Code for Numerical Generation of Crack Network

```
*      UPSTREAM(BOTTOM)BOUNDARY
      READ(1,40)X0A(2),Y0A(2),X0B(2),Y0B(2),ORIENT0(2)
40  FORMAT(F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.2)
*      LEFT BOUNDARY
      READ(1,45)X0A(3),Y0A(3),X0B(3),Y0B(3),ORIENT0(3)
45  FORMAT(F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.2)
*      RIGHT BOUNDARY
      READ(1,50)X0A(4),Y0A(4),X0B(4),Y0B(4),ORIENT0(4)
50  FORMAT(F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.2)

*      NUMBER OF ITERATION
      READ (1,55)NITER
55  FORMAT(I10)

*      ERROR CRITERIA
      READ(1,60)ERRNUM,ERRMLENGTH,ERRSTDVLENGTH,ERRMORIENT,ERRSTDVORIENT
60  FORMAT(I3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X)

*      R2 CRITERIA
      READ(1,65)R2X,R2Y,R2LENGTH,R2ORIENT
65  FORMAT(F5.3,3X,F5.3,3X,F5.3,3X,F5.3)

*****

      NITER1=0
      GLOBALERR0=1000

      IF((N-ERRNUM).LE.0)THEN
        WRITE(2,*)'N SHOULD BE GREATER THAN ERRNUM'
        GOTO 1496
      ENDIF

      PMIN=1
      DO 70 I=2,N
        NMAXP=3*I-3
        IF((NMAXP-(N-ERRNUM)).GT.-3)THEN
          PMIN=I
          GOTO 71
        ENDIF
70  CONTINUE

      71 CONTINUE
      PMIN=PMIN+4
      PMAX=(N+4)+ERRNUM

*      Q=ITERATION
      DO 900 Q=1,NITER

      NITER1=NITER1+1
      WRITE(6,73)NITER1,NITER
73  FORMAT(' ITERATION:',I4,' OF ',I4)

      DO 75 I=1,NITER1
      CALL RANDOM(SEEDX0,RANDX0)
      CALL RANDOM(SEEDY0,RANDY0)
      CALL RANDOM(SEEDORIENT,RANDORIENT0)
      SEEDX01=SEEDX0
```

```

        SEEDY01=SEEDY0
        SEEDORIENT01=SEEDORIENT
75  CONTINUE

*      P=TRIAL INITIAL NUMBER OF CRACKS(INCLUDES 4 BOUNDARIES)
        DO 898 P=PMIN,PMAX

*      CN0=CRACK CENTER FOR FIRST STAGE CRACK NETWORK
        CN0=P

* GENERATION OF A RANDOM CRACK NETWORK

* RANDOM X0,Y0 COORDINATE GENERATION
        DO 101 I=5,P
            CALL RANDOM(SEEDX01,RANDX0)
            X0(I)=RANDX0
101  CONTINUE

        DO 102 I=5,P
            CALL RANDOM(SEEDY01,RANDY0)
            Y0(I)=RANDY0
102  CONTINUE

* CRACK ORIENTATION (NORMAL DIST) GENERATION

*      UNIFORM RANDOM GENERATOR FOR CRACK ORIENTATION
        DO 125 I=5,P

122  CONTINUE

        CALL RANDOM(SEEDORIENT01,RANDORIENT0)

*      STANDAR NORMAL INVERSE FOR CRACK ORIENTATION
        CALL NORMSINV(RANDORIENT0,Z)

*      CALCULATION OF CRACK ORIENTATION FROM NORMAL STANDARD IVERSE
        VALUE Z
*      0DEGREE<=ORIENTATION ANGLE<=180DEGREE
        ORIENT0(I)=Z*STDVORIENT+MORIENT
        IF(ORIENT0(I).LT.0)THEN
            GOTO 122
        ELSEIF(ORIENT0(I).GT.180)THEN
            GOTO 122
        ENDIF

125  CONTINUE

* DEVELOPMENT OF THE CRACKS

*      CRACK END A

*      I=THE CRACK THAT IS BEING ANALYZED
        DO 238 I=5,P

        LGTH0=100
    
```

Appendix C - Computer Code for Numerical Generation of Crack Network

```
*      K=THE CRACKS THAT IS INTERSECTED BY THE CRACK THAT IS BEING
ANALYZED
      DO 135 K=1,I-1
        X0I=X0(I)
        Y0I=Y0(I)
        X4=X0A(K)
        Y4=Y0A(K)
        X5=X0B(K)
        Y5=Y0B(K)
        ORIENT0I=ORIENT0(I)
        ORIENT0K=ORIENT0(K)

        CALL CRG(X0I,Y0I,ORIENT0I,X4,Y4,X5,Y5,ORIENT0K,XA,YA,LGTH)

        IF(LGTH.LT.0.0)THEN
          IF((LGTH0-ABS(LGTH)).GT.0.0)THEN
            X0A(I)=XA
            Y0A(I)=YA
            LGTH0=ABS(LGTH)
          ENDIF
        ENDIF
135  CONTINUE

*      CRACK END B

      LGTH0=100
*      K=THE CRACKS THAT IS INTERSECT BY THE CRACK THAT IS BEING ANALYZED
      DO 235 K=1,I-1
        X0I=X0(I)
        Y0I=Y0(I)
        X4=X0A(K)
        Y4=Y0A(K)
        X5=X0B(K)
        Y5=Y0B(K)
        ORIENT0I=ORIENT0(I)
        ORIENT0K=ORIENT0(K)

        CALL CRG(X0I,Y0I,ORIENT0I,X4,Y4,X5,Y5,ORIENT0K,XA,YA,LGTH)

        IF(LGTH.GT.0.0)THEN
          IF((LGTH0-ABS(LGTH)).GT.0.0)THEN
            X0B(I)=XA
            Y0B(I)=YA
            LGTH0=ABS(LGTH)
          ENDIF
        ENDIF
235  CONTINUE

238  CONTINUE

*****
*  ITERATION TO CALCULATE FINAL CRACK NETWORK

*  INVENTARIZING THE CRACKS ENDPOINTS
```

```
*      CN=CRACK COUNTER FOR FINAL CRACK NETWORK
      CN=4

*      I=THE FIRST STAGE CRACK NUMBER THAT IS BEING ANALYZED
      DO 330 I=5,P

      NITSCT=0

      DO 250 J=I+1,P

*      CRACK END A
      XAI=X0A(I)
      YAI=Y0A(I)
      ORIENT0I=ORIENT0(I)
      X4=X0A(J)
      Y4=Y0A(J)

      CALL ENDPOINT(XAI,YAI,ORIENT0I,X4,Y4,VAL,DIST)

      IF(VAL.EQ.1)THEN
        NITSCT=NITSCT+1
        XITSCT(NITSCT)=X4
        YITSCT(NITSCT)=Y4
        DITSCT(NITSCT)=DIST
      ENDIF

*      CRACK END B
      X4=X0B(J)
      Y4=Y0B(J)

      CALL ENDPOINT(XAI,YAI,ORIENT0I,X4,Y4,VAL,DIST)

      IF(VAL.EQ.1)THEN
        NITSCT=NITSCT+1
        XITSCT(NITSCT)=X4
        YITSCT(NITSCT)=Y4
        DITSCT(NITSCT)=DIST
      ENDIF

250  CONTINUE

*      SORT ASCENDING

      DO 260 J=1,NITSCT-1

      DO 259 K=J+1,NITSCT
      PIVOTD=0
      PIVOTX=0
      PIVOTY=0
      IF(DITSCT(K).LT.DITSCT(J))THEN
        PIVOTD=DITSCT(J)
        PIVOTX=XITSCT(J)
        PIVOTY=YITSCT(J)

        DITSCT(J)=DITSCT(K)
        XITSCT(J)=XITSCT(K)
        YITSCT(J)=YITSCT(K)
```



```

        DITSCT(K)=PIVOTD
        XITSCT(K)=PIVOTX
        YITSCT(K)=PIVOTY
    ENDIF
259 CONTINUE

260 CONTINUE

*   RECORDING THE CRACK ENDPOINTS
    CN=CN+1
    X1A(CN)=X0A(I)
    Y1A(CN)=Y0A(I)

    DO 270 K=1,NITSCT
        X1B(CN)=XITSCT(K)
        Y1B(CN)=YITSCT(K)
        CN=CN+1
        X1A(CN)=XITSCT(K)
        Y1A(CN)=YITSCT(K)
    270 CONTINUE

*   CHECK UNTIL ENDPOINT OF THE CRACK I
    X1B(CN)=X0B(I)
    Y1B(CN)=Y0B(I)

330 CONTINUE

    WRITE(6,331)CN-4
331 FORMAT('NUMBER OF CRACKS FORMED: ',I3)

*   IF NUMBER OF THE FINAL CRACKS ARE GREATER THAN CRACS+ERRNUM, STOP
    ITERATION
    IF((CN-4).GT.(N+ERRNUM))THEN
        GOTO 899
    ENDIF

*****

*   CALCULATION OF COORDINATES OF CRACK MIDPOINTS
    DO 335 I=5,CN
        X1(I)=(X1A(I)+X1B(I))/2
        Y1(I)=(Y1A(I)+Y1B(I))/2
    335 CONTINUE

*   CALCULATION OF THE CRACK LENGTHS AND ORIENTATIONS
    DO 400 I=5,CN
        LGTH1(I)=SQRT((X1B(I)-X1A(I))**2+(Y1B(I)-Y1A(I))**2)

*   CHECK FOR INTERSECTION WITH HORIZONTAL BOUNDARIES
    IF(ABS(Y1B(I)-Y1A(I)).LE.0.0004)THEN
        ORIENT1(I)=0
        GOTO 399

*   CHECK FOR INTERSECTIN WITH VERTICAL BOUNDARIES
    ELSEIF(ABS(X1B(I)-X1A(I)).LE.0.0004)THEN
        ORIENT1(I)=90
        GOTO 399

```

```

ELSE
  ORIENT1(I)=ATAN((Y1B(I)-Y1A(I))/(X1B(I)-X1A(I)))*(180/3.141593)
  IF(ORIENT1(I).LT.0.00)THEN
    ORIENT1(I)=180+ORIENT1(I)
  ENDIF
ENDIF

399 CONTINUE

400 CONTINUE
*****
* CALCULATION OF THE STATISTICAL PARAMETERS
* OF THE FINAL STAGE CRACK NETWORK

* CALCULATION OF R2 X1 COORDINATES
* PROCEDURES:
* -STEP1: SORTING ASCENDING OF ABSIS(I) DATA
* -STEP2: CALCULATING CUMM DIST PROB (CDP)
* -STEP3: CALCULATE INVERSE CDP
* -STEP4: CALCULATE A AND B OF LINEAR REGRESSION
* -STEP5: CALCULATE R2X1

* I=1--> CALCULATION OF R2 X (UNIFORM DIST)
* I=2--> CALCULATION OF R2 Y (UNIFORM DIST)
* I=3--> CALCULATION OF R2 LENGTH (LOGNORMAL DIST)
* I=4--> CALCULATION OF R2 ORIENTATION (NORMAL DIST)

DO 455 I=1,4

* -STEP1: SORTING ASCENDING OF ABSIS(I) DATA
  IF(I.EQ.1) THEN
    DO 410 J=5,CN
      ABSIS(J)=X1(J)

410    CONTINUE

    ELSEIF(I.EQ.2) THEN
      DO 411 J=5,CN
        ABSIS(J)=Y1(J)
411    CONTINUE

    ELSEIF(I.EQ.3) THEN
      DO 412 J=5,CN
        ABSIS(J)=LGTH1(J)
412    CONTINUE

    ELSEIF(I.EQ.4) THEN
      DO 413 J=5,CN
        ABSIS(J)=ORIENT1(J)
413    CONTINUE

  ENDIF

DO 419 J=5,CN-1
*   PIVOT=0
DO 418 K=J+1,CN
  IF(ABSIS(K).LT.ABSIS(J))THEN

```

```
        PIVOT=ABSIS(J)
        ABSIS(J)=ABSIS(K)
        ABSIS(K)=PIVOT
    ENDIF
418 CONTINUE

419 CONTINUE

* -STEP2: CALCULATING CUMM DIST PROB (CDP)
    CN1=REAL(CN)
    DO 420 J=5,CN
        CDP(J)=((J-4)-0.5)/(CN1-4)
    420 CONTINUE

* -STEP3: CALCULATE INVERSE CDP
    DO 430 J=5,CN

        IF(I.EQ.1)THEN
            ORDINATE(J)=CDP(J)

        ELSEIF(I.EQ.2)THEN
            ORDINATE(J)=CDP(J)

        ELSEIF(I.EQ.3)THEN
*           STANDAR NORMAL INVERSE
            CALL NORMSINV(CDP(J),ZJI)
            ORDINATE(J)=EXP(ZJI)

        ELSEIF(I.EQ.4)THEN
*           STANDAR NORMAL INVERSE
            CALL NORMSINV(CDP(J),ZJI)
            ORDINATE(J)=ZJI
        ENDIF

    430 CONTINUE

* -STEP4: CALCULATE A AND B OF LINEAR REGRESSION
*   LINEAR EQUATION: ORDINATE(I)=A*ABSIS(I)+B
    SIGXY=0
    SIGX=0
    SIGY=0
    SIGXSQ=0
    SUMABSIS=0
    SUMORDINATE=0

    DO 440 J=5,CN
        SIGXY=SIGXY+ABSIS(J)*ORDINATE(J)
        SIGX=SIGX+ABSIS(J)
        SIGY=SIGY+ORDINATE(J)
        SIGXSQ=SIGXSQ+ABSIS(J)**2
        SUMABSIS=SUMABSIS+ABSIS(J)
        SUMORDINATE=SUMORDINATE+ORDINATE(J)
    440 CONTINUE

    AVGX=SUMABSIS/(CN-4)
    AVGY=SUMORDINATE/(CN-4)
```

```

A1=(SIGXY-(SIGX*SIGY/(CN1-4)))
A2=(SIGXSQ-(SIGX**2/(CN1-4)))
IF(A2.LE.0.0000)THEN
  R21=1
  GOTO 453
ENDIF
A=A1/A2
B=AVGY-A*AVGX

* -STEP5: CALCULATE R21
SST1=0
DO 451 J=5,CN
  SST1=SST1+(ORDINATE(J)-AVGY)**2
451 CONTINUE

SSE1=0
DO 452 J=5,CN
  YCAP(J)=A*ABSIS(J)+B
  SSE1=SSE1+(ORDINATE(J)-YCAP(J))**2
452 CONTINUE

R21=1-(SSE1/SST1)

453 CONTINUE

IF(I.EQ.1)THEN
  R2X1=R21
ELSEIF(I.EQ.2)THEN
  R2Y1=R21
ELSEIF(I.EQ.3)THEN
  R2LENGTH1=R21
ELSEIF(I.EQ.4)THEN
  R2ORIENT1=R21
ENDIF

455 CONTINUE

* CALCULATION OF MEAN OF CRACKS LENGTHS AND MEAN CRACK ORIENTATION
SUMLGTH1=0
SUMORIENT1=0
DO 601 I=5,CN
  SUMLGTH1=SUMLGTH1+LGTH1(I)
  SUMORIENT1=SUMORIENT1+ORIENT1(I)
601 CONTINUE

MLENGTH1=SUMLGTH1/(CN1-4)
MORIENT1=SUMORIENT1/(CN1-4)

* CALCULATION STD DEVIATION OF CRACKS LENGTHS AND CRACK ORIENTATION
SUMLGTH1DEV2=0
SUMORIENT1DEV2=0
DO 602 I=5,CN
  LGTH1DEV2=(LGTH1(I)-MLENGTH1)**2
  SUMLGTH1DEV2=SUMLGTH1DEV2+LGTH1DEV2

  ORIENT1DEV2=(ORIENT1(I)-MORIENT1)**2
  SUMORIENT1DEV2=SUMORIENT1DEV2+ORIENT1DEV2

```

602 CONTINUE

STDVLENGTH1=SQRT(SUMLGTH1DEV2/(CN1-4))
STDVORIENT1=SQRT(SUMORIENT1DV2/(CN1-4))

* CALCULATION OF THE ERRORS

ERRNUM1=ABS((CN-4)-N)

ERRMLENGTH1=ABS((MLENGTH1-MLENGTH)/MLENGTH)
ERRSTDVLENGTH1=ABS((STDVLENGTH1-STDVLENGTH)/STDVLENGTH)

ERRMORIENT1=ABS((MORIENT1-MORIENT)/MORIENT)
ERRSTDVORIENT1=ABS((STDVORIENT1-STDVORIENT)/STDVORIENT)

* ERR1=AMAX1(ERRMLENGTH1,ERRSTDVLENGTH1,ERRMORIENT1,ERRSTDVORIENT1)

* R2MIN1=AMIN1(R2X1,R2Y1,R2LENGTH1,R2ORIENT1)

C1=REAL(ERRNUM1)/REAL(N)
D1=ERRMLENGTH1
E1=ERRSTDVLENGTH1
F1=ERRMORIENT1
G1=ERRSTDVORIENT1
H1=1-R2X1
I1=1-R2Y1
J1=1-R2LENGTH1
K1=1-R2ORIENT1
GLOBALERR1=C1+D1+E1+F1+G1+H1+I1+J1+K1

* CHECK FOR CONVERGENCE

CONV=0
IF(ERRNUM1.LE.ERRNUM)THEN
 IF(ERRMLENGTH1.LE.ERRMLENGTH)THEN
 IF(ERRSTDVLENGTH1.LE.ERRSTDVLENGTH)THEN
 IF(ERRMORIENT1.LE.ERRMORIENT)THEN
 IF(ERRSTDVORIENT1.LE.ERRSTDVORIENT)THEN
 IF(R2X1.GE.R2X)THEN
 IF(R2Y1.GE.R2Y)THEN
 IF(R2LENGTH1.GE.R2LENGTH)THEN
 IF(R2ORIENT1.GE.R2ORIENT)THEN
 CONV=1
 GOTO 905
 ENDIF
 ENDIF
 ENDIF
 ENDIF
 ENDIF
 ENDIF
 ENDIF
 ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF
ENDIF

IF(GLOBALERR1.LT.GLOBALERR0)THEN
 GLOBALERR0=GLOBALERR1

```

WRITE(2,893)GLOBALERR1
893 FORMAT(1X,'SELECTED GLOBALERROR=',F7.3)
*   FIRST STAGE CRACK NETWORK
    CNØPVT=CNØ

    DO 894 I=5,P
      XØAPVT(I)=XØA(I)
      YØAPVT(I)=YØA(I)
      XØBPVT(I)=XØB(I)
      YØBPVT(I)=YØB(I)
      XØPVT(I)=XØ(I)
      YØPVT(I)=YØ(I)
      ORIENTØPVT(I)=ORIENTØ(I)
894  CONTINUE

*   FINAL STAGE CRACK NETWORK
    CNPVT=CN
    ERRNUM1PVT=ERRNUM1
    ERRMLNGTH1PVT=ERRMLNGTH1
    ERRSTDVLENGTH1PVT=ERRSTDVLENGTH1
    ERRMORIENT1PVT=ERRMORIENT1
    ERRSTDVORIENT1PVT=ERRSTDVORIENT1
    R2X1PVT=R2X1
    R2Y1PVT=R2Y1
    R2LENGTH1PVT=R2LENGTH1
    R2ORIENT1PVT=R2ORIENT1
    NITER1PVT=NITER1
    GLOBALERR1PVT=GLOBALERR1

    DO 895 I=5,CN
      X1APVT(I)=X1A(I)
      Y1APVT(I)=Y1A(I)
      X1BPVT(I)=X1B(I)
      Y1BPVT(I)=Y1B(I)
      X1PVT(I)=X1(I)
      Y1PVT(I)=Y1(I)
      LGTH1PVT(I)=LGTH1(I)
      ORIENT1PVT(I)=ORIENT1(I)
895  CONTINUE
    ENDIF

898 CONTINUE

899 CONTINUE

900 CONTINUE

    DO 902 I=5,CNPVT
      CN=CNPVT
      X1A(I)=X1APVT(I)
      Y1A(I)=Y1APVT(I)
      X1B(I)=X1BPVT(I)
      Y1B(I)=Y1BPVT(I)
      X1(I)=X1PVT(I)
      Y1(I)=Y1PVT(I)
      LGTH1(I)=LGTH1PVT(I)
      ORIENT1(I)=ORIENT1PVT(I)

```

```

ERRNUM1=ERRNUM1PVT
ERRMLENGTH1=ERRMLENGTH1PVT
ERRSTDVLENGTH1=ERRSTDVLENGTH1PVT
ERRMORIENT1=ERRMORIENT1PVT
ERRSTDVORIENT1=ERRSTDVORIENT1PVT
R2X1=R2X1PVT
R2Y1=R2Y1PVT
R2LENGTH1=R2LENGTH1PVT
R2ORIENT1=R2ORIENT1PVT
NITER1=NITER1PVT
GLOBALERR1=GLOBALERR1PVT
902 CONTINUE

DO 903 I=5,CN0PVT
CN0=CN0PVT
X0A(I)=X0APVT(I)
Y0A(I)=Y0APVT(I)
X0B(I)=X0BPVT(I)
Y0B(I)=Y0BPVT(I)
X0(I)=X0PVT(I)
Y0(I)=Y0PVT(I)
ORIENT0(I)=ORIENT0PVT(I)
903 CONTINUE

905 CONTINUE

*****
* PRINT OUTPUT

* PRINT TITLE
WRITE(2,*)
WRITE(2,*) '*****'
WRITE(2,*) '*'
WRITE(2,*) '*      A PROGRAM TO GENERATE RANDOM CRACK NETWORK      *'
WRITE(2,*) '*'
WRITE(2,*) '*      THIS PROGRAM GENERATES A RANDOM CRACK NETWORK      *'
WRITE(2,*) '*      USING THE STATISTICAL PARAMETERS OF LENGTH          *'
WRITE(2,*) '*      AND ORIENTATION OF A CRACK NETWORK                  *'
WRITE(2,*) '*'
WRITE(2,*) '*      CONNECTION AMONG CRACK ENDPOINTS                      *'
WRITE(2,*) '*      IS INCORPORATED IN THIS PROGRAM                      *'
WRITE(2,*) '*'
WRITE(2,*) '*****'

* PRINT PROJECT NAME
WRITE(2,*)
WRITE(2,*) 'PROJECT NAME: ',PRJCTNAME
WRITE(2,*)
WRITE(2,*) '*****'

WRITE(2,*)
WRITE(2,*) 'INPUT VARIABLES'
WRITE(2,*)

* PRINT INPUT VARIABLES
WRITE(2,1000)N

```

```

1000 FORMAT(1X, 'N=', I3)
      WRITE(2, *)

      WRITE(2, 1020)MLENGTH,STDVLENGTH
1020 FORMAT(1X, 'MLENGTH=', F5.3, 8X, 'STDVLENGTH=', F5.3)
      WRITE(2, *)

      WRITE(2, 1030)MORIENT,STDVORIENT
1030 FORMAT(1X, 'MORIENT=', F7.3, 6X, 'STDVORIENT=', F7.3)
      WRITE(2, *)

      WRITE(2, 1040)SEEDX0,SEEDY0
1040 FORMAT(1X, 'SEEDX0=', I10, 4X, 'SEEDY0=', I10)
      WRITE(2, 1041)SEEDORIENT
1041 FORMAT(1X, 'SEEDORIENT=', I10)
      WRITE(2, *)

      WRITE(2, *)'END POINTS COORDINATES OF BOUNDARIES'
      WRITE(2, *)'NO    X0A(m)    Y0A(m)    X0B (m)    Y0B(m)    ORIENT0(DEG) '

      DO 1051 I=1,4
        WRITE(2, 1050)I, X0A(I), Y0A(I), X0B(I), Y0B(I), ORIENT0(I)
1050 FORMAT(1X, I2, 5X, F5.3, 5X, F5.3, 5X, F5.3, 5X, F5.3, 7X, F5.1)
1051 CONTINUE

      WRITE(2, *)
      WRITE(2, 1060)NITER
1060 FORMAT(1X, 'NITER=', I10)

      WRITE(2, *)
      WRITE(2, 1070)ERRNUM
1070 FORMAT(1X, 'ERRNUM=', I3)
      WRITE(2, 1071)ERRMLENGTH,ERRSTDVLENGTH
1071 FORMAT(1X, 'ERRMLENGTH=', F5.3, 3X, 'ERRSTDVLENGTH=', F5.3)
      WRITE(2, 1072)ERRMORIENT,ERRSTDVORIENT
1072 FORMAT(1X, 'ERRMORIENT=', F5.3, 3X, 'ERRSTDVORIENT=', F5.3)
      WRITE(2, 1073)R2X, R2Y
1073 FORMAT(1X, 'R2X=', F5.3, 10X, 'R2Y=', F5.3)
      WRITE(2, 1074)R2LENGTH, R2ORIENT
1074 FORMAT(1X, 'R2LENGTH=', F5.3, 5X, 'R2ORIENT=', F5.3)

* PRINT INITIAL GENERATED CRACK NETWORK

      WRITE(2, *)
      WRITE(2, *)'*****'
      WRITE(2, *)
      WRITE(2, *)'FIRST STAGE GENERATED CRACK NETWORK'
      WRITE(2, *)
      WRITE(2, *)'CRACKS MIDPOINTS COORDINATES AND ORIENTATIONS'
      WRITE(2, *)' NO    X0 (m)    Y0 (m)    ORIENT0 (DEG) '

      DO 1102 I=5,CN0
        WRITE (2, 1100)I-4, X0(I), Y0(I), ORIENT0(I)
1100 FORMAT(1X, I3, 4X, F5.3, 3X, F5.3, 10X, F5.1)
1102 CONTINUE

      WRITE(2, *)

```


Appendix C - Computer Code for Numerical Generation of Crack Network

```
WRITE(2,*) 'CRACKS END POINTS COORDINATES'
WRITE(2,*) ' NO   X0A (m)   Y0A (m)   X0B (m)   Y0B (m) '

DO 1202 I=5,CN0
WRITE (2,1200)I-4,X0A(I),Y0A(I),X0B(I),Y0B(I)
1200 FORMAT(1X,I3,5X,F5.3,5X,F5.3,5X,F5.3,4X,F5.3)
1202 CONTINUE

WRITE(2,*)
WRITE(2,*) '*****'
WRITE(2,*)
WRITE(2,1205)NITER1
1205 FORMAT(' RESULTS AT ITERATION = ',I5)
WRITE(2,1206)GLOBALERR1
1206 FORMAT(' GLOBAL ERROR           = ',F5.3)
WRITE(2,1207)NITER1
1207 FORMAT(' MAX ITERATION           = ',I5)
WRITE(2,*)
WRITE(2,*)

WRITE(2,*) 'FINAL STAGE GENERATED RANDOM CRACK NETWORK'
WRITE(2,*)
WRITE(2,*) 'CRACKS MIDPOINTS COORDINATES'
WRITE(2,*) ' NO   X1 (m)   Y1 (m) '
DO 1302 I=5,CN
WRITE (2,1300)I-4,X1(I),Y1(I)
1300 FORMAT(1X,I3,4X,F5.3,4X,F5.3)
1302 CONTINUE

WRITE(2,*)
WRITE(2,*) 'CRACKS END POINTS COORDINATES'
WRITE(2,*) ' NO   X1A (m)   Y1A (m)   X1A (m)   Y1B (m) '

DO 1312 I=5,CN
WRITE (2,1310)I-4,X1A(I),Y1A(I),X1B(I),Y1B(I)
1310 FORMAT(1X,I3,5X,F5.3,5X,F5.3,5X,F5.3,5X,F5.3)
1312 CONTINUE

WRITE(2,*)
WRITE(2,*) 'CRACKS LENGTHS AND CRACKS ORIENTATIONS'
WRITE(2,*) ' NO   LENGTH (m)   ORIENT1 (DEG) '

DO 1402 I=5,CN
WRITE (2,1400)I-4,LGTH1(I),ORIENT1(I)
1400 FORMAT(1X,I3,8X,F5.3,11X,F5.1)
1402 CONTINUE

WRITE(2,*)
WRITE(2,*) 'STATISTICAL PARAMETERS'
WRITE(2,*)
WRITE(2,1410)CN-4
1410 FORMAT(1X,'NUMBER OF CRACKS=',I3)
WRITE(2,1411)ERRNUM1
1411 FORMAT(1X,'ERROR OF NUMBER OF CRACKS=',I3)
WRITE(2,*)
WRITE(2,1412)R2X1
1412 FORMAT(1X,'R2 X COORDINATE=',F5.3)
```

```

WRITE(2,1413)R2Y1
1413 FORMAT(1X,'R2 Y COORDINATE=',F5.3)
WRITE(2,*)

WRITE(2,1420)MLENGTH1
1420 FORMAT(1X,'MEAN LENGTH(m)=',F5.3)
WRITE(2,1421)ERRMLENGTH1
1421 FORMAT(1X,'ERROR OF MEAN LENGTH=',F8.3)
WRITE(2,*)
WRITE(2,1422)STDVLENGTH1
1422 FORMAT(1X,'STD DEVIATION LENGTH(m)=',F5.3)
WRITE(2,1423)ERRSTDVLENGTH1
1423 FORMAT(1X,'ERROR OF STD DEVIATION LENGTH=',F8.3)
WRITE(2,*)
WRITE(2,1424)R2LENGTH1
1424 FORMAT(1X,'R2 LOGNORMAL DIST OF LENGTH=',F5.3)

WRITE(2,*)
WRITE(2,1430)MORIENT1
1430 FORMAT(1X,'MEAN ORIENTATION(DEG)=',F5.1)
WRITE(2,1431)ERRMORIENT1
1431 FORMAT(1X,'ERROR OF MEAN ORIENTATION=',F7.3)
WRITE(2,*)
WRITE(2,1432)STDVORIENT1
1432 FORMAT(1X,'STD DEVIATION ORIENTATION(DEG)=',F7.3)
WRITE(2,1433)ERRSTDVORIENT1
1433 FORMAT(1X,'ERROR OF STD DEVIATION ORIENTATION=',F7.3)
WRITE(2,*)
WRITE(2,1434)R2ORIENT1
1434 FORMAT(1X,'R2 NORMAL DIST OF ORIENTATION=',F5.3)

WRITE(2,*)
WRITE(2,*)'*****'
WRITE(2,*)

IF(CONV.EQ.0)THEN
  WRITE(2,*)'MAXIMUM NUMBER ITERATIONS ARE REACHED'
  WRITE(2,*)'THE SOLUTION IS NOT CONVERGENT'
ENDIF

IF(CONV.EQ.1)THEN
  WRITE(2,*)'CONVERGENCE CRITERIA ARE ACHIEVED'
ENDIF

WRITE(2,*)
WRITE(2,*)'*****'
WRITE(2,*)

WRITE(2,*)'PMIN=',PMIN
WRITE(2,*)'PMAX=',PMAX
WRITE(2,*)

DO 1493 I=5,CN
  WRITE (2,1490)I-4,X1A(I),Y1A(I)
1490 FORMAT(1X,'CN,X1A,Y1A',3X,I3,5X,F5.3,3X,F5.3)

```

```

        WRITE(2,1492)X1B(I),Y1B(I)
1492  FORMAT(1X,'    X1B,Y1B',11X,F5.3,3X,F5.3)
        WRITE(2,*)
1493  CONTINUE

        WRITE(2,*)
        WRITE(2,*)
        DO 1496 I=5,CN0
        WRITE (2,1494)I-4,X0A(I),Y0A(I)
1494  FORMAT(1X,'CN0,X0A,Y0A',3X,I3,5X,F5.3,3X,F5.3)
        WRITE(2,1495)X0B(I),Y0B(I)
1495  FORMAT(1X,'    X0B,Y0B',11X,F5.3,3X,F5.3)
        WRITE(2,*)
1496  CONTINUE

        STOP
        END
*
*****
*
* SUBROUTINES

* SUBROUTINE TO GENERATE RANDOM NUMBERS BETWEEN 0 AND 1
  SUBROUTINE RANDOM(SEED,RANDX)

    INTEGER SEED
    REAL RANDX

    SEED=2045*SEED+1
    SEED=SEED-(SEED/1048576)*1048576
    RANDX=REAL(SEED+1)/1048577.0

    RETURN
    END

* SUBROUTINE TO CALCULATE STANDAR NORMAL INVERSE NUMBER
  SUBROUTINE NORMSINV(PROB,U2)

    INTEGER I
    REAL PROB,U1,U2,K,FXDX,FXCUMM,ERORIENT0

    FXCUMM=0
    K=-6000001

    DO 3000 I=1,12000001

      K=K+1
      U1=K/1000000
      FXDX=(EXP(-0.5*(U1)**2)/SQRT(2*3.141593))*0.000001

      FXDX=(EXP(-0.5*(U1)**2)/SQRT(2*3.141593))*0.000001
      FXCUMM=FXCUMM+FXDX
      ERORIENT0=ABS(FXCUMM-PROB)

```

```

        IF(ERORIENT0 .LE. 0.000001)THEN
            U2=U1
            RETURN
        ENDIF

3000 CONTINUE

        END

* SUBROUTINE TO GENERATE A CRACK(SIDE A)
  SUBROUTINE CRG(X0I,Y0I,ORIENT0I,X4,Y4,X5,Y5,ORIENT0K,XA,YA,LGTH)

    REAL X0I,Y0I,ORIENT0I,X4,Y4,X5,Y5,ORIENT0K,XA,YA,LGTH
    REAL M,C,M1,M2,C1,C2
    REAL L1,L2

*    ANGLE COMBINATIONS:
*    COMBINATION1: ORIENT0K=0DEG,ORIENT0I=0DEG
*    COMBINATION2: ORIENT0K=0DEG,ORIENT0I=90DEG
*    COMBINATION3: ORIENT0K=0DEG,ORIENT0I NOT=0 OR NOT= 90DEG,

*    COMBINATION4: ORIENT0K=90DEG,ORIENT0I=0DEG
*    COMBINATION5: ORIENT0K=90DEG,ORIENT0I=90DEG
*    COMBINATION6: ORIENT0K=90DEG,ORIENT0I NOT=0 NOT= 90DEG,

*    COMBINATION7: ORIENT0K NOT=0 OR NOT=90DEG,ORIENT0I=90DEG
*    COMBINATION8: ORIENT0K NOT=0 OR NOT=90DEG,ORIENT0I
NOT=90DEG,ORIENT0K=ORIENT0I
*    COMBINATION9: ORIENT0K NOT=0 OR NOT=90DEG,ORIENT0I
NOT=90DEG,ORIENT0K NOT= ORIENT0I

*    COMBINATION1 (NO INTERSECTION POINT):
    IF(ABS(ORIENT0K).LE.0.0004)THEN
        IF(ABS(ORIENT0I).LE.0.0004)THEN
            XA=100
            YA=100
            LGTH=200
            GOTO 3100
*    COMBINATION3 (INTERSECTION POINT):
        ELSEIF(ABS(ORIENT0I-90).LE.0.0004)THEN
            YA=X4
            XA=X0I
            LGTH=ABS(Y0I-Y4)
            GOTO 3090
*    COMBINATION3 (INTERSECTION POINT):
        ELSEIF(ABS(ORIENT0I-90).GT.0.0004)THEN
            M=TAN(ORIENT0I*3.141593/180)
            C=Y0I-M*X0I
            YA=Y4
            XA=(YA-C)/M
            LGTH=SQRT((X0I-XA)**2+(Y0I-YA)**2)
            GOTO 3090
        ENDIF

```

```

ENDIF

* COMBINATION4 (NO INTERSECTION POINT):
IF (ABS(ORIENT0K-90).LE.0.0004) THEN
  IF (ABS(ORIENT0I).LE.0.0004) THEN
    XA=X4
    YA=Y0I
    LGTH=ABS(X0I-X4)
    GOTO 3090
  * COMBINATION5 (NO INTERSECTION POINT):
  ELSEIF (ABS(ORIENT0I-90).LE.0.0004) THEN
    XA=100
    YA=100
    LGTH=200
    GOTO 3100
  * COMBINATION6 (INTERSECTION POINT):
  ELSEIF (ABS(ORIENT0I-90).GT.0.0004) THEN
    M=TAN(ORIENT0I*3.141593/180)
    C=Y0I-M*X0I
    XA=X4
    YA=M*XA+C
    LGTH=SQRT((X0I-XA)**2+(Y0I-YA)**2)
    GOTO 3090
  ENDF
ENDIF

IF (ABS(ORIENT0K-90).GT.0.0004) THEN
* COMBINATION7 (INTERSECTION POINT):
  IF (ABS(ORIENT0I-90).LE.0.0004) THEN
    M=TAN(ORIENT0K*3.141593/180)
    C=Y4-M*X4
    XA=X0I
    YA=M*XA+C
    LGTH=SQRT((X0I-XA)**2+(Y0I-YA)**2)
    GOTO 3090
  ELSEIF (ABS(ORIENT0I-90).GT.0.0004) THEN
* COMBINATION8 (NO INTERSECTION POINT):
    IF (ABS(ORIENT0K-ORIENT0I).LE.0.0004) THEN
      XA=100
      YA=100
      LGTH=200
      GOTO 3100
    * COMBINATION9 (INTERSECTION POINT)
    ELSEIF (ABS(ORIENT0K-ORIENT0I).GT.0.0004) THEN
      M1=TAN(ORIENT0I*3.141593/180)
      M2=TAN(ORIENT0K*3.141593/180)
      C1=Y0I-M1*X0I
      C2=Y4-M2*X4
      XA=(C2-C1)/(M1-M2)
      YA=M1*XA+C1
      LGTH=SQRT((X0I-XA)**2+(Y0I-YA)**2)
      GOTO 3090
    ENDF
  ENDF
ENDIF

3090 CONTINUE

```

* CHECK RELATIVE POSITION OF XA,YA AGAINST X4,Y4 AND X5,Y5

```

IF((ABS(XA)-AMAX1(ABS(X4),ABS(X5))).LE.0.0)THEN
  IF((ABS(XA)-AMIN1(ABS(X4),ABS(X5))).GE.0.0)THEN
    IF((ABS(YA)-AMAX1(ABS(Y4),ABS(Y5))).LE.0.0)THEN
      IF((ABS(YA)-AMIN1(ABS(Y4),ABS(Y5))).GE.0.0)THEN
        LGTH=LGTH
        GOTO 3095
      ELSE
        XA=100
        YA=100
        LGTH=200
        GOTO 3100
      ENDIF
    ELSE
      XA=100
      YA=100
      LGTH=200
      GOTO 3100
    ENDIF
  ELSE
    XA=100
    YA=100
    LGTH=200
    GOTO 3100
  ENDIF
ELSE
  XA=100
  YA=100
  LGTH=200
  GOTO 3100
ENDIF

```

3095 CONTINUE

```

* CHECK SIDE(SIDEA: L1 OR L2 < 0)
  L1=(XA-X0I)/COS(ORIENT0I*3.141593/180)
  L2=(YA-Y0I)/SIN(ORIENT0I*3.141593/180)
  IF((L1.LT.0).OR.(L2.LT.0))THEN
    LGTH=LGTH*(-1)
  ENDIF

```

3100 CONTINUE

RETURN

END

* SUBROUTINE TO INVENTARIZE FINAL CRACK ENDPOINTS

SUBROUTINE ENDPOINT(XAI,YAI,ORIENT0I,X4,Y4,VAL,DIST)

```

REAL XAI,YAI,ORIENT0I,X4,Y4,DIST
REAL M,C,YI,XI
INTEGER VAL

```

```

IF(ABS(ORIENT0I-90).LE.0.0004)THEN

```

```
XI=XAI
IF (ABS(X4-XI) .LE. 0.0004) THEN
  VAL=1
  DIST=SQRT((Y4-YAI)**2)
ELSE
  VAL=0
ENDIF
ELSE
  M=TAN(ORIENT0I*3.141593/180)
  C=YAI-M*XAI
  YI=M*X4+C
  IF (ABS(Y4-YI) .LE. 0.0004) THEN
    VAL=1
    DIST=SQRT((X4-XAI)**2+(Y4-YAI)**2)
  ELSE
    VAL=0
  ENDIF
ENDIF
RETURN
END
```

C.2 An Example of Input File of Computer Code for Numerical Generation of Crack Network

```
LARGESCALE_LATFLOW_TEST_1(NETW_1-1)
44
0.144  0.107
87.500  52.500
0.528  0.267
0.508  0.268
      12357      12345      12346
0.000  1.000  1.000  1.000  0.00
0.000  0.000  1.000  0.000  0.00
0.000  0.000  0.000  1.000  90.00
1.000  0.000  1.000  1.000  90.00
      10000
      2
0.100  0.100  0.100  1.000
0.100  0.100  0.100  0.100
0.900  0.950  0.950  0.950
```


C.3 An Example of Output File of Computer Code for Numerical Generation of Crack Network

```

*****
*
*      A PROGRAM TO GENERATE RANDOM CRACK NETWORK      *
*
*      THIS PROGRAM GENERATES A RANDOM CRACK NETWORK  *
*      USING THE STATISTICAL PARAMETERS OF LENGTH    *
*      AND ORIENTATION OF A CRACK NETWORK            *
*
*      CONNECTION AMONG CRACK ENDPOINTS               *
*      IS INCORPORATED IN THIS PROGRAM               *
*
*****

PROJECT NAME:LARGESCALE_LATFLOW_TEST_1(NETW_1-1)

*****

INPUT VARIABLES

N= 44

MLENGTH=0.144      STDVLENGTH=0.107
MORIENT= 87.500    STDVORIENT= 52.500
MXMID=0.528        STDVXMID=0.267
MYMID=0.508        STDVYMID=0.268

SEEDX0=    12357
SEEDY0=    12345
SEEDORIENT0= 12346

END POINTS COORDINATES OF BOUNDARIES
NO   X0A(m)   Y0A(m)   X0B (m)   Y0B(m)   ORIENT0(DEG)
1     0.000    1.000    1.000    1.000     0.0
2     0.000    0.000    1.000    0.000     0.0
3     0.000    0.000    0.000    1.000    90.0
4     1.000    0.000    1.000    1.000    90.0

NITER=    10000

ERRNUM= 2
ERRMLENGTH=0.100  ERRSTDVLENGTH=0.100
ERRMORIENT=0.100  ERRSTDVORIENT=1.000
ERRMXMID=0.100    ERRSTDVXMID=0.100
ERRMYMID=0.100    ERRSTDVYMID=0.100
R2XMID=0.950      R2YMID=0.950
R2LENGTH=0.900    R2ORIENT=0.950

```

FIRST STAGE GENERATED CRACK NETWORK

CRACKS MIDPOINTS COORDINATES AND ORIENTATIONS

NO	X0 (m)	Y0 (m)	ORIENT0 (DEG)
1	0.671	0.457	91.4
2	0.399	0.582	150.0
3	0.569	0.404	77.3
4	0.998	0.346	166.5
5	0.894	0.294	105.9
6	0.659	0.123	26.5
7	0.999	0.617	148.4
8	0.075	0.199	131.8
9	0.560	0.259	34.3
10	0.967	0.657	48.7
11	0.162	0.724	119.6
12	0.328	0.744	104.3
13	0.573	0.023	98.5
14	0.606	0.173	90.8
15	0.206	0.764	9.0
16	0.315	0.867	29.6
17	0.262	0.926	101.7
18	0.595	0.640	23.7
19	0.074	0.821	23.2
20	0.202	0.313	8.2

CRACKS END POINTS COORDINATES

NO	X0A (m)	Y0A (m)	X0B (m)	Y0B (m)
1	0.683	0.000	0.657	1.000
2	0.672	0.424	0.000	0.812
3	0.478	0.000	0.585	0.474
4	1.000	0.345	0.672	0.424
5	0.978	0.000	0.871	0.376
6	0.486	0.036	0.679	0.133
7	1.000	0.616	0.662	0.824
8	0.253	0.000	0.000	0.283
9	0.532	0.241	0.674	0.337
10	0.955	0.644	1.000	0.695
11	0.167	0.715	0.005	1.000
12	0.365	0.601	0.263	1.000
13	0.577	0.000	0.565	0.076
14	0.607	0.097	0.604	0.290
15	0.145	0.754	0.319	0.782
16	0.299	0.858	0.549	1.000
17	0.293	0.778	0.247	1.000
18	0.426	0.566	0.666	0.671
19	0.022	0.799	0.101	0.832
20	0.000	0.284	0.561	0.365

RESULTS AT ITERATION = 9497
GLOBAL ERROR = 1.239
MAX ITERATION = 10000

FINAL STAGE GENERATED RANDOM CRACK NETWORK

CRACKS MIDPOINTS COORDINATES

NO	X1 (m)	Y1 (m)
1	0.681	0.066
2	0.677	0.235
3	0.673	0.381
4	0.672	0.424
5	0.669	0.548
6	0.664	0.748
7	0.660	0.912
8	0.672	0.424
9	0.629	0.449
10	0.505	0.520
11	0.395	0.584
12	0.266	0.658
13	0.095	0.757
14	0.011	0.805
15	0.482	0.018
16	0.509	0.139
17	0.546	0.303
18	0.573	0.420
19	0.935	0.361
20	0.771	0.400
21	0.924	0.188
22	0.526	0.056
23	0.586	0.086
24	0.643	0.115
25	0.978	0.630
26	0.809	0.734
27	0.126	0.141
28	0.568	0.265
29	0.639	0.314
30	0.978	0.669
31	0.156	0.735
32	0.123	0.793
33	0.053	0.916
34	0.342	0.692
35	0.309	0.820
36	0.281	0.929
37	0.571	0.038
38	0.606	0.193
39	0.219	0.766
40	0.306	0.780
41	0.424	0.929
42	0.270	0.889
43	0.546	0.619

44 0.062 0.815
45 0.280 0.325

CRACKS END POINTS COORDINATES

NO	X1A (m)	Y1A (m)	X1A (m)	Y1B (m)
1	0.683	0.000	0.679	0.133
2	0.679	0.133	0.674	0.337
3	0.674	0.337	0.672	0.424
4	0.672	0.424	0.672	0.424
5	0.672	0.424	0.666	0.671
6	0.666	0.671	0.662	0.824
7	0.662	0.824	0.657	1.000
8	0.672	0.424	0.672	0.424
9	0.672	0.424	0.585	0.474
10	0.585	0.474	0.426	0.566
11	0.426	0.566	0.365	0.601
12	0.365	0.601	0.167	0.715
13	0.167	0.715	0.022	0.799
14	0.022	0.799	0.000	0.812
15	0.478	0.000	0.486	0.036
16	0.486	0.036	0.532	0.241
17	0.532	0.241	0.561	0.365
18	0.561	0.365	0.585	0.474
19	1.000	0.345	0.871	0.376
20	0.871	0.376	0.672	0.424
21	0.978	0.000	0.871	0.376
22	0.486	0.036	0.565	0.076
23	0.565	0.076	0.607	0.097
24	0.607	0.097	0.679	0.133
25	1.000	0.616	0.955	0.644
26	0.955	0.644	0.662	0.824
27	0.253	0.000	0.000	0.283
28	0.532	0.241	0.604	0.290
29	0.604	0.290	0.674	0.337
30	0.955	0.644	1.000	0.695
31	0.167	0.715	0.145	0.754
32	0.145	0.754	0.101	0.832
33	0.101	0.832	0.005	1.000
34	0.365	0.601	0.319	0.782
35	0.319	0.782	0.299	0.858
36	0.299	0.858	0.263	1.000
37	0.577	0.000	0.565	0.076
38	0.607	0.097	0.604	0.290
39	0.145	0.754	0.293	0.778
40	0.293	0.778	0.319	0.782
41	0.299	0.858	0.549	1.000
42	0.293	0.778	0.247	1.000
43	0.426	0.566	0.666	0.671
44	0.022	0.799	0.101	0.832
45	0.000	0.284	0.561	0.365

Appendix C - Computer Code for Numerical Generation of Crack Network

CRACKS LENGTHS AND CRACKS ORIENTATIONS

NO	LENGTH (m)	ORIENT1 (DEG)
1	0.133	91.4
2	0.205	91.4
3	0.087	91.4
4	0.000	0.0
5	0.247	91.4
6	0.153	91.4
7	0.176	91.4
8	0.000	0.0
9	0.100	150.0
10	0.184	150.0
11	0.070	150.0
12	0.228	150.0
13	0.167	150.0
14	0.026	150.0
15	0.037	77.3
16	0.209	77.3
17	0.128	77.3
18	0.112	77.3
19	0.133	166.5
20	0.205	166.5
21	0.391	105.9
22	0.088	26.5
23	0.046	26.5
24	0.081	26.5
25	0.053	148.4
26	0.344	148.4
27	0.379	131.8
28	0.087	34.3
29	0.084	34.3
30	0.068	48.7
31	0.045	119.6
32	0.090	119.6
33	0.193	119.6
34	0.186	104.3
35	0.079	104.3
36	0.146	104.3
37	0.077	98.5
38	0.193	90.8
39	0.150	9.0
40	0.026	9.0
41	0.287	29.6
42	0.227	101.7
43	0.262	23.7
44	0.085	23.2
45	0.566	8.2

STATISTICAL PARAMETERS

NUMBER OF CRACKS= 45

ERROR OF NUMBER OF CRACKS= 1

```
MEAN LENGTH(m)=0.152
ERROR OF MEAN LENGTH=  0.055

STD DEV LENGTH(m)=0.112
ERROR OF STD DEV LENGTH=  0.050

R2 LOGNORMAL DIST OF LENGTH=0.926

MEAN ORIENTATION(DEG)= 86.4
ERROR OF MEAN ORIENTATION=  0.013

STD DEV ORIENTATION(DEG)= 11.649
ERROR OF STD DEV ORIENTATION=  0.778

R2 UNIFORM DIST OF ORIENTATION=0.968

MEAN X COORD CRACK MIDPOINT=0.498
ERROR OF MEAN X COORD CRACK MIDPOINT=0.057

STD DEV OF X COORD CRACK MIDPOINT=0.255
ERROR OF STD DEV OF X COORD CRACKMIDPOINT=0.046

R2 UNIFORM DIST OF X COORD CRACK MIDPOINT=0.959

MEAN Y COORD CRACK MIDPOINT=0.502
ERROR OF MEAN Y COORD CRACK MIDPOINT=0.012

STD DEV Y COORD CRACK MIDPOINT=0.255
ERROR OF STD DEV Y COORD CRACK MIDPOINT=0.050

R2 UNIFORM DIST OF Y COORD CRACK MIDPOINT=0.991

*****

CONVERGENCE CRITERIA ARE ACHIEVED

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