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Numerical study on the effect of crack network representation on water content in cracked soil

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Abstract. The presence of cracks changes the water content pattern during seepage through a cracked soil as compared to that of intact soil. In addition, several different crack networks may form in one soil type. These two factors result in a variation of water contents in the soil matrix part of a cracked soil during seepage. This paper presents an investigation of the effect of crack network representation on the water content of the soil matrix part of cracked soil using numerical models. A new method for the numerical generation of crack networks incorporating connections among crack endpoints was developed as part of the investigation. Numerical analysis results indicated that the difference in the point water content was large, whereas the difference in the average water content was relatively small, indicating the uniqueness of the crack network representation on the average water content of the soil matrix part of cracked soil.

Keywords: water content; numerical model; drying; shrinkage; crack network; unsaturated soils

1. Introduction

Cracked soil can be considered to consist of two parts: (i) Crack network and (ii) Soil matrix. Crack network is defined as the cracks that exist in a cracked soil whereas soil matrix is defined as the uncracked part of the soil (Li and Zhang 2010, Li and Zhang 2011, Krisnanto *et al.* 2014, Krisnanto *et al.* 2016).

The presence of cracks changes the water content pattern during seepage through a cracked soil as compared to that of intact soil (Oda *et al.* 1996, Zhang *et al.* 2012, Galeandro *et al.* 2013, Galeandro *et al.* 2014, Krisnanto *et al.* 2014, Krisnanto *et al.* 2016). Water content pattern during seepage influences the mechanical behavior of geotechnical structure (e.g., Rulon and Freeze 1985, Zhang and Chen 2006). During a lateral seepage through cracked soil, there are two types of water flow: (i) Flow through the crack network and (ii) Seepage through the soil matrix part of cracked soil. In the seepage through the soil matrix part of cracked soil, the seepage directions are from the crack wall to the center part of crack cells. Since the crack orientations vary in a crack network, there are several different directions of seepage into the soil matrix in a cracked soil. In addition, in one soil type, several different crack networks may form (e.g., Corte and Higashi 1960, Atique *et al.* 2010). These two factors result in a variation of water content of the soil matrix part of cracked soil during seepage. Thus, in the analysis of water content during seepage in a cracked soil, the variation of crack network in a cracked soil needs to be considered.

Several studies of water content quantification of soil matrix of cracked soil have been performed. Brownswijk *et al.* (1995) measured water content at several locations of cracked soil in the field and found that water content varied among the locations. Novák *et al.* (2000) developed a computer program to quantify water content in soil matrix of cracked soil with parallel cracks. Zhan *et al.* (2007) measured water content at several locations of cracked soil in the field and found the locations closer to the crack network had higher water contents as compared to those farther from the crack. In each of those studies, the analysis was performed only for one crack network. The possibility of variation of crack network in one soil was not considered. In other words, the previous studies did not consider the effect of the variation of crack networks of one soil type on water content in the soil matrix part of the cracked soil. In addition, the previous studies idealized the actual crack network as parallel crack network or uniform polygon crack network.

In the previous studies, crack network in cracked soil was characterized using statistical parameters of crack length, crack orientation, and crack midpoint X- and Y-coordinates (D'Astous *et al.* 1989, Lakshmikantha *et al.* 2009, Mizuguchi *et al.* 2005, Tang *et al.* 2008, Li and Zhang 2010). The variation of crack network with the same statistical parameters can be simulated by generating the crack network numerically (Long *et al.* 1982, Stietel *et al.* 1996, Li and Zhang 2007, Li *et al.* 2009). In these methods,

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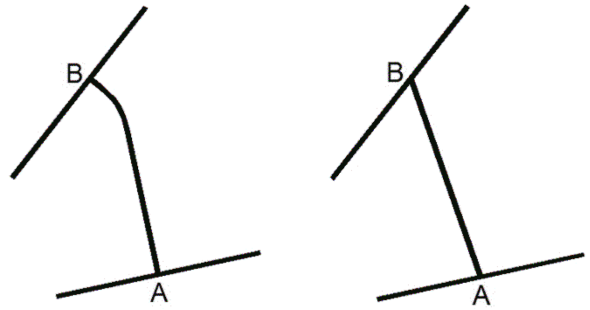
the crack networks were generated by superimposing several cracks that vary in length, orientation, and crack midpoint X- and Y-coordinates. The crack length, orientation, and crack midpoint X- and Y-coordinates follow a particular distribution function. In the field, the existence of connections among crack endpoints in cracked soil and the condition that the cracks terminate at a crack intersection point are obvious (Corte and Higashi 1960, Vogel *et al.* 2005, Peron *et al.* 2009, Vallejo 2009, Atique *et al.* 2010, Krisnanto *et al.* 2016). However, in the previous methods of crack network generation, the connectivity among cracks was not considered. Thus, a crack end may not be located at a crack intersection but inside a crack cell. This condition indicates that the existing methods of numerical crack network generation need to be improved to better imitate crack networks in a real cracked soil. Therefore, a new method of numerical generation of crack networks needs to be developed.

Although the variation in water content of the soil matrix during seepage through cracked soil depends on the seepage direction and variation in crack network (Li and Zhang 2007, Li *et al.* 2009), the statistical homogeneity of a cracked soil can be calculated based on soil physical parameters (e.g., void ratio, porosity). The change in water content during seepage in a cracked soil is affected not only by the porosity of the soil matrix but also by the seepage direction from the crack walls to the soil matrix in all crack cells. Krisnanto *et al.* (2011) proposed an averaging technique for water content of the soil matrix part of cracked soil experiencing changes in water content. In the study, the average water content of the soil matrix part of cracked soil was calculated for only one crack network for each soil type. This condition suggests an investigation on how the variation in crack networks affects the average water content of the soil matrix part of cracked soil. In other words, the characteristics of the changes in water content are not yet fully understood. Therefore, a new method to analyze the effect of variation of crack network in water content of the soil matrix of cracked soil is required.

This paper presents the results of investigation of the effect of crack network representation on the water content of the soil matrix part of cracked soil. A new method for the numerical generation of crack networks incorporating connectivity among crack endpoints was developed as part of the investigation. Computer program to implement the numerical crack network generation scheme was also developed. The generated crack network was then modeled as boundary conditions in a numerical model using a commercial software. Several models with different crack networks were generated using one set of crack statistical parameters. Two types of water content were then analyzed for the cracked soil specimens: (i) The point water contents at several locations within the intact soil matrix part of cracked soil specimens (Krisnanto *et al.* 2016) and (ii) The average water content of the intact soil matrix part of cracked soil specimens (Krisnanto *et al.* 2011).



(a) Curved crack portion near crack intersection point (b) Idealized crack

Fig. 1 Schematic diagram of crack intersection assumed in this study

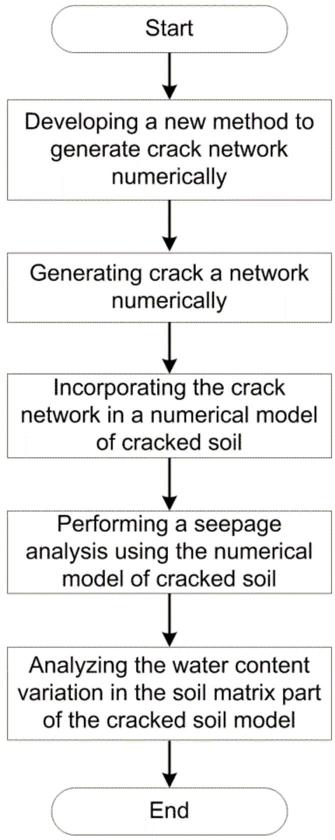
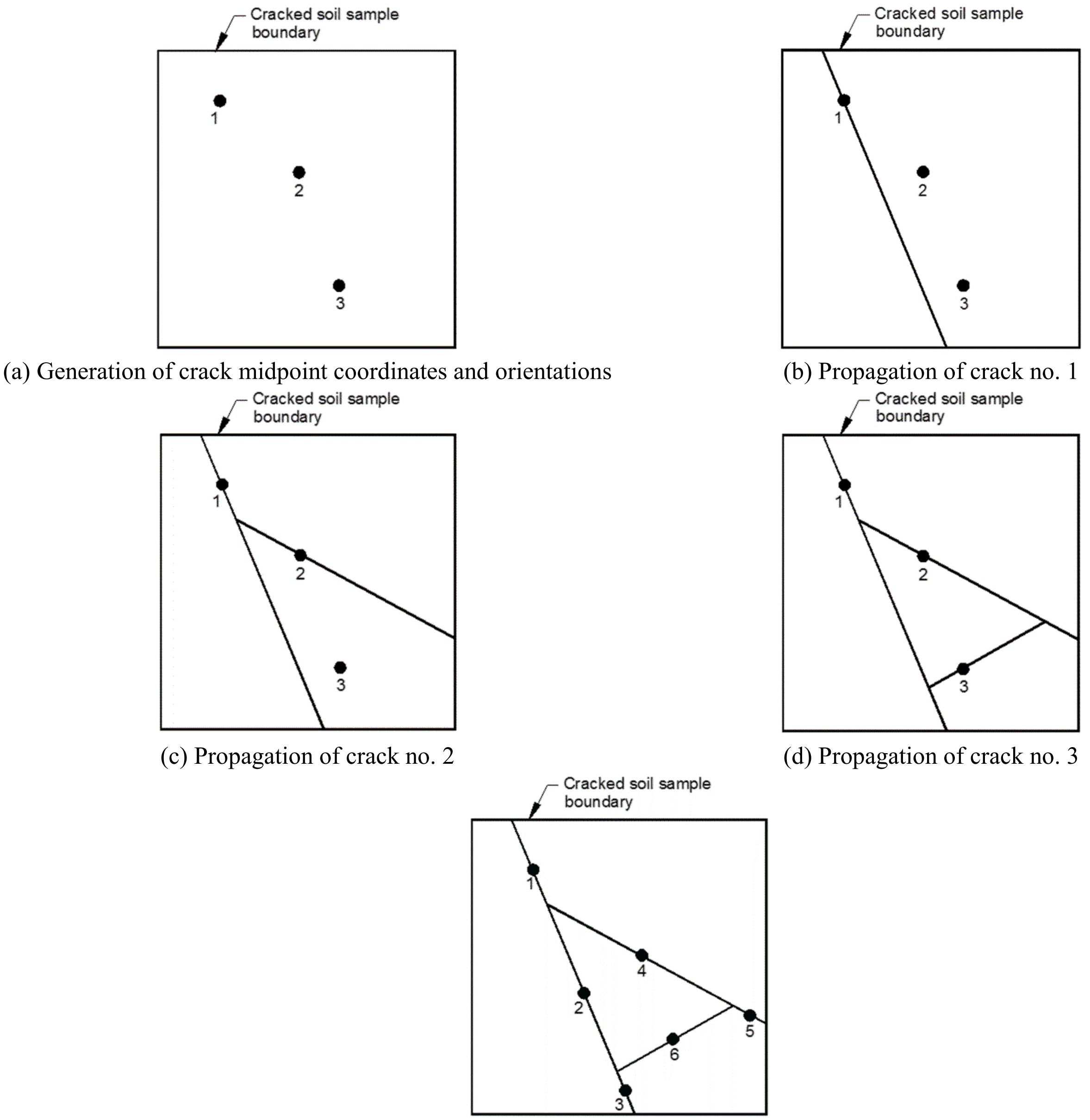


Fig. 2 Flow chart of methodology of study

2. Research program

Development of crack network follows the idealization of: (i) A crack starting at random position, (ii) A crack propagates from the starting point and stop when it meets another crack, and (iii) The water content of intact soil matrix is idealized using averaging technique. The study of Atique *et al.* (2010) indicates that crack starts at the center of a rectangular sample and crack starts from the edge of a circular sample. Therefore, for a square sample analyzed in this study, it can be idealized that crack starts at random position. This confirms the first idealization.

Several studies indicate that there are two conditions of crack intersection: (i) Cracks intersect at right angle, and (ii) Cracks intersect at 120º (Corte and Higashi 1960, Lau 1987, Kodikara *et al.* 1998, 2000, Atique *et al.* 2010). In this study, it is assumed that the development of crack



(a) Generation of crack midpoint coordinates and orientations (b) Propagation of crack no. 1

(c) Propagation of crack no. 2 (d) Propagation of crack no. 3

(e) Inventory of the crack network

Fig. 3 An example of the iterative stage of the proposed method for generating a crack network

network follows the first condition. In the first condition, when a crack propagation tends to intersect another crack which is not perpendicular, the crack curved to intersect another crack in the perpendicular direction (Fig. 1(a)). In this study, this condition is idealized as shown in Fig. 1(b).

A previous study (Krisnanto *et al.* 2011) indicates that an averaging technique may be used to quantify the water content in soil matrix part of the cracked soil. In this study, the averaging technique is used to quantify water content of the soil matrix part of cracked soil.

The flow chart of the methodology of this study is shown in Fig. 2. Firstly, a new method to generate crack network numerically was developed. Secondly, several crack networks were then generated using this new method. Thirdly, numerical models of cracked soil were developed. Each numerically generated crack network was incorporated in the numerical model of cracked soil. Then, a seepage analysis was performed for each numerical model of cracked soil. Finally, variation in water content was analyzed for each numerical model of cracked soil. The point water content and the average water content were calculated for each model.

The first step in the development of method to generate crack network numerically was to obtain the statistical parameters of crack networks. This was done by analyzing the cracked soil specimens used in Krisnanto *et al.* (2016). Secondly, a novel method for the numerical generation of a crack network was developed that incorporates connections among crack endpoints. This method was then used to generate a crack network, as illustrated in Fig. 3. In this method, the target crack parameters (number of cracks, probability distribution function, mean, and standard deviation of crack midpoint coordinates, crack length, and crack orientation) as well as the maximum error of each

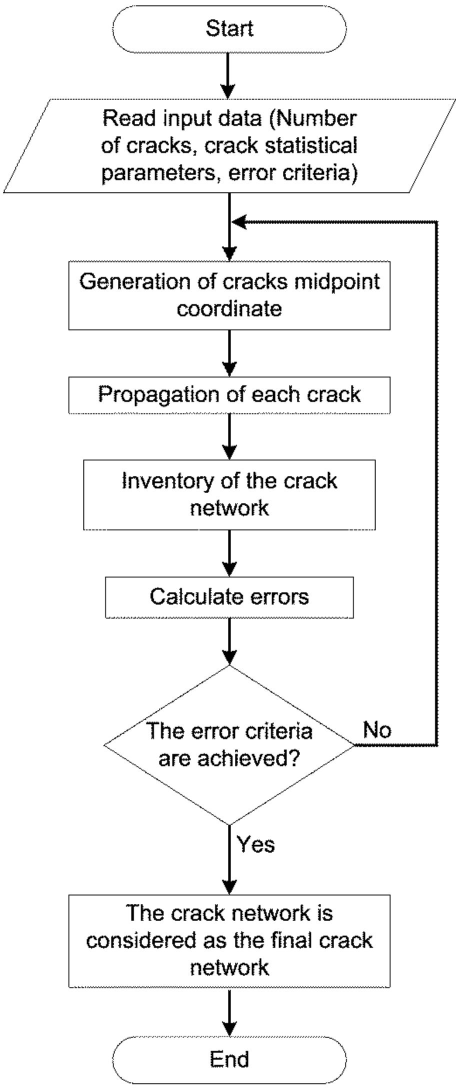


Fig. 4 Flow chart of the computer program for crack network generation

parameter are determined first. The numerical generation of crack network starts with the generation of the crack midpoint coordinates and crack orientation (Fig. 3(a)). Random numbers between 0 and 1 are generated following a uniform distribution function. The method of Ang and Tang (1984) is used to convert a random number between 0 and 1 into a random number between 0 and 180 degrees for the crack orientation. No conversion is needed for the crack midpoint X- and Y-coordinates since the dimensions of the cracked soil specimen in Krisnanto *et al.* (2016) are 1 m x 1 m. Each crack is then extended from each crack midpoint associated with each crack orientation. Each crack is extended until it reaches another crack or the specimen boundary. Crack no. 1 is generated first, followed by cracks no. 2 to 3 (Figs. 3(b)-3(d)).

The algorithm to generate crack networks is implemented in a computer program. The flow chart of the computer program for crack network generation is shown in Fig. 4. The newly formed crack network (Fig. 3(e)) is then inventoried. In the crack inventory, one crack is defined as the crack existing between two crack intersection points. This definition is consistent with that used by Li and Zhang (2007), Li *et al.* (2009), and Krisnanto *et al.* (2014). The midpoint X- and Y-coordinates of each crack are then recalculated as the midpoint coordinates between the coordinates of two crack endpoints. The crack length is calculated as the distance between two crack endpoints. The mean and standard deviation of the crack length are calculated and compared with the target mean and standard deviation of the crack length. The frequency distribution of the crack midpoint coordinates is compared with the target probability distribution function. The error is defined to quantify the difference between the target and achieved values for each statistical parameter. At this point of the generation process, the crack network is said to be at the iterative stage. This process is iterated until the error of the statistical parameters of the crack network is smaller than or equal to the target error of each parameter. A crack network that satisfies the target parameters condition is considered as the final crack network.

In this study, the computer program was developed using FORTRAN 77. The crack length was generated following a lognormal distribution, whereas the crack orientation and the midpoint X- and Y-coordinates were generated following uniform distributions.

In general, the computer program consists of two main parts: (i) Crack propagation part (Appendix A) and (ii) Inventory of the crack network part (Appendix B). In the crack propagation part of the computer program, firstly, random initial crack midpoint X- and Y-coordinates (Fig. 3(a)) with a uniform distribution were generated. The method proposed by Etter (1990) was used to generate uniform random numbers between 0 and 1 for the crack midpoint X- and Y-coordinates and the crack orientations. The crack midpoint X- and Y-coordinates are termed X0 and Y0 in the computer program. Input seed numbers (any integer number larger than one) termed SEEDX01 and SEEDY01 were used to generate random numbers between 0 and 1 for the crack midpoint X- and Y-coordinates, respectively. Secondly, random crack orientations were generated. An input seed number (any integer number larger than one) termed SEEDORIENT01 was used to generate a random number generation between 0 and 1, and the method of Ang and Tang (1984) was then used to convert the random number into a random number between 0 and 180 degrees for the crack orientation. Next, the crack propagated in two directions from the crack midpoint (the two crack endpoints were termed CRACK END A and CRACK END B). Crack propagation from each side terminated when the crack either met the specimen boundary or intersected with another crack. This crack propagation process was implemented using a subroutine to generate cracks:
CRG(X0I,Y0I,ORIENT0I,X4,Y4,X5,Y5,ORIENT0K,XA,YA, LGTH)).
Crack length was then calculated as the distance between two crack endpoints.

In the subroutine to generate cracks, once a crack network does not comply with the error criteria, new random crack midpoint coordinates are generated. To achieve better convergence, the same midpoint coordinates are not used anymore. The method of random number generation from Etter (1990) accommodates this condition.

In the inventory of the crack network part of the computer program (Appendix B), the crack inventory was performed in the following sequence:

• Calculation of the crack endpoint X- and Y-coordinates.

• Recalculation of the crack midpoint X- and Y-coordinates using crack endpoint X- and Y-coordinates.

• Calculation of the mean and standard deviation of the crack midpoint X-coordinates and R^2 in the uniform distribution plot. The calculation of R^2 is based on Montgomery and Runger (2007).

• Calculation of the mean and standard deviation of the crack midpoint Y-coordinates and R^2 in the uniform distribution plot.

• Calculation of the mean and standard deviation of the crack length and R^2 in the lognormal distribution plot.

• Calculation of the mean and standard deviation of the crack orientation and R^2 in the uniform distribution plot.

• Calculation of the difference between the achieved mean, standard deviation, and R^2 in the distribution plot of the crack length, crack orientation, and crack midpoint X- and Y-coordinates and the target mean, standard deviation, and R^2 in the distribution plot of the crack length, crack orientation, and crack midpoint X- and Y-coordinates. The differences were quantified by error parameters.

The performance of the crack network at each iterative stage of the crack network as compared to the target crack network was assessed using the following parameters:

• Error of the number of cracks (*ErrNum*).

• Error of the mean of crack length (*ErrMLength*)

• Error of the standard deviation of crack length (*ErrStdvLength*).

• Error of the mean of crack orientation (*ErrMOrient*).

• Error of the standard deviation of crack orientation (*ErrStdvOrient*).

• Error of the mean of crack midpoint X-coordinate (*ErrStdvXmid*).

• Error of the standard deviation of crack midpoint X-coordinate (*ErrStdvXmid*).

• Error of the mean of crack midpoint Y-coordinate (*ErrMYmid*).

• Error of the standard deviation of crack midpoint Y-coordinate (*ErrStdvYmid*).

• R^2 of the lognormal frequency distribution plot of the crack length.

• R^2 of the uniform frequency distribution plot of the crack orientation.

• R^2 of the uniform frequency distribution plot of the crack midpoint X-coordinate.

• R^2 of the uniform frequency distribution plot of the crack midpoint Y-coordinate.

The error and R^2 criteria are input parameters in the numerical crack generation process.

The error criteria are defined as follows:

$$ErrNum = N1 - N \tag{1}$$

$$ErrMLength = \frac{|MLength1 - MLength|}{MLength} \tag{2}$$

$$ErrStdvLength = \frac{|StdvLength1 - StdvLength|}{StdvLength} \tag{3}$$

$$ErrMOrient = \frac{|MOrient1 - MOrient|}{MOrient} \tag{4}$$

$$ErrStdvOrient = \frac{|StdvOrient1 - StdvOrient|}{StdvOrient} \tag{5}$$

$$ErrMXMid = \frac{|MXmid1 - MXmid|}{MXmid} \tag{6}$$

$$ErrStdvXMid = \frac{|StdvXmid1 - StdvXmid|}{StdvXmid} \tag{7}$$

$$ErrMYMid = \frac{|MYmid1 - MYmid|}{MYmid} \tag{8}$$

$$ErrStdvYMid = \frac{|StdvYmid1 - StdvYmid|}{StdvYmid} \tag{9}$$

where *N*1 is the number of cracks during the iterative stage of the crack network and *N* is the target number of cracks; *MLength*1 is the mean of crack length during the iterative stage of the crack network and *MLength* is the target mean of crack length in the crack network; *StdvLength*1 is the standard deviation of the crack length during the iterative stage of the crack network and *StdvLength* is the target standard deviation of the crack length; *MOrient*1 is the mean of crack orientation during the iterative stage of the crack network and *MOrient* is the target mean of crack orientation in the crack network; *StdvOrient*1 is the standard deviation of crack orientation of the iterative stage crack network and *StdvOrient* is the target standard deviation of crack orientation of the crack network; *MXmid*1 is the mean of crack midpoint X-coordinate during the iterative stage of the crack network and *MXmid* is the target mean of crack midpoint X-coordinate of the crack network; *StdvXmid*1 is the standard deviation of crack midpoint X-coordinate during the iterative stage of the crack network and *StdvXmid* is the target standard deviation of the crack midpoint X-coordinate of the crack network; *MYmid*1 is the mean of crack midpoint Y-coordinate of the iterative stage crack network and *MYmid* is the target mean of crack midpoint Y-coordinate of the crack network; *StdvYmid*1 is the standard deviation of crack midpoint Y-coordinate during the iterative stage of the crack network and *StdvYmid* is the target standard deviation of crack midpoint Y-coordinate of the crack network. In the crack network generation process, maximum error is selected for each error criterion. All the error criteria should be smaller than or equal to each error criterion.

The R^2 of the frequency distribution plot was calculated after plotting the data in the corresponding distribution plot. The R^2 calculation and distribution plotting, as explained in Montgomery and Runger (2007) was used in this paper. The R^2 was calculated for the following distribution plots:

• Lognormal distribution plot for the crack length.

• Uniform distribution plot for the crack orientation, midpoint X-coordinate, and midpoint Y-coordinate.

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

After the crack network has been generated (Fig. 4), changes in the water content of the intact soil matrix part of the cracked soil models were simulated using numerical analyses. The method of modeling crack as boundary conditions proposed in Krisnanto *et al.* (2016) was used in the numerical analyses. Representative crack aperture (Krisnanto *et al.* 2014) was obtained for all cracks in the cracked soil specimens in Krisnanto *et al.* (2016). In the numerical analysis of the crack soil models, the crack aperture was assigned to each crack according to its crack length rank. The largest crack aperture was assigned to the longest crack.

In this study, point and average water contents were obtained from the numerical analyses. The point water content is the water content at a point location of the intact soil matrix part of the cracked soil model. In the analyses, these point water contents were determined at the same locations as the water content measurements in cracked soil specimens performed by Krisnanto *et al.* (2016). The purpose of these analyses was to observe the effect of crack network variation on water content at the same locations as in the cracked soil specimens used in the laboratory tests. The average water content is the water content of the soil matrix part of the cracked soil model. The averaging technique of the water content for the cracked soil models (Krisnanto *et al.* 2011) was used to obtain the average water content of the intact soil matrix part of the cracked soil. The average water content values were then calculated at several time intervals during the lateral flow. These analyses were performed to observe the effect of crack network variation on the average water content of the intact soil matrix part of cracked soils.

Three crack networks were generated per set of statistical parameters obtained from the cracked soil specimens in Krisnanto *et al.* (2016). As there were two sets of crack statistical parameters and three crack networks were generated based on each set of crack statistical parameters, this combination resulted in a total of six cracked soil models that were analyzed using SVFlux (Soil Vision 2009).

Table 1(a) Summary of the statistical parameters of the crack network of large-scale lateral flow test 1: Mean and standard deviation

Crack Parameter	Mean	Standard Deviation
Length	0.144 m	0.107
Orientation	87.5 deg	52.5
Midpoint X-coordinate	0.528 m	0.267
Midpoint Y-coordinate	0.508 m	0.268

Table 1(b) Summary of the statistical parameters of the crack network of large-scale lateral flow test 1: R^2 of the uniform, normal, and lognormal distributions

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
Midpoint X-coordinate	0.98	0.96	0.90
Midpoint Y-coordinate	0.98	0.96	0.92

Table 2(a) Summary of the statistical parameters of the crack network of large-scale lateral flow test 2: Mean and standard deviation

Crack Parameter	Mean	Standard Deviation
Length	0.121 m	0.093
Orientation	87.3 deg	52.9
Midpoint X-coordinate	0.515 m	0.212
Midpoint Y-coordinate	0.563 m	0.277

Table 2(b) Summary of the statistical parameters of the crack network of large-scale lateral flow test 2: R^2 of the uniform, normal, and lognormal distributions

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
Midpoint X-coordinate	0.98	0.95	0.96
Midpoint Y-coordinate	0.98	0.95	0.81

3. Results and discussion

The statistical parameters of the crack network of large-scale lateral flow tests 1 and 2 specimens performed in Krisnanto *et al.* (2016) are shown in Tables 1 and 2, respectively. Observations of the R^2 values in Tables 1(b) and 2(b) indicate that the largest R^2 values for crack length, crack orientation, and crack midpoint X- and Y-coordinates correspond to the lognormal, uniform, and uniform distributions, respectively. Based on these results, it was concluded that the crack length follows a lognormal distribution, while the crack orientation and crack midpoint X- and Y-coordinates follow a uniform distribution. Therefore, the use of lognormal and uniform distribution in the computer program complies with the length and midpoint X- and Y-coordinates of the actual crack network.

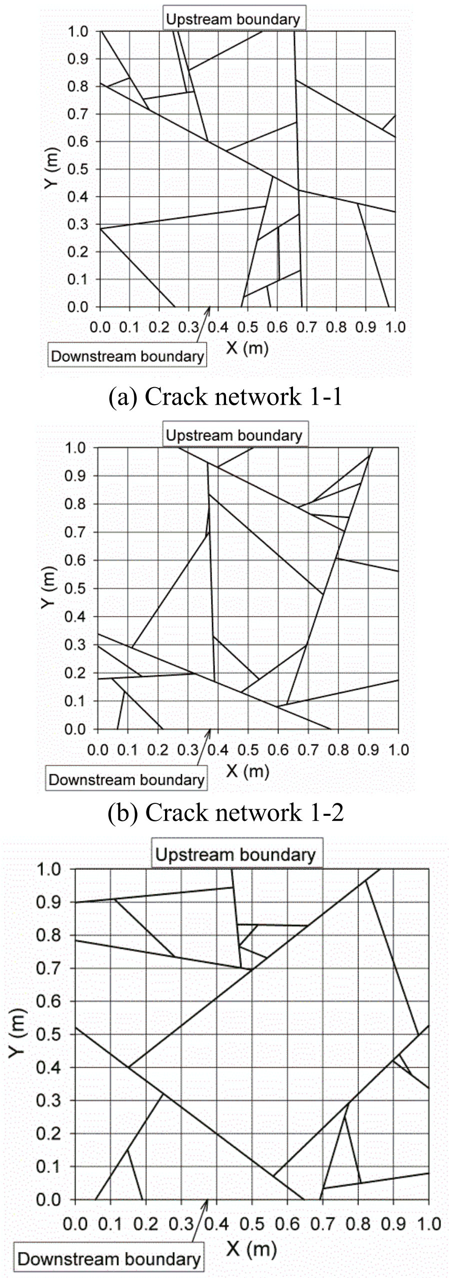
Infinite numbers of crack network could be generated using each set of statistical parameters and Monte Carlo simulation could be used to analyze the effect of crack network on water content of the intact soil matrix part of the cracked soil models. This study serves as a first step in the study of the effect of crack network on water content of the intact soil matrix part of the cracked soil. Three crack networks were generated based on each set of crack statistical parameters in Tables 1 and 2. The behavior of water content was observed for these three crack networks.

The criteria used for crack network generation are shown in Table 3. Figs. 5 and 6 show the crack networks generated from the statistical parameters in Tables 1 and 2, respectively. In Table 3, the error criteria with respect to the standard deviation of the crack statistical crack parameters ($ErrStdvLength$, $ErrStdvOrient$, $ErrStdvXMid$,

Table 3 Criteria for the generation of crack network

Name of crack network:	• Crack network 1-1 • Crack network 1-2 • Crack network 1-3	• Crack network 2-1 • Crack network 2-3 • Crack network 2-3
Source of statistical parameters of the crack network:	Large-scale lateral flow test 1 (Krisnanto *et al.* 2016)	Large-scale lateral flow test 2 (Krisnanto *et al.* 2016)
***ErrNum*:**	2	2
***ErrMLength*:**	0.1	0.1
***ErrStdvLength*:**	0.5	0.5
***ErrMOrient*:**	0.1	0.1
***ErrStdvOrient*:**	1	1
***ErrMXmid*:**	0.1	0.1
***ErrStdvXmid*:**	0.5	0.5
***ErrMYmid*:**	0.1	0.1
***ErrStdvYmid*:**	0.5	0.5
R^2 of crack length:	0.90	0.90
R^2 of crack orientation:	0.95	0.95
R^2 of midpoint X-coordinate:	0.95	0.95
R^2 of midpoint Y-coordinate:	0.95	0.95

ErrStdvYMid) are set higher than the error criteria with respect to the mean of the crack statistical parameters (*ErrMLength*, *ErrMOrient*, *ErrMXMid*, *ErrMYMid*). The algorithm of the proposed method of numerical crack network generation (Fig. 4) places emphasis on achieving the error criteria with respect to the crack statistical parameters (*ErrMLength*, *ErrMOrient*, *ErrMXmid*, *ErrMYmid*). These affect the convergence to achieve the error criteria with respect to the standard deviation of the crack statistical parameters (*ErrStdvLength*, *ErrStdvOrient*, *ErrStdvXmid*, *ErrStdvyYmid*). It is difficult to achieve all the error criteria when all of the error criteria are set to very low values. Tang *et al.* (2008) performed several desiccation tests and measured the mean of the crack length and the standard deviation of the crack length for each desiccation test. Considering the average mean of the crack length of all desiccation tests as *MLength*1 and the crack length of each desiccation test as *MLength*, *ErrMLength* of all desiccation tests are in the range between 0.071 and 0.22 as obtained using Eq. (2). Considering the average standard deviation of the crack length of all desiccation tests as *StdvLength*1 and the standard deviation of crack length of each desiccation test as *MStdvLength*, *ErrStdvLength* of all desiccation tests are in the range between 0.050 to 0.95 as obtained using Eq. (3). Perret *et al.* (1999) performed a 3-D measurement of crack network in undisturbed samples. Considering the average mean of the crack length of all samples as *MLength*1 and the crack length of each sample as *MLength*, *ErrMLength* of all samples are in the range between 0.0048 and 0.17 as obtained using Eq. (2). Considering the average standard deviation of the crack length of all samples as *StdvLength*1 and the standard deviation of each crack length of each sample as *MStdvLength*, *ErrStdvLength* of all the samples are in the range between 0.19 to 0.47 as obtained using Eq. (3). Considering the average mean of the crack orientation of all samples as *MOrient*1 and the crack orientation of each sample as *MOrient*, *ErrMOrient* of all the samples are in the range between 0.03 and 0.13 as obtained using Eq. (4). Considering the average standard deviation of the crack orientation of all samples as *StdvOrientation*1 and the standard deviation of each crack orientation of each sample as *MStdvOrient*, *ErrStdvOrient* of all the samples are in the range between 0.015 to 0.15 obtained using Eq. (5). These

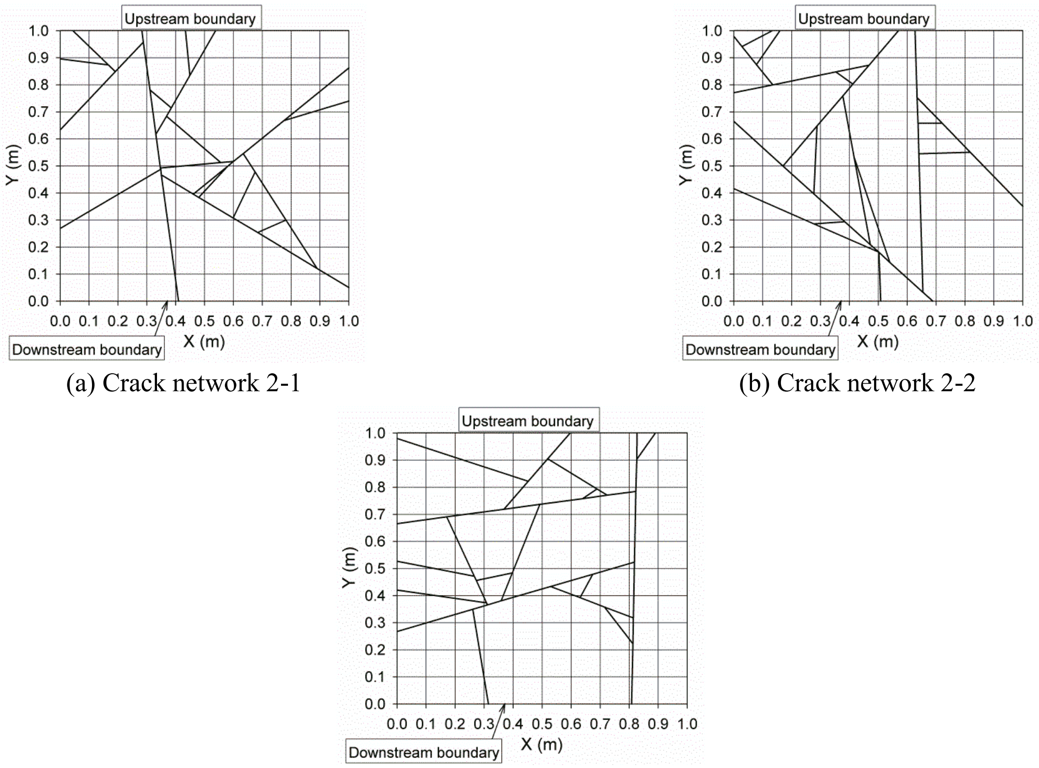


(a) Crack network 1-1

(b) Crack network 1-2

(c) Crack network 1-3

Fig. 5 Crack networks generated numerically from the statistical parameters of the large-scale lateral flow test 1 specimen

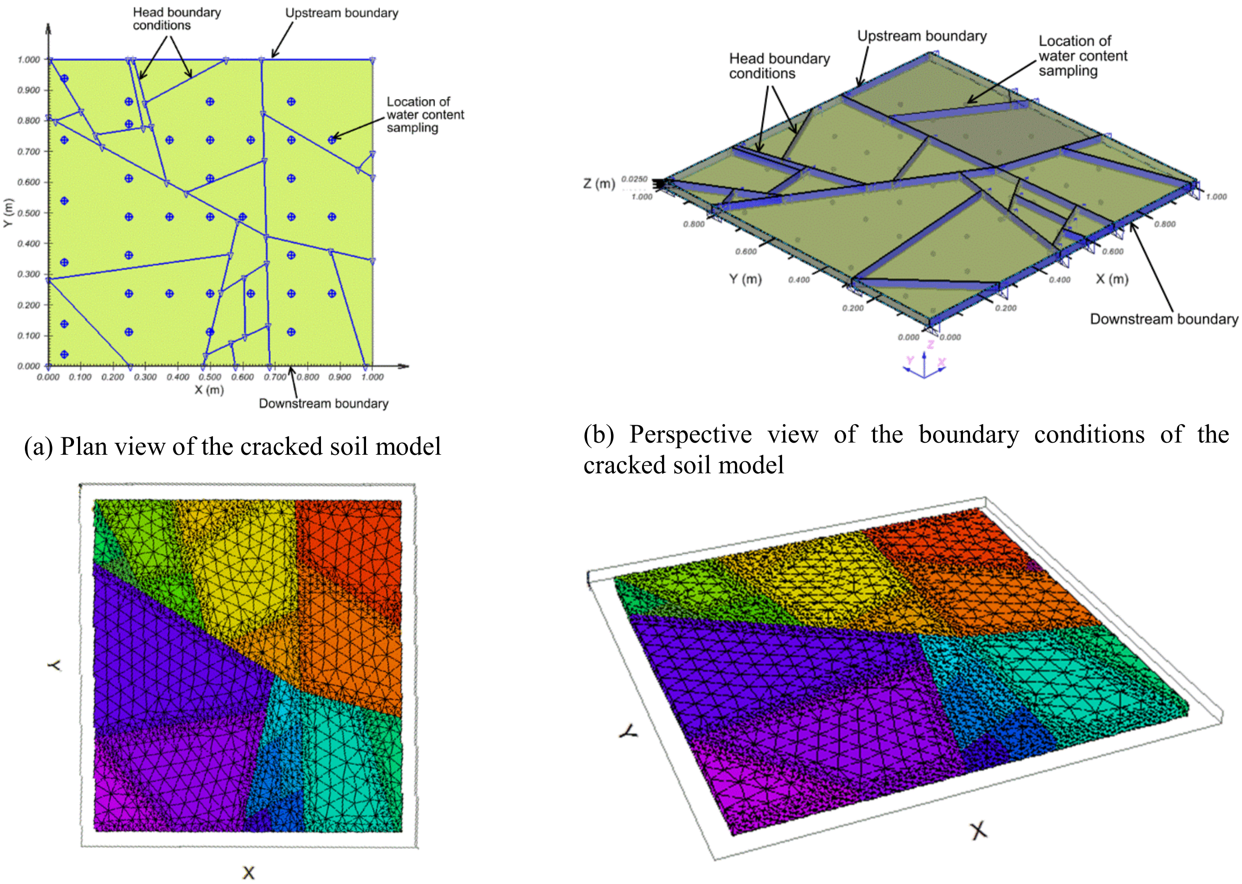


(a) Crack network 2-1

(b) Crack network 2-2

(c) Crack network 2-3

Fig. 6 Crack networks generated numerically from the statistical parameters of the large-scale lateral flow test 2 specimen



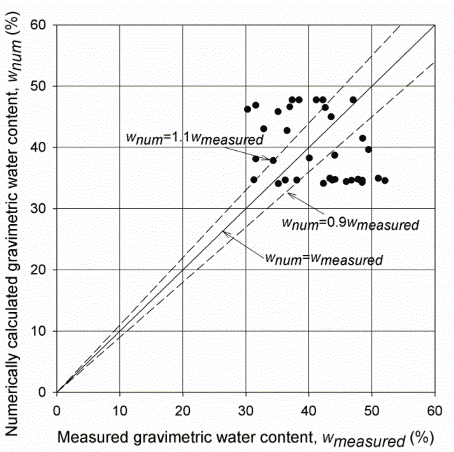
(a) Plan view of the cracked soil model

(b) Perspective view of the boundary conditions of the cracked soil model

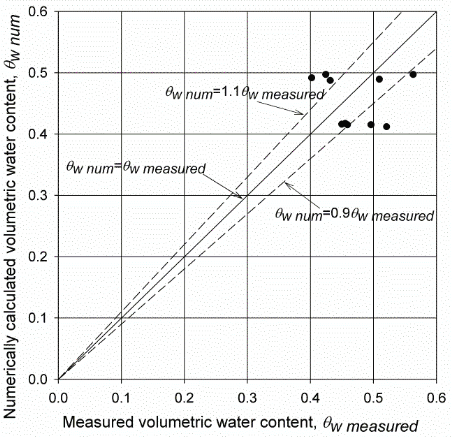
(c) Plan view of the finite element mesh

(d) 3D view of the finite element mesh

Fig. 7 Numerical model incorporating crack network 1-1



(a) Comparison of gravimetric water content



(b) Comparison of volumetric water content

Fig. 8 Comparison of water content values obtained from sampling at various positions within the intact soil matrix part of a cracked soil specimen at the end of large-scale lateral flow test 1 and the water content values obtained from numerical analysis of the cracked soil model incorporating network 1-1

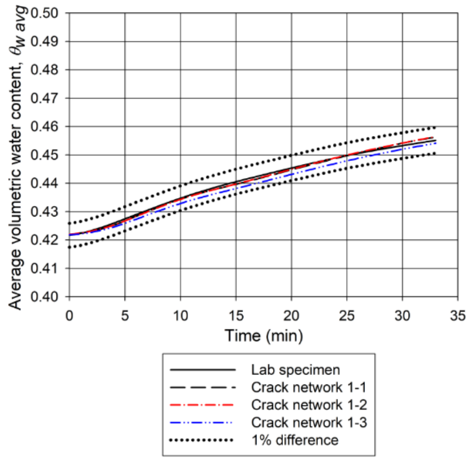


Fig. 9 Comparison of average water content of the intact soil matrix part of the cracked soil models incorporating the crack networks generated numerically from the statistical parameters of the large-scale lateral flow test 1

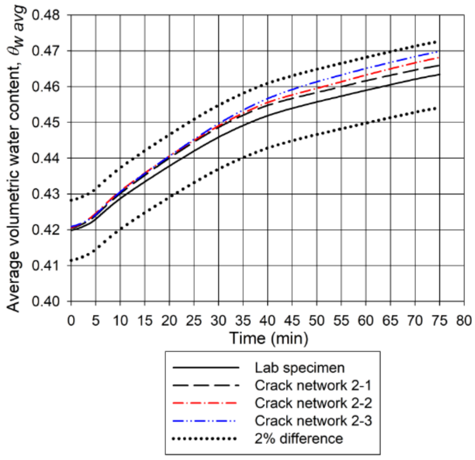


Fig. 10 Comparison of average water content of the intact soil matrix part of the cracked soil models incorporating the crack networks generated numerically from the statistical parameters of the large-scale lateral flow test 2

values indicate that the error criteria used in Table 3 are within the measured values of the actual crack network in cracked soil.

Three numerical models were developed for each set of crack statistical parameters in Tables 1 and 2. The method of modeling the cracks in the soil using boundary conditions, as proposed by Krisnanto *et al.* (2016), was used to develop the numerical model in this study. The use of boundary condition complies with the finding that when a cracked soil was wetted, water seeped laterally into the soil matrix (Chai *et al.* 2015). In addition, Song *et al.* (2018) indicated that the permeability of crack-clay matrix interface was about one order of magnitude higher than that of saturated soil matrix. This means no additional seepage resistance in the crack wall and the use of flow boundary condition in the numerical model is justified. Each crack network in Figs. 5 and 6 was incorporated in each model. An example of a numerical model incorporating crack network 1-1 is shown in Fig. 7.

As there were six numerical models in total, the first stage of the numerical analyses resulted in six sets of results. Fig. 8 provides an example of the first stage results. This figure shows that the point water content values obtained from the numerical analysis are different from the measured water content values. The numerical analyses of the soil models incorporating other crack networks (i.e., Figs. 5(b) and 5(c), 6(a)-6(c)) show similar results. This is quite logical since the distance from one point to the crack wall will differ between the laboratory specimen and the cracked soil model. Krisnanto *et al.* (2016) found that, for an intact soil matrix, a difference in the distance to the cracked wall resulted in different water contents during the wetting process even when the initial water contents were the same. Therefore, the point water content is not adequate to quantify the water content of the intact soil matrix part of the cracked soil because it does not give consistent results among different cracked soil models with the same set of statistical parameters.

In the second stage of numerical analyses, the same models as in the first stage were used to obtain the average water content of the intact soil matrix part of the cracked soil models. The results of the analyses are shown in Figs. 9 and 10. These figures indicate that the variation in the average water content for the intact soil matrix part of cracked soil models with three different crack networks for each set of statistical parameters is relatively small. For large-scale lateral flow test 1, the maximum variation in average water content was within 1% deviation from the average water content of the laboratory specimen. For large- scale lateral flow test 2, the maximum difference in the average water content was within 2% deviation from the average water content of the laboratory specimen. The variation of crack network did not affect the average water content of the intact part of cracked soil. In other words, this small difference indicates the uniqueness of the crack network on the average water content of the intact soil matrix part of cracked soil.

The above discussion illustrates that different crack networks show significant differences in the point water content of the intact soil matrix part of cracked soil. On the other hand, the difference in the average water content of the intact soil matrix part of cracked soil is small. Therefore, the average water content shows a more consistent water content representation of the intact soil matrix part of cracked soil. However, this conclusion is limited to three crack networks generated from one set of crack statistical parameters.

4. Conclusions

- The existing method for the numerical generation of a crack network was improved by incorporating connectivity among cracks.
- Computer program was developed to implement the newly proposed method of crack network generation.
- Using only one set of statistical parameters, different crack networks can be numerically generated.
- Different crack networks generated from the same set of statistical parameters will result in different point water content values at the same location within the intact soil matrix part of cracked soil models. This difference indicated that the method to quantify the water content of cracked soils by obtaining point water values content at several locations in the intact soil matrix part of cracked soils is not adequate.
- The variation in the average water content of the intact soil matrix part of cracked soil models with different crack networks observed in this study was small. This small difference indicated the uniqueness of the crack network on the average water content of the intact soil matrix part of cracked soil.
- The average water content shows a more consistent water content representation of the intact soil matrix part of cracked soil. However, this conclusion is limited to the three crack networks generated from one set of crack statistical parameters.

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GC

Appendix A: Crack propagation part of the computer program

```
* RANDOM X0,Y0 COORDINATES (UNIFORM DIST)
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 (UNIFORM DIST) GENERATION
DO 125 I=5,P
122 CONTINUE

CALL RANDOM(SEEDORIENT01,RANDORIENT0)
*      0DEGREE<=ORIENTATION ANGLE<=180DEGREE
ORIENT0(I)=RANDORIENT0*180
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
*      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
```

Appendix B: Inventory of the crack network part of the computer program

```
* ITERATION OF THE INVENTORY OF THE ITERATIVE
STAGE OF THE CRACK NETWORK

* INVENTORY OF THE CRACK 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
```