Advancement in the Analysis of Seepage through Cracked Soils

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Abstract. Seepage is an important problem analyzed in geotechnical engineering. Conventionally, the analysis is performed in conditions where the soil is intact. The presence of desiccated cracks requires a seepage analysis that considers not only the soil matrix part of the cracked soil but also the crack network. Currently, there are three approaches in the analysis of seepage through cracked soils: (i) analysis by modeling the cracked soil as an intact material with cracks being represented as macropores; (ii) analysis by modeling the cracked soil as a material with a bimodal pore-size distribution; and (iii) analysis by modeling two components of the cracked soil separately: the soil matrix and the crack network. Each approach is reviewed and discussed in this paper. It was found that each approach is suitable for specific cases: (i) the first method is suitable for seepage analysis of cracked soil deep below the ground surface; (ii) the second method is suitable for seepage analysis of cracked soil at the ground surface under a drying process; (iii) the third method is suitable for seepage analysis of cracked soil at the ground surface experiencing rainwater infiltration. Choosing the appropriate method is essential in modeling the appropriate seepage mechanism.

Keywords: *cracked soils; methodology of analysis; numerical model; seepage; unsaturated soils; water content.*

1 Introduction

Seepage is an important problem analyzed in geotechnical engineering. This problem ranges from seepage in slopes due to rainwater infiltration and seepage in agricultural fields to seepage from liquid waste ponds. Conventionally, the analysis is performed in conditions where the soil is intact (e.g. [1,2]).

The presence of cracks changes the flow mode of cracked soil as compared to that of intact soil (e.g. [3]). In cracked soil, water exists in both the soil matrix part and the crack network part. Therefore, the presence of desiccated cracks

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requires a seepage analysis that considers not only the soil matrix part but also the crack network.

Several methods have been proposed to analyze seepage in cracked soils (e.g. [4-22]). The methods differ in their assumptions regarding the quantification of the water flow through the soil matrix part and the crack network. The difference in assumptions leads to a difference in the flow analysis in these two components of cracked soil.

Choosing the appropriate method of analysis is essential. The use of an incorrect method may lead to a wrong analysis, which may endanger geotechnical constructions. Therefore, it is important to understand the working principles and the applicability of each method.

This paper presents a summary of the advancement in methods of analysis of water seepage through cracked soils. A review of the applicability of each method is also discussed in this paper.

2 Review of Methods of Analysis

Bear [4] showed that in terms of permeability, a crack network can be represented by an intact material that has an anisotropy in permeability. An ellipse can be used to quantify the permeability, which varies with respect to direction. Li & Zhang [5] used the works of Bear [4] and Long, *et al.* [6] to represent the ellipse of permeability for crack networks with particular statistical parameters (i.e. crack length, crack orientation, and crack density). The ratio between the long and short axes of the ellipse of permeability represents the anisotropy of permeability of the represented intact material. The larger the ratio between the long and short axes of the ellipse of permeability, the larger the anisotropy of permeability. A crack network with cracks that have two orthogonally predominant orientations results in an ellipse of permeability with a large ratio between the long and short axes. A crack network with cracks that do not have a predominant orientation results in a circle of permeability (a circle can be viewed as an ellipse with the ratio between the long and short axes equal to one). Li, *et al.* [7] computed the representative elementary volume (REV) of a crack network related to the work of Li & Zhang [5].

Huysmans, *et al.* [8] modeled a deep cracked soil as an intact representative material with an equivalent permeability. The permeability of the intact representative material was computed by proportionally averaging the permeability of the intact soil matrix and the permeability of the cracks. Peters & Klavetter [9] analyzed the permeability of a cracked soil and came up with the permeability of the soil matrix part, the permeability of the crack network and combined them as the permeability of the cracked soil. The permeability of the soil matrix and the permeability of the crack network were computed based on their respective pore-size distributions. A method to compute the permeability of the represented material was developed by utilizing the pore-size distribution of the crack, the pore-size distribution of the soil matrix, water compressibility, bulk (matrix and crack) compressibility, and crack compressibility.

Fredlund, *et al.* [10] modeled a cracked soil as a soil with a bimodal pore-size distribution. In the model, with an increase in matric suction, the cracks desaturate first and then the soil matrix desaturates with a further increase in matric suction. The permeability of the cracks was computed using the methods proposed by Kozeny [11] and Carman [12]. A method of superposition was proposed to compute the saturated permeability of cracked soil from the permeability of the saturated intact soil matrix and the permeability of the cracks. The permeability function of cracked soil was then calculated using the method from Irmay [13] utilizing the bimodal SWCC and the saturated permeability of cracked soil. Fredlund & Hung [14] proposed a method of seepage analysis for cracked soils using the permeability of cracked soil computed using a bimodal pore-size distribution.

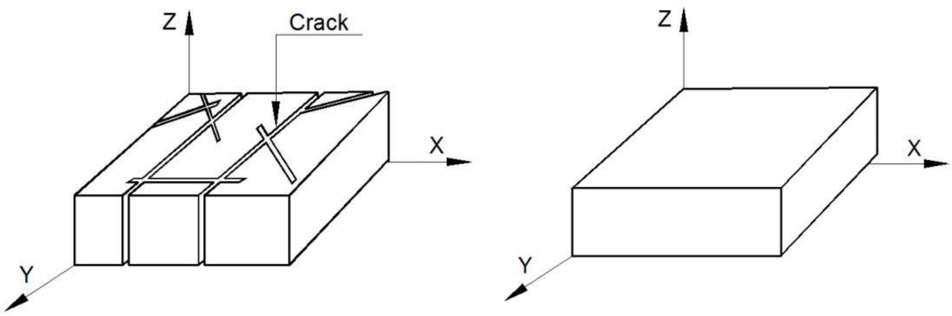
Mitchell and van Genuchten [15] analyzed water flow from cracks to the soil matrix during irrigation. In this method, a lysimeter was used to measure the infiltration rate, evapotranspiration, and volumetric water content of cracked soil in the field. From the change of volumetric water content versus depth at several times of observation it was observed that during infiltration water filled the cracks first and then seeped laterally into the soil matrix. Bronswijk, *et al.* [16] measured the water content of the soil matrix at several locations during water flow through a cracked soil. The water content was measured randomly at several locations in the field. The distance between the point of water content measurement and the crack varied between the points of water content measurement. This resulted in variation of water content at the same time of measurement. The closer the distance between the point of water content measurement and the crack, the higher the measured water content at the same time of measurement. However, no quantification was performed regarding the distance between the point of water content measurement and the crack. Van Dam [17] developed a numerical model to analyze water seepage from a crack network into the soil matrix part of a cracked soil. In the numerical model, water filled the crack first and then seeped laterally into the soil matrix. Zhan, *et al.* [18] performed an extensive *in situ* water content measurement in the soil matrix part of a cracked soil. This study was similar to that performed by Bronswijk, *et al.* [16], but an analysis was performed regarding the distance between the point of water content measurement and the crack. Zhang & Zhang

[19] numerically modeled seepage through a slope with a cracked ground surface using the commercial software Slope/W and Seep/W (Geo-Slope [20]). In the 2D numerical model, cracks were modelled as vertical strips using a sand material SWCC and the permeability function of intact soil matrix and cracks (vertical strips of sand) were incorporated in the numerical model. Krisnanto, *et al.* [21-22] represented the soil matrix and the crack network as two different materials. The crack network was modeled as boundary conditions from where water seeped into the soil matrix. Common to these methods is the treatment of the soil matrix and the crack network as two different materials.

3 Discussions on the Methods of Analysis

From the previous studies, it can be summarized that there are three approaches for the analysis of seepage through cracked soils: (i) analysis by modelling cracked soil as an intact representative material with a unimodal pore-size distribution (the cracks are represented as macropores); (ii) analysis by modeling cracked soil as an intact representative material with a bimodal pore-size distribution; and (iii) analysis by modelling two components in the cracked soil separately: the soil matrix and the crack network. The difference among the methods lies in the manner the soil matrix part and the crack network are modeled.

In the first method, the crack network is considered as macropores and the soil matrix contains micropores and soil solids (e.g. [7-9]). The cracked soil is thus an intact material that contains macropores, micropores and soil solids. The cracked soil (Figure 1(a)) is treated as an intact representative material (Figure 1(b)).



(a) Actual cracked soil

(b) Cracked soil model (intact representative material)

Figure 1 Analysis by modeling cracked soil as an intact representative material.

The soil-water characteristic curve (SWCC) and the permeability function are then developed for this intact representative material. The SWCC and the permeability function take the shape of an SWCC and permeability function of soil with a unimodal pore size distribution (Figure 2).

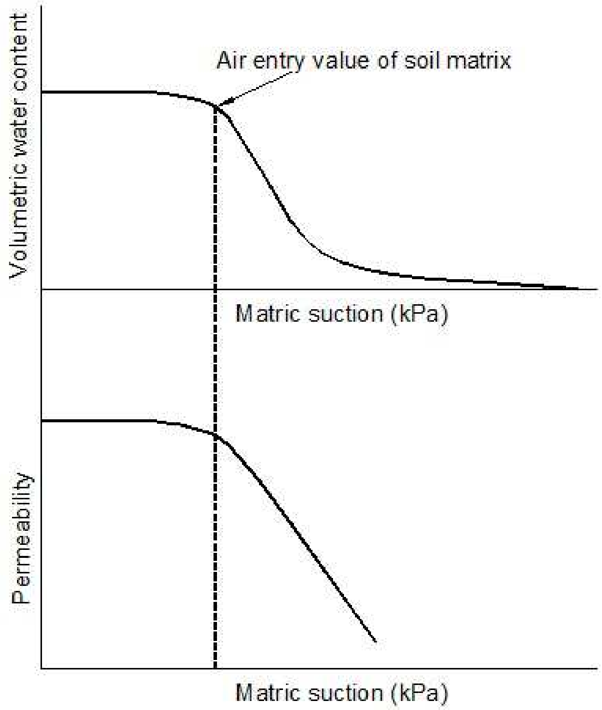


Figure 2 Schematic of SWCC and permeability function of cracked soil considering the cracked soil as a material with a unimodal pore size distribution.

The method of analysis by modeling cracked soil as an intact representative material requires a condition that when the soil is wetted (matric suction is reduced), water enters the small pores first. With a further reduction in matric suction, water enters the larger pores. This is in accordance with the condition of capillary rise explained in Taylor [23], as shown in Figure 3.

The sequence of water entering macropores, as shown in Figure 3, occurs when the cracks are deep below the ground surface, as described by Peters and Klavetter [9] and Miyazaki [24]. In addition, there is no connection of the cracks with open air in the ground surface. In a cracked ground surface, rainwater fills the cracks very rapidly and the sequence of water entering the macropores as shown in Figure 3 does not occur.

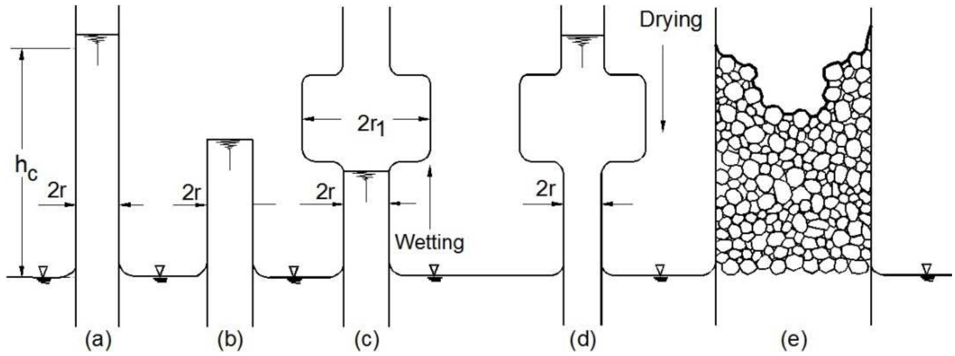


Figure 3 Capillary rise in soil (redrawn from Taylor, [23]).

In the second method, the cracked soil is considered as an intact representative material (Figure 1) with a bimodal pore-size distribution (e.g. [10,14]). During the drying process, the cracks desaturate first, followed by desaturation of the soil matrix. The SWCC and the permeability function take the shape of an SWCC and permeability function for soil with a bimodal pore size distribution, as shown in Figure 4. It also implies that during the wetting process, water first fills micropores in the soil matrix before filling the cracks. Therefore, this method is applicable for the condition of the drying process of a cracked soil and a wetting process where water fills the cracks slowly.

The drying process with cracks being desaturated occurs first in the ground surface, whereas the wetting process by water filling up the cracks slowly occurs deep below the ground surface (e.g. [9,24]). The condition where water fills the cracks very rapidly, as when rain falls onto a cracked ground surface, cannot be modeled by this method.

In the third method, the intact soil matrix and the crack network are analyzed as two different materials (e.g. [15-19,21,22]). Water enters the crack network instantaneously even though the soil matrix has not been completely saturated. Thus, in this condition the soil wetting process follows the sequence as shown in Figure 5. In this condition, the cracks in the cracked soil (Figure 6(a)) can be modeled as head boundary conditions (Figure 6(b)), as in Krisnanto [22].

A cracked ground surface is subjected to rainfall. As rain falls onto the ground surface, water enters the cracks instantaneously even though the soil matrix has not been completely saturated. Thus, the third method is applicable for the ground surface subjected to rainfall.

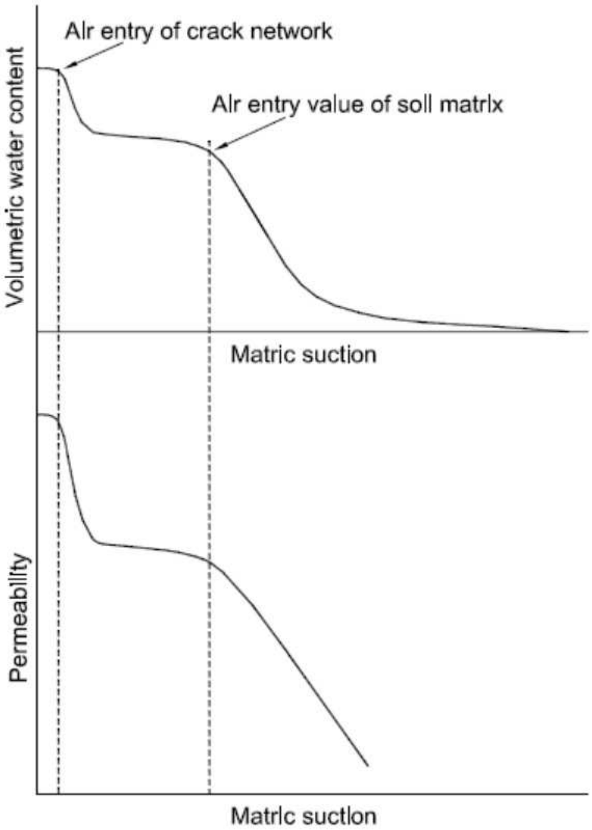


Figure 4 Schematic of the SWCC and permeability function of cracked soil considering the cracked soil as a material with a bimodal pore size distribution.

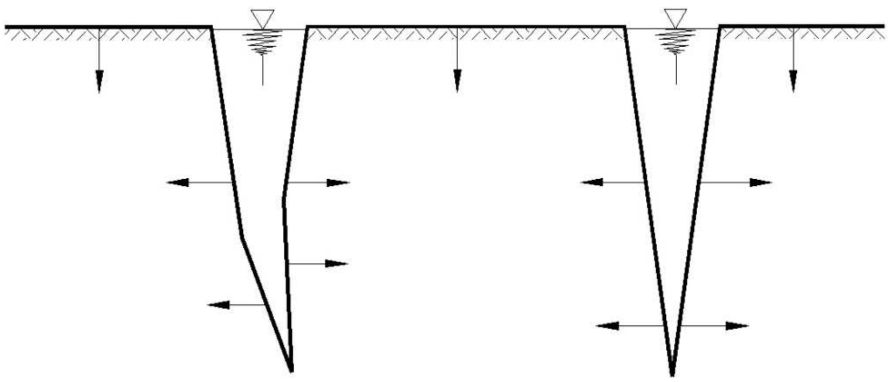
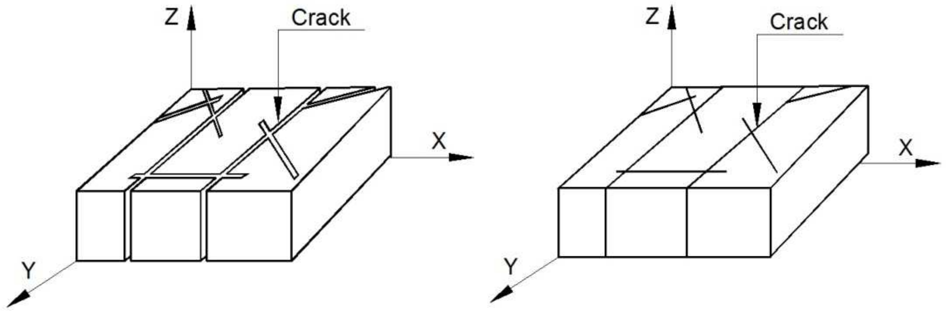


Figure 5 Sequence of water entering the soil during rainwater infiltration.



(a) Actual cracked soil

(b) Cracked soil model (cracks is modeled as head boundary conditions)

Figure 6 Analysis by modelling crack and soil matrix as different materials.

In the condition where the crack network is filled instantaneously with water, the seepage into the soil matrix is analyzed using the saturated-unsaturated unsteady-state seepage equation. For an isotropic soil with respect to the coefficient permeability, the saturated-unsaturated unsteady-state equation can be written as in Eq. (1)[2]:

$$\frac{\partial}{\partial x}\left(k_w \frac{\partial h_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right) = m_2^w \rho_w g \frac{\partial h_w}{\partial t} \tag{1}$$

where $\partial h_w / \partial x$ is the hydraulic head in the x-direction, $\partial h_w / \partial y$, k_w is the coefficient of permeability with respect to the water phase in the x- and y-directions (isotropic soil), m_2^w is the coefficient of water volume change with respect to a change in matric suction, ρ_w is the density of water, g is the gravitational acceleration, t is time.

An example of a plan view of a 3-D numerical model of a laboratory specimen of cracked soil experiencing lateral flow is shown in Figure 7. The third method was used in the analysis (i.e. the water in the crack network was modeled as head boundary conditions). The analysis was performed using the SVFlux software application [25]. The contour of the water content of the numerical model of the laboratory specimen of cracked soil is shown in Figure 8. It is clear that the water content near the crack walls is higher than that at the center of the soil matrix, indicating seepage from the crack walls towards the center of the soil matrix.

Both cracked soil and gravel have macropores, but they behave differently in terms of seepage. The difference is because in gravel macropores and micropores are located randomly, as shown in Figure 9. This is called a single grain structure (e.g. [26,27]). On the other hand, in cracked soil the macropores are connected, forming cracks (Figure 5).

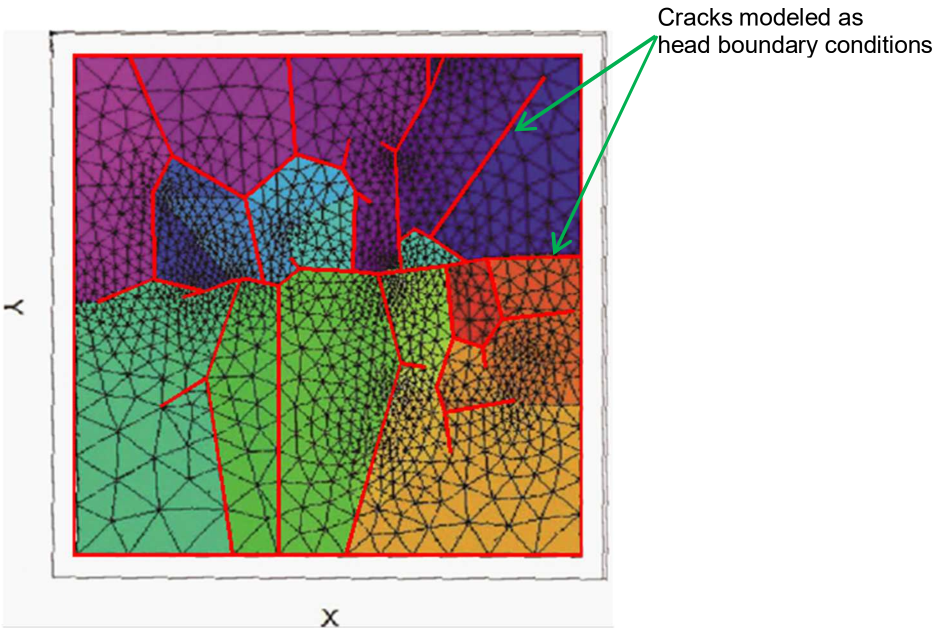


Figure 7 Example of plan view of a 3-D numerical model of a cracked soil specimen after 33 minutes of lateral flow.

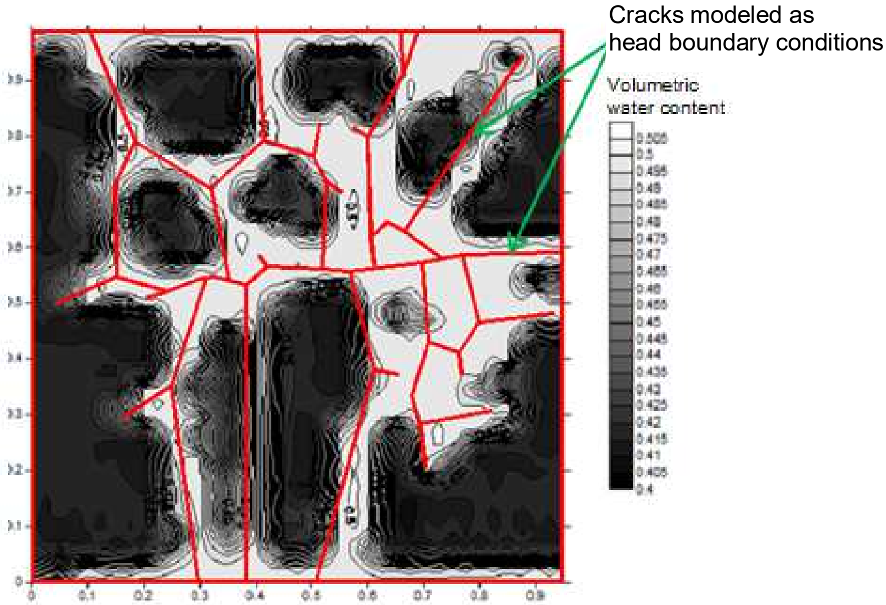


Figure 8 Example of a contour of water content in the numerical model of a cracked soil specimen after 33 minutes of lateral flow.

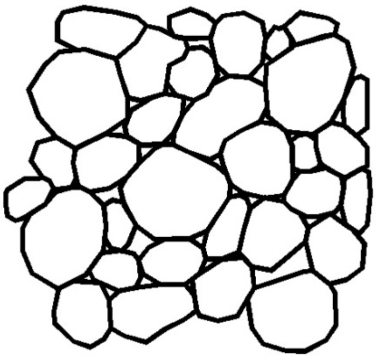


Figure 9 Single grain structure.

4 Conclusions

There are three approaches in the analysis of seepage through cracked soils: (i) analysis by modeling cracked soil as an intact representative material with a unimodal pore size distribution (the cracks are represented as macropores); (ii) analysis by modeling cracked soil as an intact representative material with a bimodal pore-size distribution; and (iii) analysis by modeling two components in cracked soil separately: the soil matrix part and the crack network (the cracks are modeled as head boundary conditions).

The first method is suitable for seepage analysis of cracked soil deep below the ground surface. The second method is suitable for seepage analysis of cracked soil at the ground surface under a drying process. The third method is suitable for seepage analysis of cracked soil at the ground surface experiencing rainwater infiltration.

References

[1] Freeze, R.A. & Cherry, J.A., *Groundwater*, Prentice Hall, Englewood Cliffs, New Jersey, 1979.
[2] Fredlund, D.G. & Rahardjo, H., *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, Inc., New York, 1993.
[3] Inoue, H., *Lateral Water Flow in a Clayey Agricultural Field with Cracks*, Geoderma, **59**, pp. 311-325, 1993.
[4] Bear, J., *Dynamics of Fluid in Porous Media*, Dover Publications, New York, 1972.
[5] Li, J.H. & Zhang, L.M., *Water Flow through Random Crack Network in Saturated Soils*, Geotechnical Special Publication 170, American Society of Civil Engineers, Reston, Virginia, pp. 205-214, 2007.

[6] Long, J.C., Remer, J.S., Wilson, C.R. & Witherspoon, P.A., *Porous Media Equivalents for Networks of Discontinuous Fractures*, Water Resources Research, **18**(3), pp. 645-658, 1982.
[7] Li, J.H., Zhang, L.M. & Fredlund, D.G., *Permeability Tensor and Representative Elementary Volume of Saturated Cracked Soil*, Canadian Geotechnical Journal, **46**(8), pp. 928-942, 2009.
[8] Huysmans, M., Berckmans, A. & Dassargues, A., *Effect of Excavation Induced Fractures on Radionuclide Migration through the Boom Clay (Belgium)*, Applied Clay Science, **33**, pp. 207-218, 2006.
[9] Peters, R.R. & Klavetter, E.A., *A Continuum Model for Water Movement in Unsaturated Fractured Rock Mass*, Water Resources Research, **24**(3), pp. 416-430, 1988.
[10] Fredlund, D.G., Houston, S.L., Nguyen, Q. & Fredlund, M.D., *Moisture Movement through Cracked Clay Soil Profiles*, Geotechnical and Geological Engineering, **28**(6), pp. 865-888, 2010.
[11] Kozeny, J., *Ueber Kapillare Leitung des Wassers im Boden*, Wien Akad. Wiss., **136**, No. 2a, 271 p., 1927.
[12] Carman, P.C., *Permeability of Saturated Sands, Soils and Clays*, J. Agric. Sci., **29**, pp. 262-273, 1939.
[13] Irmay, S., *A Model of Flow of Liquid-Gas Mixtures in Porous Media and Hysteresis of Capillary Potential*, Israel Institute of Technology, Haifa, 1971.
[14] Fredlund, D.G. & Hung, V.Q., *Assessment of Moisture Flux Boundary Conditions for Near-Ground-Surface Geotechnical Engineering Problems*, paper presented at Vietnamese Geotechnical Day, Hanoi, 2010.
[15] Mitchell, A.R. & van Genuchten, M.Th., *Flood Irrigation of a Cracked Soil*, Soil Science America Journal, **57**, pp. 490-497, 1993.
[16] Bronswijk, J.J.B., Hamminga, W. & Oostindie, K., *Field-scale Solute Transport in a Heavy Clay Soil*, Water Resources Research, **31**, pp. 517-526, 1995.
[17] Dam, J.C. van, *Simulation of Field-scale Water Flow and Bromide Transport in a Cracked Clay Soil*, Hydrological Process, **14**, pp. 1101-1117, 2000.
[18] Zhan, L.T., Ng, C.W.W., Bao, C.G., Gong, B.W. & Fredlund, D.G., *Field Study of Rainfall Infiltration into a Grassed Unsaturated Expansive Soil Slope*, Canadian Geotechnical Journal, **44**(4), pp. 392-408, 2007.
[19] Zhang, H. & Zhang, W.W., *Rainfall Infiltration in Cracked Soil and Its Effect on Slope Stability Analysis*, Unsaturated Soils – Buzzi, Fityus & Sheng (eds), pp. 313-318, 2010.
[20] Geo-Slope International, *Slope/W Version 5 for Slope Stability Analysis*, Geo-Slope International, Calgary, Canada, 2002.

[21] Krisnanto, S., Rahardjo, H., Fredlund, D.G. & Leong, E.C., *Mapping of Cracked Soils and Lateral Water Flow Characteristics through a Network of Cracks*, Engineering Geology, **172**, pp. 12-25, 2014.

[22] Krisnanto, S., Rahardjo, H., Fredlund, D.G. & Leong, E.C., *Water Content of Soil Matrix during Lateral Water Flow through Cracked Soil*, Engineering Geology, **210**, pp. 168-179, 2016.

[23] Taylor, D.W., *Fundamentals of Soil Mechanics*, John Wiley, New York, 1948.

[24] Miyazaki, T., *Water Flow in Soils*, 2nd Ed., Taylor and Francis, Boca Raton, 2006.

[25] Soil Vision, *SVFlux, Saturated/Unsaturated Finite Element 2D/3D Seepage Modeling*, 2009.

[26] Harr, M.E., *The Mechanics of Particulate Media*, McGraw Hill, 1977.

[27] Craig, R.F., *Soil Mechanics, Seventh Edition*, Spon Press, 2004.