Determination of the Hydraulic Properties of Unsaturated Soils




Joonyong Lee
Senior Researcher
Korea Institute of Construction Technology
(joonyong.lee@kict.re.kr)

Jean Parks
Geotechnical Engineer
Golder Associate
(jean_parks@golder.com)

John McCartney
Assistant Professor
University of Colorado at Boulder
(john.mccartney@colorado.edu)

Dobroslav Znidarčić
Professor
University of Colorado at Boulder
(Znidarci@colorado.edu)

1. Introduction

The flow of water through unsaturated soils has been under investigation for over 100 years, but it is still an active frontier for research. In geotechnical engineering, there are several areas in which water flow due to soil-atmosphere interactions can have important consequences on the performance of engineered structures. Below are pictures of several examples, including rainfall-induced landslides (Fig. 1), pavement systems (Fig. 2), and alternative cover systems for landfills or mining waste reservoirs (Fig. 3).


Fig. 1 Infiltration triggered slide (McCartney, 2007)

An important challenge in the analysis of water flow through unsaturated soils is that the hydraulic properties of soils governing water flow vary depending on the driving process behind water flow (infiltration, evaporation, seepage). The hydraulic properties of unsaturated soils include the soil-water retention curve (SWRC) and hydraulic conductivity function (HCF) for unsaturated soils. The SWRC is required in analysis to define the driving potential for water flow processes, while the HCF is required in analysis to define the resistance to water flow in unsaturated flow problems.

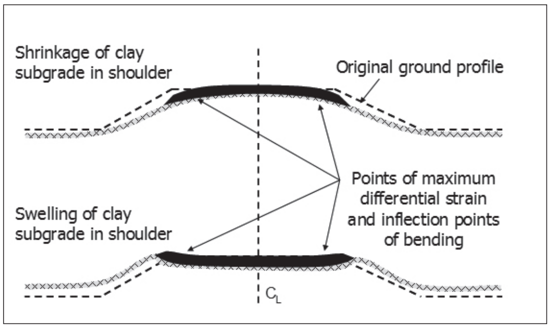


Fig. 2 Volume change in pavement to water flow (McCartney, 2007)

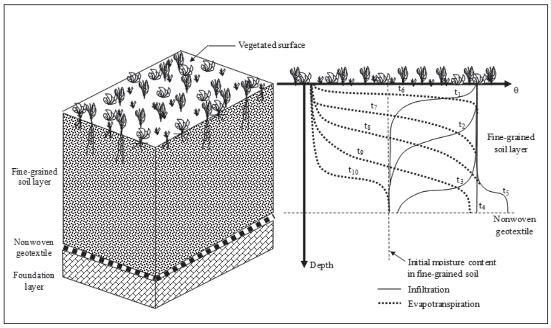
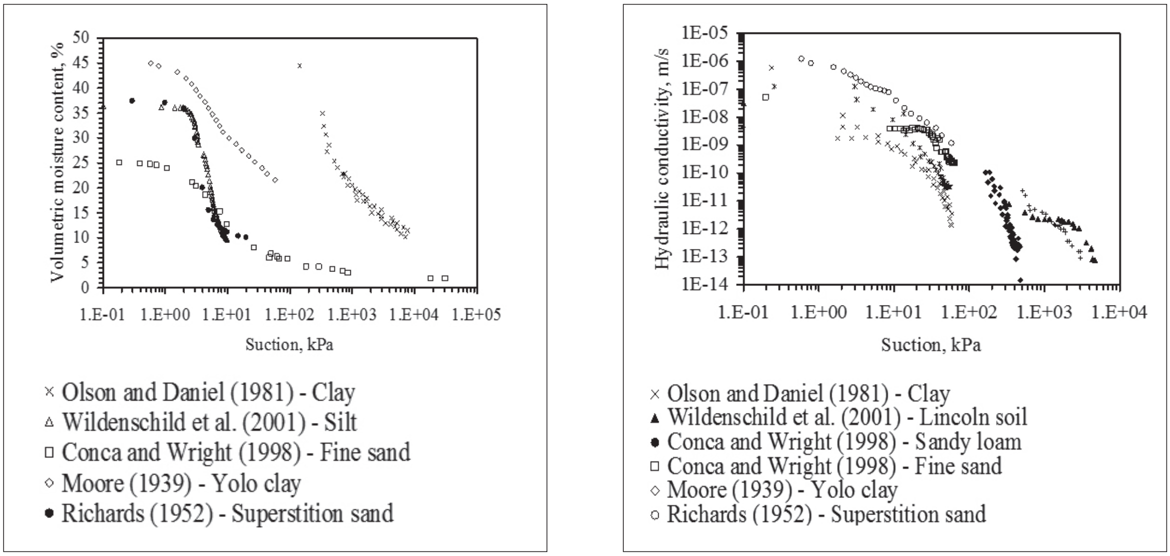


Fig. 3 Moisture content profiles in a capillary break cover (McCartney, 2007)



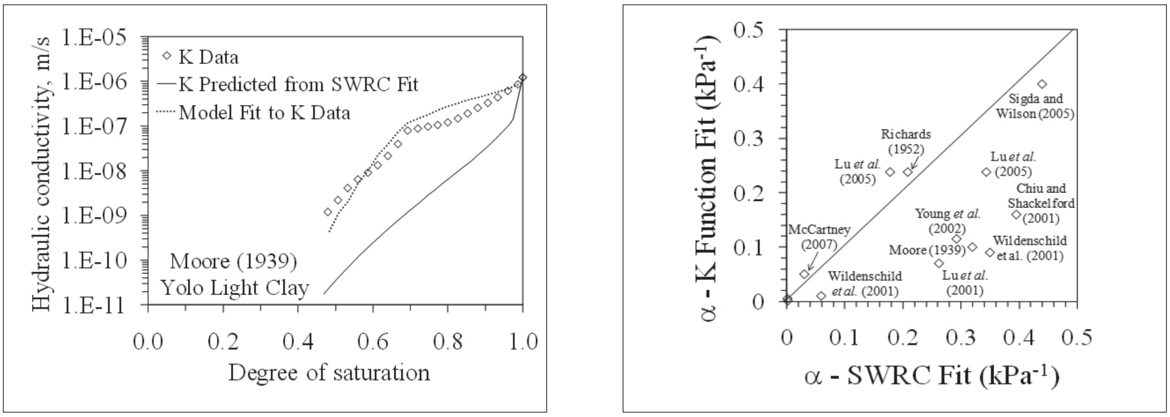
(a) (b)

Fig. 4 Hydraulic properties of unsaturated soils: (a) SWRC; (b) HCF (McCartney, 2007)

SWRC and HCF data for different materials are shown in Figures 4(a) and 4(b), respectively.

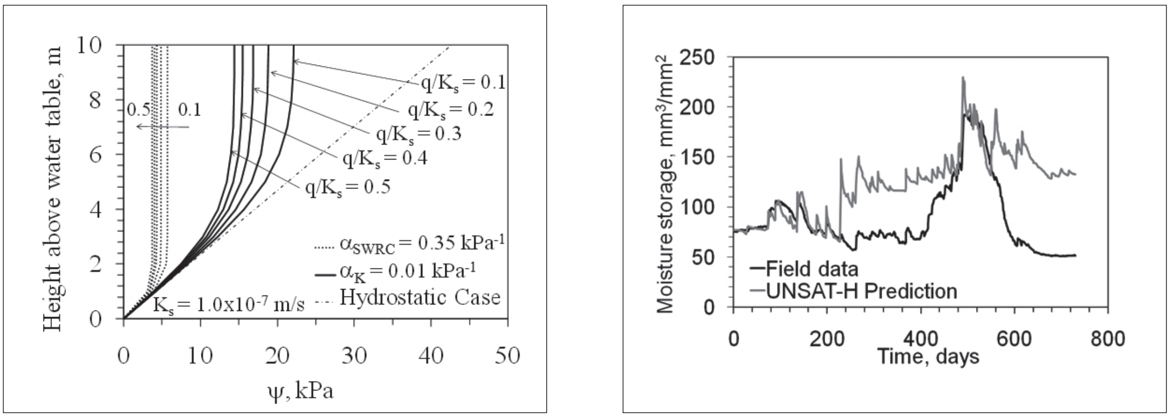
The current approach used by engineers to addressing this challenge is to measure the SWRC over a wide range of water contents (using different water flow mechanisms), and using analytical techniques to predict the HCF.

Although a predictive approach may save time, it may lead to significant errors in the predicted shape of the HCF, as shown in Figure 5(a) below. The solid curve in this figure represents the predicted HCF obtained by fitting a smooth function to the SWRC of this soil and using the parameters of this function in a predictive relationship. An error of hydraulic conductivity of up to two orders of magnitude is noted. This is not unique to this particular soil, but is endemic of this approach. A comparison of a fitting parameter alpha, which represents the shape of the HCF, in Fig 5(b) indicates a significant discrepancy when the value represents a fit directly to the HCF data and when it is



(a) (b)

Fig. 5 (a) Fitted and predicted HCFs; (b) Parameter for fitted and predicted HCFs (McCartney and Parks, 2009)



(a) (b)

Fig. 6 (a) Effect of parameter on suction profiles during infiltration;
(b) Predicted and measured moisture storage of a soil layer over time (McCartney, 2007)

obtained from the SWRC.

The error observed in Figure 5 can have a significant influence on the results of analyses of moisture flow, as shown in Fig. 6(a), which shows moisture profiles for different values of alpha, and 6(b), which shows a comparison between field data and numerical modeling predictions (which employed a predicted HCF). The errors noted in the analysis results can have a significant impact on the decisions made by engineers and policy makers with respect to these engineering systems.

2. Research Objectives

The research team at the University of Colorado at Boulder had formed a set of research objectives geared toward addressing the gap between analysis and hydraulic properties. These include:

1. Development and validation of improved techniques that can be used to accurately and expediently determine the hydraulic properties of unsaturated soils, considering any variables that may impact their shapes.
2. Development of analyses to process the data from these tests to determine the SWRC and HCF.
3. Formulation of analyses that appropriately employ the experimental hydraulic properties to consider water flow through unsaturated soils.

3. Experimental Techniques

Two systems were being used at the University of Colorado to characterize the hydraulic properties of unsaturated soils: These include a centrifuge permeameter and a flexible-wall flow pump permeameter.

3.1. Centrifuge Permeameter

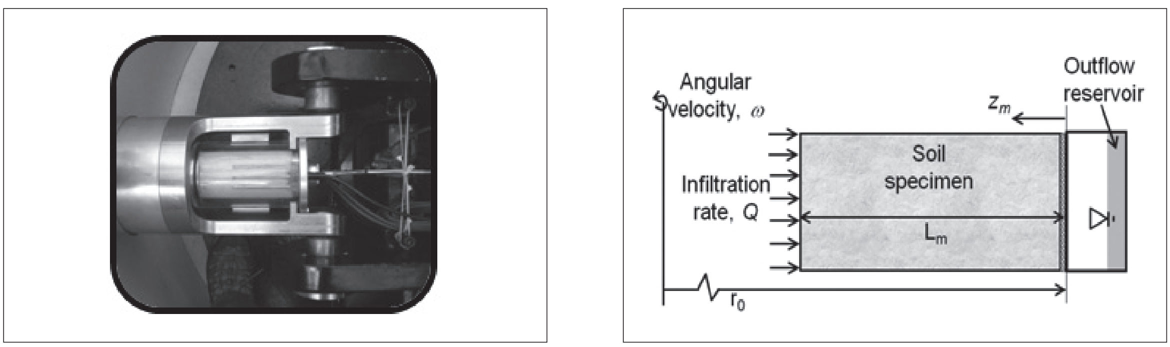
The centrifuge permeameter is suitable for characterization of relatively large-area soil specimens involving steady flow of water. A picture and schematic of the centrifuge permeameter is shown in Figs. 7(a) and 7(b), respectively. The results obtained for the determination of a single point on the SWRC and HCF are shown in Figs. 8(a) through 8(d).

3.2. Flow Pump Permeameter

The flow pump permeameter is suitable for characterization of the flow of water through soil elements where stress state and volume change are of importance. A picture and schematic of the flexible-wall flow pump permeameter are shown in Figs. 9(a) and 9(b), respectively.

The flow pump permeameter technique involves application of controlled flow rates to the soil specimen until the suction in the specimen reaches a target value. The pump is then stopped and the suction is measured. The pump can then be restarted if the suction decreases below the target value. Suction and flow results during hydraulic hysteresis are shown in Fig. 10. The SWRC is then obtained by calculating the volumetric moisture content from the outflow data after a stable suction values has been reached, as shown in Fig. 11.

With the SWRC data from suction-saturation test based on the flow pump technique and optimization



(a) (b)

Fig. 7 Centrifuge permeameter: (a) Picture; (b) Schematic (McCartney, 2007)

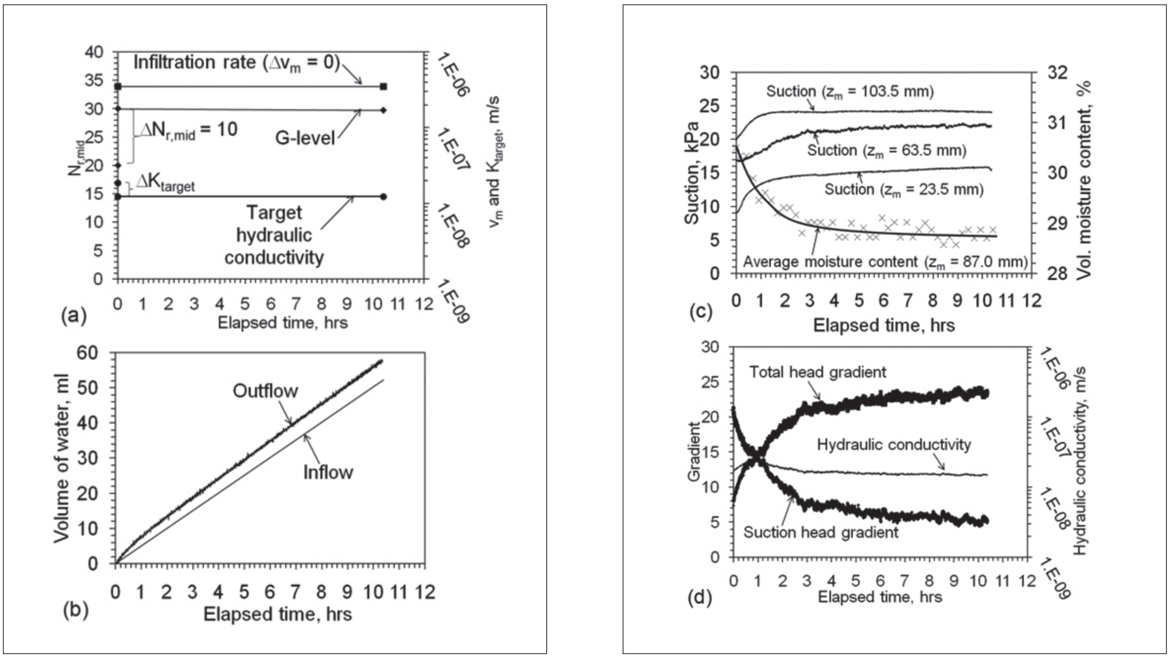
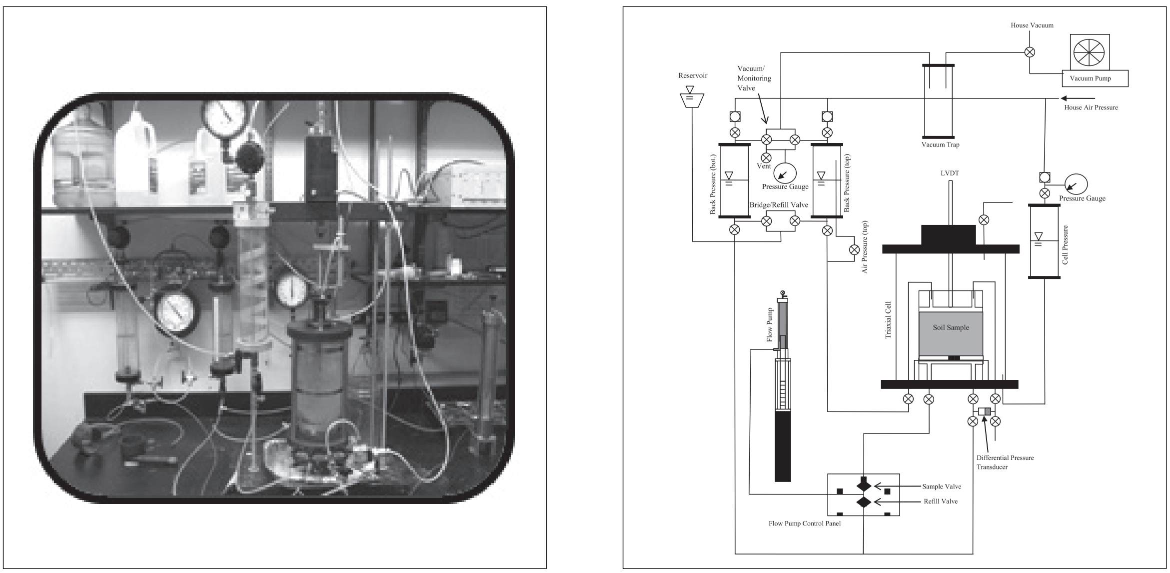


Fig. 8 (a) Target centrifuge speed and infiltration rate; (b) Inflow and outflow; (c) Suction and moisture content during flow; (d) Gradient and hydraulic conductivity (McCartney, 2007)



(a) (b)

Fig. 9 Flow pump permeameter system: (a) Picture; (b) Schematic (Lee, 2011)

technique, the HCF can be obtained using the inverse problem solution technique. Inverse problem solution

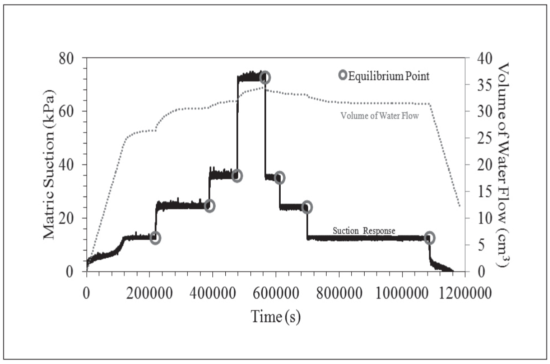


Fig. 10 Suction time series and flow pump outflow (Lee, 2011)

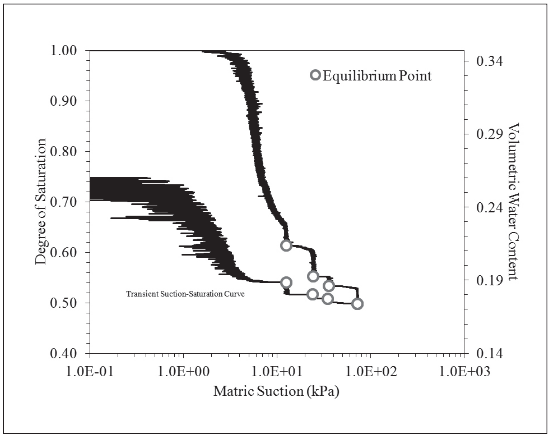


Fig. 11 Synthesized SWRCs for both drying and wetting cycles (Lee, 2011)

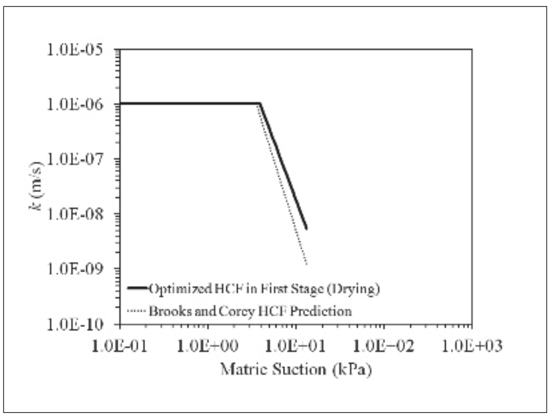


Fig. 12 Predicted and inversely-determined HCF from the flow pump (Lee, 2011)

technique can adjust parameters of HCF for unsaturated flow until the fit between numerical model outputs and test results by flow pump technique is optimized in the weighted least squares sense, with results shown in Fig. 12.

4. Final comments

This research had the goal of better understanding the water flow processes in unsaturated soils systems, primarily by improving the definition of the SWRC and HCF. Advances in laboratory experiments and data analyses were being developed and validated, with the goal of characterizing soil behavior under various water flow velocities to soils ranging from sands and silts to clays.

Reference

1. Brooks, R. H., and Corey, A. T. (1964), "Hydraulic Properties of Porous Media," Colorado State University, Hydrology Paper, 3, March.
2. Lee, J., (2011). "Limits to Continuity of Water Flow in Unsaturated, Compacted Soils," Ph.D. Dissertation, University of Colorado at Boulder, Boulder, Colorado.
3. McCartney, J. S. (2007). "Determination of the Hydraulic Characteristics of Unsaturated Soils using a Centrifuge Permeameter," Ph.D. Thesis, University of Texas at Austin, Austin, Texas.
4. McCartney, J. S and Parks, J. (2009). "Uncertainty in Predicted Hydraulic Conductivity Functions of Unsaturated Soils," 17th ICSMGE Conference, Alexandria, Egypt.
5. McCartney, J. S and Zornberg, J.G. (2010). "Centrifuge Permeameter for Unsaturated Soils I: Theoretical Basis and

Experimental Developments," Journal of Geotechnicaland and Geoenvironnental Engineering, 136(8):1051–1063.

6. McCartney, J. S and Zornberg, J.G. (2010). "Centrifuge Permeameter for Unsaturated Soils II: Measurement of The Hydraulic Characteristics of an Unsaturated Clay," Journal of Geotechnical and Geoenvironnental Engineering, 136(8):1064–1076.

7. Parks, J. M. (2010). "Investigation of Infiltration and Drainage Flow Processes in Unsaturated Soil Using a Centrifuge Permeameter," M.S. Thesis, University of Colorado at Boulder, Boulder, Colorado.

8. Parks, J. M., Stewart, M. A., and McCartney, J. S. (2012). "Validation of a Centrifuge Permeameter for Investigation of Transient Infiltration and Drainage Flow Processes in Unsaturated Soil," Geotechnical Testing Journal, 35(1)

9. Znidarcic, D., Illangasekare, T., and Manna, M. (1991). "Laboratory Testing and Paramter Estimation for Two–Phase Flow Problems." In Mclean et al (ed.) Proc.of the Geotechnical Engineering Congress. Boulder, CO.1991. ASCE, NewYork.