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Using inverse analysis to estimate hydraulic properties of unsaturated sand from one-dimensional outflow experiments

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ABSTRACT

A one-dimensional (1-D) vertical draining test for Jumunjin sand was carried out in one-step and multi-step outflow conditions. An inverse analysis method was conducted to determine the hydraulic properties of unsaturated soil. A non-linear optimization method combining a finite element code and inversion analysis was used to minimize the objective function, defined by the difference between observed and predicted data. Unsaturated hydraulic parameters in van Genuchten model were estimated using soil suction measurements in 10 cm intervals and an outflow rate at the bottom of a sand column. The predicted hydraulic properties and the experimental results were in close agreement when the measurements were compared from the one-step and multi-step outflow experiments. The results also showed that the multi-step outflow experiment was more appropriate in determining the unsaturated hydraulic properties than the one-step outflow experiment. The comparison between predicted and measured results concluded that the inverse analysis based on the 1-D outflow experiment was reliable and useful to determine the hydraulic properties of unsaturated soils.

1. Introduction

The hydraulic properties of saturated and unsaturated soils are very important parameters that determine movement of gas, water and solute in geological systems. These properties govern and affect many fundamental problems of soils such as seepage, slope stability, bearing capacity, consolidation and settlement and water contamination in various fields: geotechnical engineering, environmental engineering, soil science, agricultural engineering, groundwater hydrology, etc. However, obtaining reliable hydraulic properties is still difficult, especially unsaturated hydraulic conductivity and water contents at various suctions. Therefore, reasonable and simple methods to accurately determine the hydraulic properties of unsaturated soils are very necessary and essential. Up until now, many useful hydraulic measurements including direct, indirect, numerical and semi-empirical methods have been developed to assess the hydraulic properties of soils. Since direct measurements are usually time-consuming, expensive and especially difficult to obtain (Klute, 1972; Olson and Daniel, 1981; Hillel, 1982), indirect, semi-empirical measurements or numerical modeling were generally considered effective and widely used (Brooks and Corey, 1964; Green and Corey, 1971; Mualem, 1976; van Genuchten, 1980; Fredlund et al., 1994).

The hydraulic properties of unsaturated soil are represented by two relationships: volumetric water content–soil suction (θ–ψ) and hydraulic conductivity–soil suction (k–ψ). The θ–ψ relationship is called the soil–water characteristic curve (SWCC) in geotechnical engineering or water retention curve (WRC) in agricultural engineering. The SWCC plays an important role in unsaturated soil mechanics because it is directly related to many mechanical properties such as volume change, diffusivity, shear strength functions, adsorption, etc. (Fredlund and Rahardjo, 1993). Numerous studies have described the effective use of SWCC to predict the hydraulic conductivity of unsaturated soils (Gardner, 1958; Brooks and Corey, 1964; Brutsaert, 1966; van Genuchten, 1980; Fredlund and Xing, 1994; Fredlund et al., 2011). The hydraulic conductivity in the k–ψ relationship of unsaturated soils can be displayed as unsaturated hydraulic conductivity (k_u) or relative hydraulic conductivity (k_r), which is expressed as the ratio between unsaturated hydraulic conductivity at a given soil suction and saturated hydraulic conductivity (van Genuchten, 1980; Fredlund et al., 1994; Ruana and Illangasekare, 1999).

In recent decades, one of the most popular experimental methods to measure hydraulic properties of unsaturated soils in the laboratory is a one-dimensional (1-D) column test. Researchers typically use three types of methodologies: one-step outflow experiments (instantaneous application of one large pressure step), multi-step outflow experiments (application of several smaller pressure steps) and continuous flow experiments (application of the smooth continuous change in the pressure gradient) (Schultze and Durner, 1996). These experiments were performed under steady or transient conditions including wetting or drying processes. The hydraulic properties of unsaturated soils were determined from discharge water velocity, evolution of soil suction and water content during the test.

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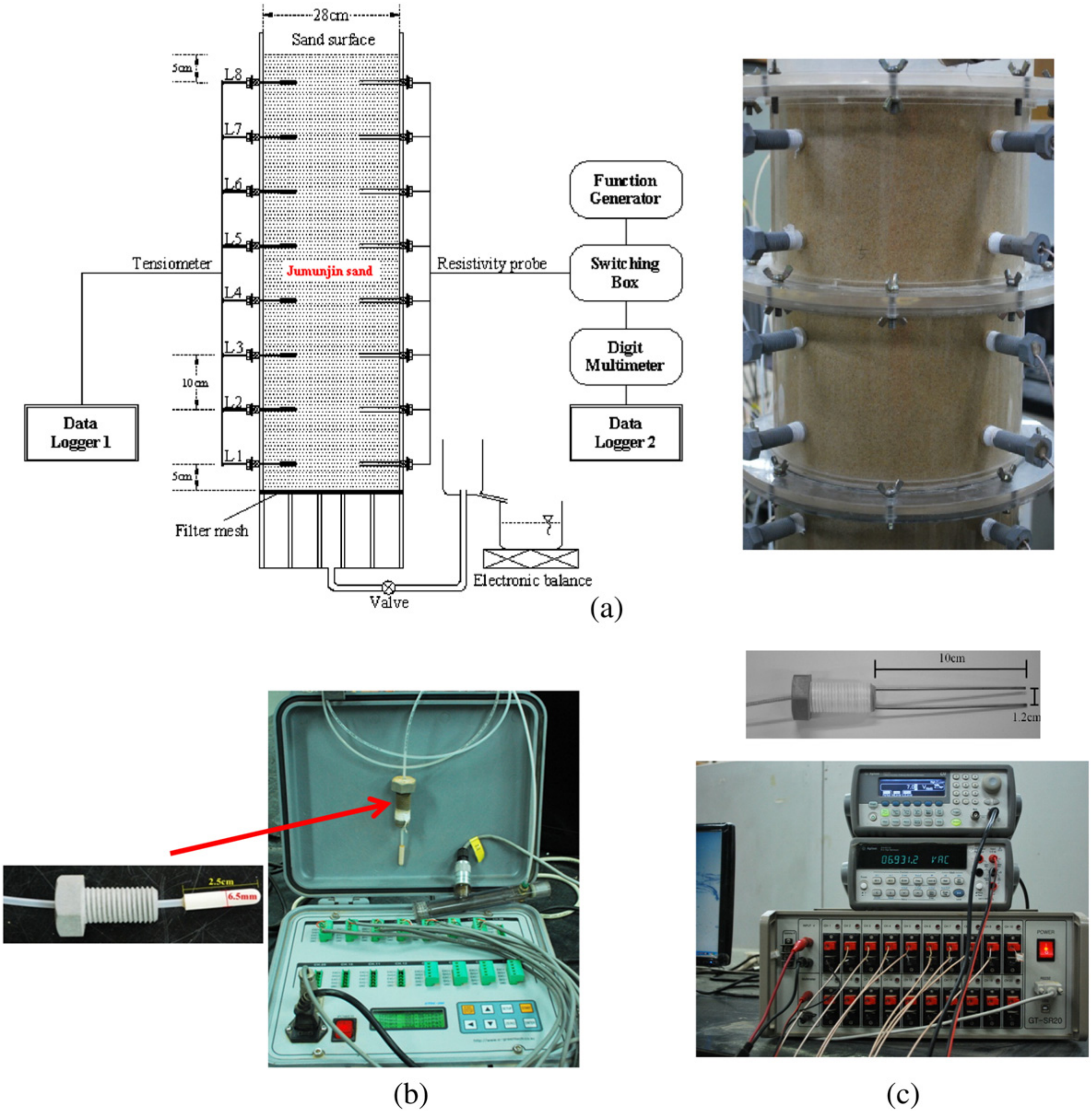

Fig. 1. (a) The schematic diagram of column test, (b) tensiometer equipment, (c) electrical resistivity tester.

Nowadays, numerical methods combined with an optimization code have become promising tools to solve hydraulic problems easily and effectively. With these methods, the unknown parameters of hydraulic properties are estimated by minimizing the difference between the predicted and observed measurements of flow rate, water content and soil suction. The application of the inverse solution technique to one-step outflow experiments was proposed early to estimate hydraulic properties using only cumulative outflow data (Kool et al., 1985a,b; Kool and Parker, 1988).

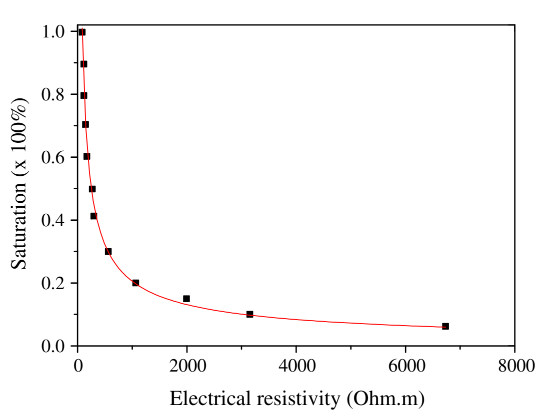

Fig. 2. Calibration relationship between electrical resistivity and saturation for Jumunjin sand.

Since soils are inherently heterogeneous and complex material, inversion analysis for hydraulic properties can lead to non-unique solution (Levasseur et al., 2009). Therefore, to overcome non-uniqueness in inversion analysis, it has been recommended to include additional $\theta(\psi)$ (Hudson et al., 1991; van Dam et al., 1992; Bohne et al., 1993; Simunek et al., 1998), or tensiometer measurements (Toorman et al., 1992; Eching and Hopmans, 1993) in the objective function (Crescimanno and Iovino, 1995). Thus, combination of outflow, volumetric water content and suction over time could be used for the inversion of parameters for SWCC (Durner et al., 1997).

Table 1
Properties of Jumunjin sand.

Sample	G_s	C_u	C_c	D_{50} (mm)	e_{max}	e_{min}
Jumunjin sand	2.66	1.65	0.94	0.55	0.992	0.596