Unsaturated Hydraulic Conductivity of a Silty Sand with the Instantaneous Profile Method

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Abstract. The unsaturated hydraulic conductivity of a silty sand at different initial void ratios is measured using the instantaneous profile method. The variation of the suction and volumetric water content is recorded during the infiltration process as a function of time. Accordingly, an infiltration column was developed with a height of 600 mm and an inner diameter of 170 mm. The suction and volumetric water content were measured simultaneously every 100 mm along the column by means of small tensiometers and TDRs, respectively. Hydraulic conductivity is calculated by dividing the water flow velocity by the hydraulic gradient. The soil is reconstituted from Ruedlingen (Canton Schaffhausen, Switzerland), where landslide triggering experiments were carried out in October 2008 and March 2009. The hydraulic conductivity functions are determined and the laboratory values are compared to the in-situ measurements of hydraulic conductivity carried out in the course of the landslide triggering experiments.

Keywords: hydraulic conductivity, unsaturated soils, instantaneous profile method, landslides, silty sand.

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1 Introduction

Hydraulic conductivity is one of the most important soil properties, which affects the water flow processes such as infiltration and pore pressure redistribution in saturated and unsaturated conditions. A precise evaluation of the hydraulic conductivity is necessary, in order to define the pore pressure distributions for stability analysis of slopes prone to failure due to rainfall.

In order to determine the hydraulic conductivity in unsaturated soils, more complex experimental methods are required than in saturated soils (Muñoz et al. 2008). The hydraulic conductivity of unsaturated soil is a function of variables describing the pores structure (e.g., void ratio or porosity), the pore fluid properties (e.g., density and viscosity), and the relative amount of pore fluid in the system (e.g., water content and degree of saturation). The dependence of the hydraulic conductivity on the pore structures reflects the importance of the sample size and the scale effects in the determination of unsaturated hydraulic conductivity function. The unsaturated hydraulic conductivity function describes the dependence of hydraulic conductivity on the relative amount of pore fluid in the soil structure (Lu & Likos 2004).

The Instantaneous Profile Method (IPM) is a technique that can be used to capture the unsaturated hydraulic conductivity function of soils (Daniel 1982). In this method, the changes of the suction profile within a column of soil are measured as a function of time during the infiltration. The suction measurements can be performed by means of tensiometers or psychrometers, depending on the expected suction range. The water content profile can be determined using the Water Retention Curve (WRC) of the soil and the measured suction profiles. In this paper, the water content is measured directly using TDRs to diminish the uncertainties of the WRC such as the hysteresis and the scale effects.

The primary focus of this work is to derive the unsaturated hydraulic conductivity function of a silty sand soil.

2 Instantaneous Profile Method (IPM)

The experimental method to determine the hydraulic conductivity in unsaturated soil used in this paper is the Instantaneous Profile Method (IPM), (Daniel 1982). According to Darcy's law (Darcy 1856), the hydraulic conductivity k is calculated by dividing the water flow velocity by the hydraulic gradient:

$$k = \frac{v}{i} = \frac{q}{A \cdot i} = \frac{V_w}{\Delta t \cdot A \cdot i} \tag{1}$$

where, k is the hydraulic conductivity (m/s), v is the velocity of water flow (m/s), i is the hydraulic gradient (-), q is the discharge (m^3/s), A is the cross sectional area of the infiltration column (m^2), V_w is the volume of water flowing through a section of the column (m^3), and Δt is the time step. In this formula, the hydraulic gradient between two tensiometers is calculated based on their elevations and the measured pressure heads. The volume of water passing through any cross-sectional area over a given time increment is equal to the change in the volume of water between the considered point j and the top of the specimen (the water flow is from bottom to the top) (Fig. 1).

$$V_w = A.\left(\int_{h_j}^{H} \theta(t_2)dh - \int_{h_j}^{H} \theta(t_1)dh\right) \approx$$
$$\approx \sum_{j}^{5}\left[\left(\frac{\theta_{j+1}(t_2)+\theta_j(t_2)}{2} - \frac{\theta_{j+1}(t_1)+\theta_j(t_1)}{2}\right).(h_{j+1}-h_j)\right] \tag{2}$$

where, $\theta_j(t)$ is the volumetric water content at point j at time t, h_j is the elevation of point j and H is the elevation of the last pair of sensors (H = 50 cm). The IPM is applied to evaluate the variation of the suction and volumetric water content profile within an infiltration column as a function of time during the infiltration process. The suction and volumetric water content measurements are performed by means of 5 sets of tensiometers and small TDRs, respectively. The hydraulic column used in these tests (Fig. 2) is a vertically oriented, rigid-wall cylinder with a height of 60 cm and a diameter of 17 cm. A boundary control port is located at the bottom of the specimen for water injection. Measurement ports for suction (tensiometers) and water content (ECH$_2$O EC-5 Decagons) are located at the same height with 10 cm vertical spacings.

3 Soil Characterisation

The Ruedlingen soil can be classified as medium to low plasticity silty sand according to USCS (Springman et al. 2009). The soil is statically compacted in the infiltration column to the desired unit weight in 12 layers of 5 cm height.

The Water Retention Curves (WRC) at different void ratios for this soil have been determined from suction controlled tests (Casini et al. 2010). The WRCs were also determined during the infiltration tests by using the measured values of suction and water contents at the same time at the same height of the column (IPM water retention curves). The results of both methods are illustrated in Fig. 3. This figure suggests that the average trend line of the suction-controlled WRCs after the air entry value (AEV) is steeper than that of the ones from IPM. This observation can be attributed to the fact that the suction controlled curves have been derived from a one dimensional drainage path in a 6.5 cm-diameter sample, while in the 17 cm-diameter infiltration column there is a tendency towards more local three-dimensional flow within the soil matrix that has led to a higher macro permeability in the cylindrical specimen. Hence, the differential water capacity (c) defined in equation (3) is higher in larger samples than in the smaller ones in the range of low matric suctions

$$c = \frac{d\theta}{ds} \tag{3}$$

where, s is the matric suction.

Askarinejad et al. (2010) also reported similar differences between the small-scale-suction-controlled WRCs and the in-situ WRCs for Ruedlingen soil. This difference may result in slower infiltration predictions from the small-scale-determined WRCs. These observations indicate the need to pay more attention to the effects of scale on soil hydraulic properties (Pachepsky et al. 2001).

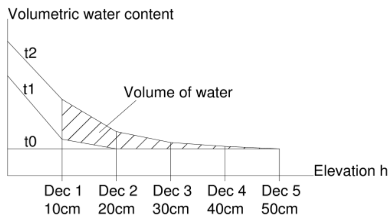

Fig. 1. Schematic of water flow (Beck 2010).

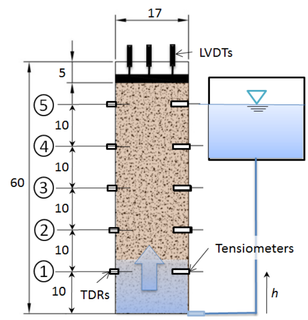

Fig. 2. Infiltration column (dimensions in cm), (after Beck 2010).

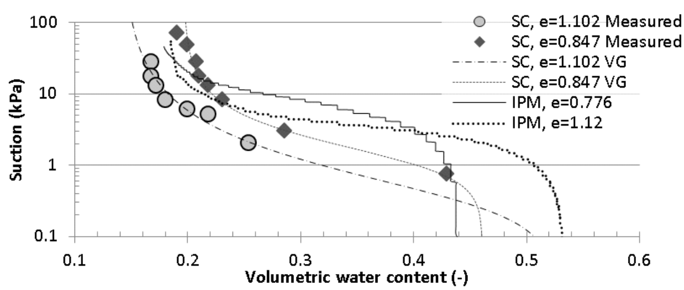

Fig. 3. The water retention curves of Ruedlingen soil, (SC: suction controlled, VG: fitting based on van Genuchten 1980).

4 Hydraulic Conductivity Functions

The hydraulic conductivity functions for different void ratios have been calculated using the IPM water retention curves and the suction controlled (SC) curves. The tensiometers used for the calculations are in all cases: Tensiometer 1 at an elevation of 10 cm and Tensiometer 2 at an elevation of 20 cm from the lowest part of the soil column.

The saturated hydraulic conductivities for two different void ratios are reported in Table 1. Greater differences are seen in values derived from the IPM water retention curves for different void ratios. This can be due to the difference between natural and reconstituted samples, and the scale effect.

The comparison of the hydraulic functions is illustrated in Fig. 4. The results show that the conductivity reaches 10% of the saturated one within the first 10 kPa of suction increase. However, at 30 kPa suction the conductivity is around 1% of the saturated one. The hydraulic conductivities decrease in the region of small suctions (<5 kPa). This observation is made because of the accuracy range of tensiometers. They show the soil suction with an accuracy of $\mp 2\,kPa$ (Beck 2010).

The function derived from the IPM water retention curve for sample with e=0.776 does not show similar trend as the other functions. This can be attributed to the difference in reaction time of the tensiometers and TDRs.

Table 1. The saturated hydraulic conductivity between h=10 and 20 cm.

WRC	e (-)	k_{sat} (m/s)
SC[a]	0.776	2.24 E-06
SC	1.12	2.79 E-06
IPM	0.776	1.35 E-06
IPM	1.12	3.97 E-06

[a] Suction controlled.

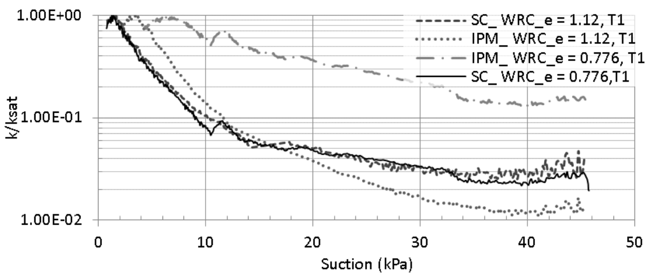

Fig. 4. Comparison of the hydraulic conductivity functions of Ruedlingen soil.

5 Discussion of the Results and Comparison to the in-situ Measurements

The unsaturated hydraulic conductivity functions of Ruedlingen soil were determined from the instantaneous profile method and they showed two orders of magnitude decrease with increasing suction. The saturated conductivity is measured to be about 10^{-6} m/s (Table 1). The in-situ measured hydraulic conductivity using the inverse auger-hole method varies between 10^{-4} to 10^{-5} m/s (Brönnimann et al. 2009). Furthermore, Askarinejad et al. (2010) reported the arrival time of the water front to the tensiometers installed at different depths of the soil profile for the triggering experiment in March 2009 (Table 2). The initial values of suction before the artificial rainfall were below 5 kPa in this experiment. Thus, initial conditions have been assumed to be almost saturated and conductivities have been calculated dividing the depth of the Tensiometer by the time the water front needs to reach the instrument. The differences between the laboratory and in-situ measurements can be explained by the influence of the difference in micro- and macro-porosities in the reconstituted soil and the insitu conditions. For example, rotten roots provide preferential paths for water in the structure of the natural soil matrix.

Table 2. *Saturated* hydraulic conductivities from the in-situ measurements.

Tensiometer depth (cm)	Water front arrival time (s)	k (m/s)
30	3300	9.1 E -05
60	4200	1.4 E-04
120	5700	2.1 E-04
150	12300	1.1 E-04

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