Measuring near-saturated hydraulic conductivity of soils by quasi unit-gradient percolation—2. Application of the methodology

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Abstract

Sarkar et al. (this issue) proposed a laboratory measurement method for obtaining the hydraulic conductivity of soil at near-saturated moisture conditions, bridging the gap between measurements that can be obtained with the evaporation method in the medium dry region, and measurements of the saturated conductivity by traditional methods. The method is based on a tension infiltration on a limited part of the surface of a soil sample and drainage of the sample at the same tension, leading to a divergent flow field. Despite equal tensions at top and bottom of the sample ("unit gradient"), the water flux in the sample is smaller than the corresponding value of the soil hydraulic conductivity at the applied tension. From numerical analysis of the flow problem, they concluded that unsaturated conductivity can be obtained with an accuracy of 10% for all texture classes of the USDA soil texture triangle. In this paper, we test the methodology for three different soil types using an appropriate apparatus. The results match well with independent saturated conductivity measurements on the wet side, and with unsaturated conductivity measurements in the medium moisture range that were obtained with the evaporation method.

Key words: HYPROP® / KSAT® / measurement method / near saturated hydraulic conductivity / saturated hydraulic conductivity / soil hydraulic properties / tension disk infiltrometer / unit-gradient experiment

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1 Introduction

Percolation experiments on soil columns under unit-gradient conditions at various constant suctions are the most straightforward way to measure unsaturated hydraulic conductivity near saturation (*Dirksen*, 1999) and are needed to validate or falsify indirect estimation methods. Due to the experimental difficulty and the non-availability of commercial apparatus, they are, however rarely performed in the lab. The application of water by tension infiltrometry through a porous plate is problematic, if the disk covers the whole surface area of the soil or if it is tightly fitted to the sample's wall, because this does not allow a proper ventilation of the soil, which is needed to replace water by air when the suction is successively increased.

To solve this problem, *Sarkar* et al. (2019) have investigated a variant of the unit-gradient method, in which the area of the tension infiltrometer is reduced as compared to the cross-sectional area of the soil sample. By numerical simulations, they showed that a simple relationship exists between the size of the infiltration disk and the observed steady-state percolation rate through the soil. Furthermore, the simulations showed that for a given disk size, the ratio between percolation rate q in the soil sample and unsaturated conductivity k_u is almost constant for a range of small suctions and only weakly dependent on soil type. Specifically, for a soil sample size as used in the commercial devices KSAT© (METER AG, Munich) and HYPROP© (METER AG, Munich) (5 cm high, 8 cm wide, 250 cm^3), and a diameter of an infiltration disk of 4.5 cm, as used in the commercial Mini Disk Infiltrometer (Decagon Inc., Pullman), they showed that the steady-state flow rate is approximately $f \approx 0.7$ times the unsaturated conductivity at suction heads > 0.5 cm, with a relative error of less than 10%. This allows to calculate unsaturated hydraulic conductivity from a steady-state percolation experiment with the same relative error. For soils with bimodal pore systems and extremely steep falling conductivity in the near-saturated region, this error can increase in the corresponding pressure range up to 40%.

The objective of this study is to develop and test an apparatus that applies the proposed methodology. Along that, we investigate the use of electronic sensors with automated data acquisition to monitor the hydraulic state variables with higher resolution and better accuracy than could be reached by manual readings, and to minimize manual interference to the measuring process.

2 Material and methods

2.1 Materials

Three different soil types from areas near Braunschweig were investigated, namely SAU (pure sand), JKI (sandy loam), and

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GG (silt loam), named after their place of collection Schunteraue, Julius-Kühn-Institute, and Groß Gleidingen, respectively. Undisturbed soil samples of 250 cm^3 were collected in two replicates from approx. 25 cm depth under the soil surface. The soil samples were contained in steel cylinders of 5 cm height and 8 cm diameter. Some basic properties of the soil materials are listed in Tab. 1. After sampling, the undisturbed soil samples were saturated by capillary uptake of tap water for around 24 h. Then, they were placed on a porous disk and partially immersed in water to obtain full saturation.

2.2 Methods

The experimental procedure with the real soil samples consisted of three stages, which will be described in some more detail in the next subsections. The first stage was the measurement of the near-saturated conductivity with the proposed new method. For convenience, we will refer to this as "KuSAT" measurement. To complement the KuSAT results, the same samples were then subject to measurements of the saturated conductivity. Finally, the unsaturated conductivity in the medium dry range was measured with the simplified evaporation method. The results from the second and third stage will help to better assess the results from first stage. All experiments were conducted in the Soil-Physics Laboratory at Technische Universität Braunschweig (Germany) at 20 ± 2°C.

Table 1: Basic soil physical properties of the investigated samples.

Name	Land use	Texture	Bulk density	Organic carbon
SAU	Brownfield	Pure Sand	1.47 g cm^{-3}	0.2%
GG	Agricultural	Silt Loam	1.43 g cm^{-3}	0.9%
JKI	Agricultural	Loamy Sand	1.53 g cm^{-3}	0.7%

2.2.1 KuSAT measurements

The double-membrane percolation was performed with a modified KSAT® (METER Group AG, Munich) device with a tension infiltrometer placed on the top of the soil sample and a reversed flow direction (vertical downward instead of vertical upward) (Fig. 1). The original KSAT device is described in section 2.2.2. Infiltration occurred with the Mini Disk Tension Infiltrometer (Meter Group Inc., Pullman), connected to a large water reservoir. According to the manufacturer, the tension infiltrometer disk is made of sintered stainless steel, 4.5 cm diameter, 3 mm thick, and has a suction range of 0 to 7 cm of suction (*METER Group Inc.*, 2018). At the bottom of the soil sample drainage was enforced through a porous polyethylene disk at a suction equal to the suction applied at top by tension infiltrometer. The bottom suction was obtained by a hanging water column connected to a constant-level outflow reservoir. The applied suctions at the top and at bottom were equal. They were controlled by the height levels of the ventilation tube in the Mariotte bottle (tension infiltrometer) and the height level of the constant-level outflow reservoir (base disk). These height levels were kept fixed during the whole experiment. The suctions could be changed simultaneously by changing the vertical position of the soil sample with respect to the water infiltration and drainage level (Fig. 1).

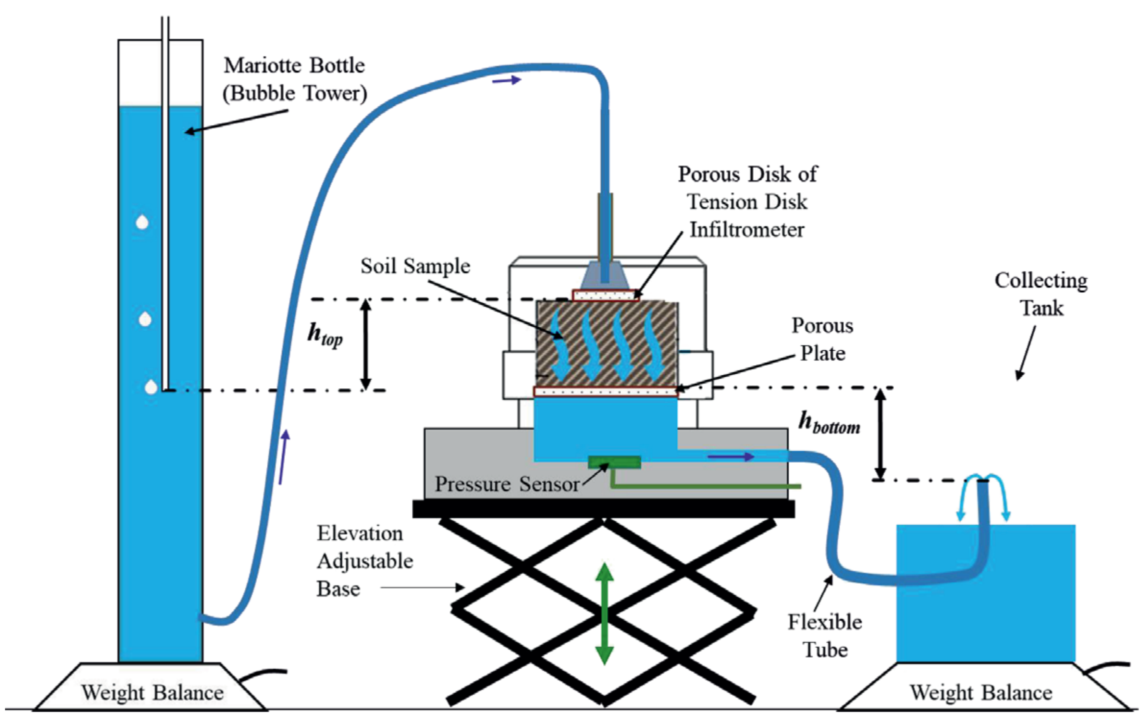

Figure 1: Schematic diagram of experimental set-up for this study, explaining the basic design of the KuSAT device with equal suction head at top and bottom of the soil sample, applied through two porous plates. Water discharge, Q_{out} is calculated from the weight change of the collecting tank and actual suction is measured by the pressure sensor.

The pressure below the bottom plate (and thus the applied drainage suction) was electronically measured with an accuracy of 0.01 cm by the internal pressure transducer of the KSAT device. The outflow was determined from the weight increase over time in a collecting tank that was placed on an electronic balance (accuracy 0.1 g), which was also connected to the PC. Suction heads and the weight increase of the collection tank were recorded digitally in time intervals of 10 s, using the software TensioVIEW (*METER Group AG*, 2017). The experiment started with a suction of h = 0 cm at top and bottom of the soil sample. Then, the suction was increased step by step up to 10 cm, remained there for a while, and was then stepwise reduced back to 0 cm pressure. The length of one step was five minutes which was assumed sufficient from the numerical simulations (*Sarkar* et al., 2019) to allow equilibration to a steady flow state. A typical example of time-varying boundary conditions with four rounds, reflecting two full drainage and imbibition cycles, is shown in Fig. 4.

2.2.2 Saturated hydraulic conductivity measurements

Immediately after the k_u measurements, saturated hydraulic conductivity k_s was determined for each soil sample by the falling-head method, using the original KSAT® device. In short, the sample was demounted from the KuSAT apparatus and placed on a high-permeability porous plate. On top of the sample, a crown was mounted with free overflow of water across its ridge. The water level at the crown acts as constant head outflow boundary. The assembly was then mounted on the KSAT device and fixed with the screw-cap. Water was supplied from a burette with a water level higher than the outlet water level. After opening the connection, water started to flow vertically upward through the sample. The software KSAT VIEW (provided with the KSAT apparatus) continuously records the pressure head data with an accuracy of 0.01 cm and automatically computes the perlocation rate from the recorded pressure head change. K_s is obtained by inverting Darcy's law (*Klute* and *Dirksen*, 1986). Experimental details can be found in the KSAT operating manual (*METER Group AG*, 2016). Figure 2 shows a schematic of the device.

2.2.3 Evaporation method

After measuring the saturated hydraulic conductivity of the soil samples, they were subject to evaporation experiments, using the HYPROP® device (METER Group AG, Munich). Evaporation experiments yield the water retention curve (not of primary interest in this paper) in the range between water saturation and about 1000 cm suction and the hydraulic conductivity curve roughly in the range between 100 cm and 1000 cm suction. The measurement principle is based on the theory first presented by *Wind* (1968), later simplified by *Schindler* (1980) and verified by *Wendroth* et al. (1993) and *Peters* and *Durner* (2008). In essence, two tensiometers are inserted at two depths of a soil sample in a sample ring. The soil surface is kept open to the ambient atmosphere, so that the soil water can evaporate whereas the bottom is closed. The hydraulic gradient is calculated from the difference of the two tensions, and the concurrent evaporative water flux is calculated from the change of the sample mass over time, by repeated weighing of the sample. Using flux rate and gradient in an inversion of Darcy's law yields the hydraulic conductivity data for each measurement time. For quantitative details of the method, the reader is referred to *Peters* and *Durner* (2008) and *Peters* et al. (2015). The data recording and evaluation is automated by the evaluation software HYPROP-FIT (*Pertassek* et al., 2015). The total measuring time of the evaporation method was several days, depending on the soil texture. Figure 3 shows photographs of the KSAT device and three HYPROP measurements.

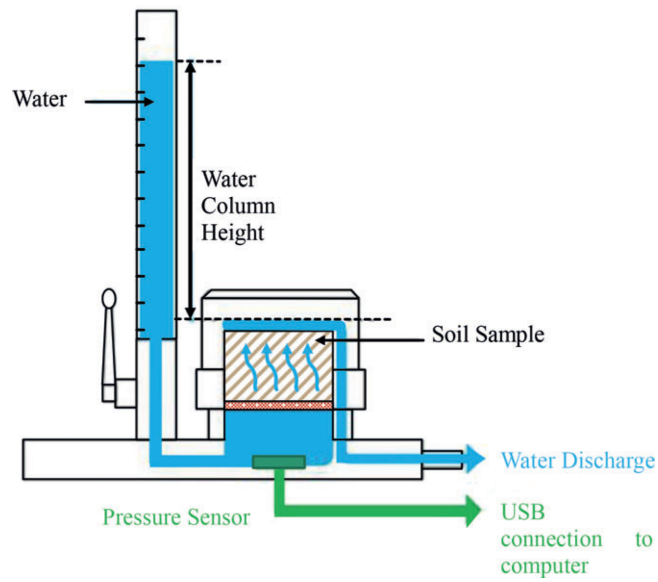

Figure 2: Schematic experimental set-up for KSAT® measurements. Figure by courtesy of METER AG, Munich (modified).

Figure 3: Experimental set-up for KSAT® (top) and HYPROP® (bottom) in the Soil Physics Lab of TU Braunschweig.

3 Results and discussion

3.1 KuSAT and KSAT

The three soil types SAU, JKI and GG were investigated with the KuSAT device in two replicates, each. Each sample underwent three or four cycles of drainage and imbibition with suctions varying from 0 cm to 10 cm and 10 cm to 0 cm again. In all experiments, 1st and 3rd round were drainage branches and 2nd and 4th were wetting branches. Figure 4a shows the boundary pressure head $h(t)$ (blue line) and the cumulative weight of the outflow tank (red line) during two cycles of drainage and imbibition for the first replicate of the soil SAU. The respective data for the other soils and replicates are available in the repository (*Data Repository*, 2018). Additionally, the flow rate $q(t)$ is shown (right part of Fig. 4, green line), calculated from the derivative of the cumulative discharge *vs*. time and normalized to the soil's cross sectional area. In the upper part of the figure (Fig. 4 a, b), a whole experiment with two cycles is shown, the lower part (Fig. 4 c, d) is a magnification of the first drainage cycle. The corresponding results for the soils GG and JKI are given in the data repository (*Data Repository*, 2018).

The decrease of the percolation rate with increasing suction, as illustrated in Fig. 4d, is in agreement with fundamental expectations and our numerical findings (*Sarkar* et al., 2019). Also, we find that the flow rates immediately after a pressure change are qualitatively in agreement with the outflow dynamics predicted by the simulations. However, the time until steady-state conditions are reached appears to be longer in the real experiments, as compared to the numerical analysis. Actually, we do no longer recognize the steady-state flow conditions at the end of the pressure steps, particularly at higher suctions. For the finer soils, this effect is even more pronounced and flow equilibrium is hardly reached, even after providing a relatively long time with constant suction (couple of hours). This observation is in contrast to our numerical findings and indicates "hydraulic non-equilibrium", *i.e.*, a non-uniqueness of the relation between local water content and local pressure head, as discussed by *Diamantopoulos* and *Durner* (2012) and experimentally found in many types of transient flow experiments (*Diamantopoulos* et al., 2015). The effect of hysteresis can also be observed from the graphs of flow rates. As Fig. 4b illustrates, the flow rates at given suctions were always higher in the drainage branches as compared to the wetting branches.

After completing all rounds of experiments in the KuSAT apparatus, each soil sample was transferred to the KSAT device to determine saturated hydraulic conductivity, k_s. For each sample, k_s was measured by the falling head method. The results are listed in Tab. 2.

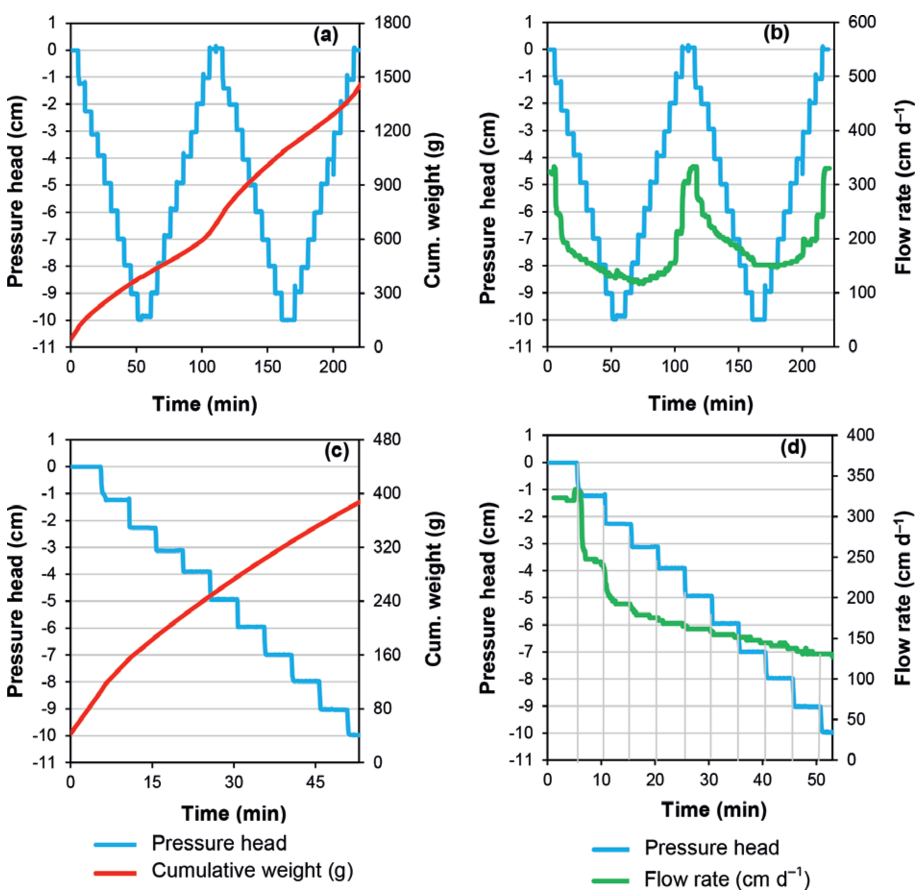

Figure 4: Measurements of cumulative weight of outflowing water and corresponding flow rates with time for a whole experiment (a and b) and only for the first round (c and d) for SAU (sand).

3.2 Combination of KSAT, KUSAT and HYPROP measurements

Figure 5 combines all experimental results that were obtained for the three soil types and the two replicates, showing the calculated conductivity data *vs*. suction. The triangular data points in these figures are obtained from HYPROP, the circular ones are from different rounds of KuSAT experiments, and the diamond ones are from KSAT measurements. The raw data of the evaporation experiments are given as HYPROP-FIT files (format .bhdi) in the data repository (*Data Repository*, 2018). Since the suctions for all three methods range now from full saturation to 1000 cm, we express the suction on a log scale, using the *pF* unit, defined by $pF = log10\ |h|$ with h in cm.

The HYPROP data confirm the main limitation of the evaporation method, specifically its inability to provide data points in the moisture range near saturation. Only when the unsaturated conductivities drop to values in the range of the evaporation rates (≈ 0.3 cm d^{-1}), the hydraulic gradients in the samples

Table 2: Saturated hydraulic conductivity k_s of soil samples.

Soil type	Sample number	k_s (cm d^{-1})
SAU	1	1012
	2	1206
JKI	1	51
	2	38
GG	1	12
	2	1.5

become sufficiently high to calculate k_u values [see *Peters* and *Durner* (2008) for details]. For the three investigated soil types this occurred at approximately $pF = 1.6$ (GG), $pF = 1.8$ (SAU), and $pF = 2.1$ (JKI). The slope of $k(pF)$ at these suctions shows three (JKI, GG) to four (SAU) orders of magnitude change of k_u per pF unit. Since the saturated conductivities are at around 1000 cm d^{-1} (SAU), 60 cm d^{-1} (JKI), and 10 cm d^{-1} (GG), the difference between the KSAT values and the highest HYPROP k_u data is 3.5, 2.0, and 1.5 orders of magnitude, leaving a big gap between k_s and k_u from the evaporation method.

The k_u data from the KuSAT experiments are shown in Fig. 5 as round symbols in four colours (green, blue, brown, red), representing the four rounds in the two consecutive cycles of drainage and imbibition. The depicted values have been obtained by dividing the observed experimental flux rates at the end of each pressure step by $f = 0.7$, as obtained from the numerical simulation study (*Sarkar* et al., 2019). The KuSAT k_u data cover the suction range $pF = 0$ (resp. h = 1 cm) to $pF = 1$ (resp. h = 10 cm). They are all higher than the HYPROP k_u data and fit very nicely into the gap between KSAT and HYPROP data, improving the information about the form of the conductivity function in the near saturated suction range.

Finally, Fig. 5 shows fitted lines (in blue), which have been obtained by fitting a parametric function to the data [bimodal VG-PDI function; see *Pertassek* et al. (2015) and *Peters* et al. (2015) for details], using the HYPROP-FIT software. Parameters of the fitted function can be taken from the .bhdxi files in the supplementary information (*Data Repository*, 2018). Note that only KuSAT data from the first drainage (green circles) have been used to obtain the functions.

None of the investigated samples shows dramatic structure effects, indicated by a decrease of conductivity of less than half an order of magnitude between range $pF = 0$ and $pF = 1$. The absence of structure or macropores was confirmed by a visual inspection of the samples. Hysteresis between k_u data from the drainage branch and the imbibition branch is visible, indicated by a systematic difference in particular between data from the first drainage round and those from the subsequent imbibition branches. However, given the fact that unsa-

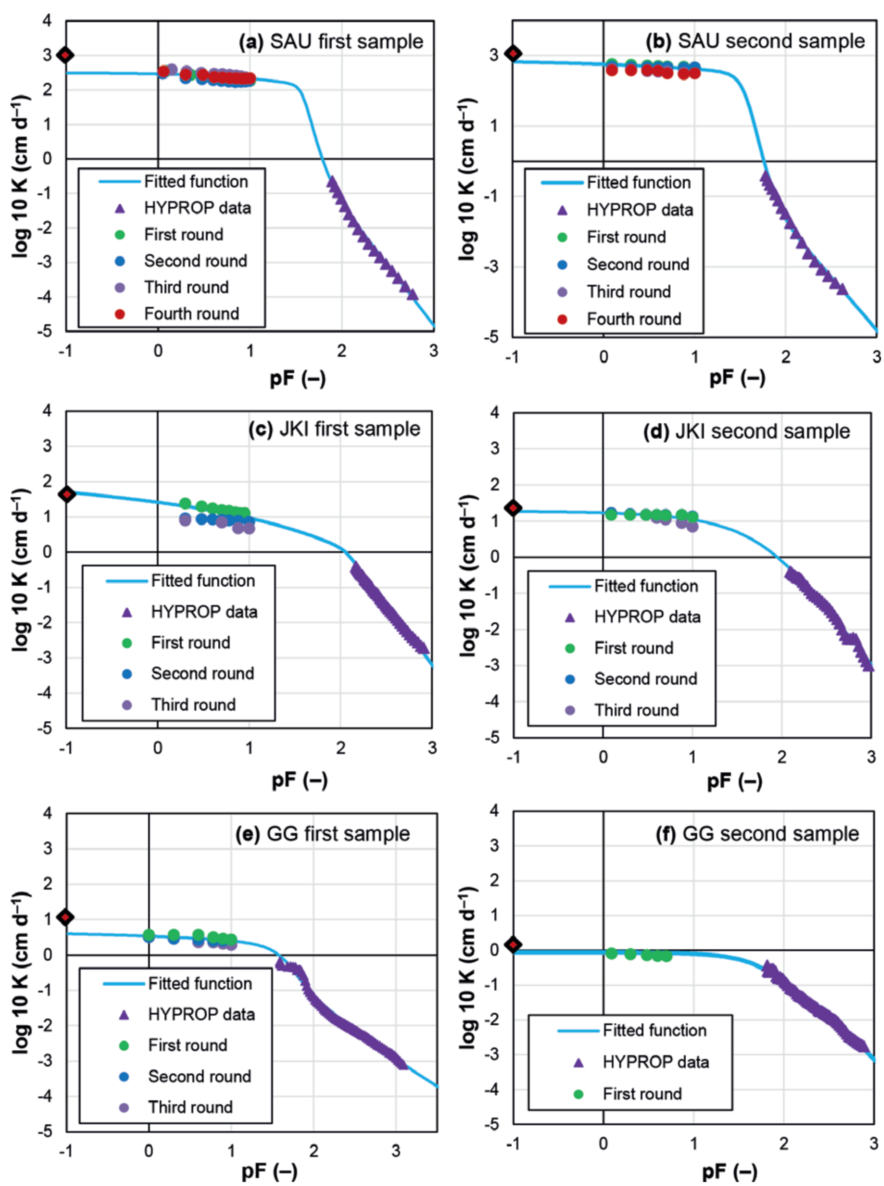

Figure 5: Hydraulic conductivity curves; combined experimental results of KuSAT, KSAT, and HYPROP for each soil sample of SAU (sand), JKI (sandy loam), and GG (silt) for different rounds of experiments. The diamond points indicate saturated hydraulic conductivity k_s of the respective soil sample, obtained from KSAT measurements. Note that k_s is was not included in the fitting of the k_u function.

turated conductivity functions vary over many orders of magnitude, the hysteresis effect appears to be rather small.

4 Conclusions

From real experiments with six soil samples of three different soil textures, we found that k_u values determined with the proposed KuSAT method matched well to the saturated conductivity k_s that was obtained by the falling head method and to unsaturated conductivity data that were obtained with the evaporation method. We thus conclude that the proposed method is valid and the used device is a suitable tool to determine the conductivity function in the very wet range by direct measurement.

We also like to mention some drawbacks, which should not be concealed. The total experimental time to reach the consecutive sequence of steady-state flux conditions was very time consuming, particularly for the fine soils with low conductivity. Furthermore, the time to reach the constant steady-state percolation at each suction step was longer than expected from numerical simulations. Even after providing a long measurement time at a given suction step, the observed flow rate did not reach steady state in some cases. We relate this to "dynamic non-equilibrium" (*Weller* et al., 2011; *Diamantopoulos* and *Durner*, 2012) in water flow and see a need for further research in this respect. Associated with a long measurement time, considerable amounts of water may be needed for percolation, which either requires large vessels for water supply and drainage water, or frequent and quick refills, which disturb the measurement process. Also, despite the use of electronic data acquisition, the manual work of preparing the measurements and waiting for equilibrium steady-state conditions before changing the suction step-by-step is still laborious.

Still, we could show that the method bridges the gap between the results for saturated conditions and results in the medium dry range from the evaporation method. The uncertainty about the shape of the hydraulic conductivity function in the important range between saturation and medium dry conditions is thus greatly reduced.

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