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Determination of wetting soil water characteristics curve from disk infiltrometer measurements

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Abstract. A wetting soil water characteristic curve ($SWCC_w$) is necessary for understanding and interpreting the re-distribution of infiltrated rainwater, percolation rate, and contaminant transport. Direct determination of $SWCC_w$ is tedious and needs destructive sampling and invasive sensor installation. This study demonstrates an indirect method for determining $SWCC_w$ based on infiltration measurements using a mini disc infiltrometer (MDI). Under controlled initial conditions, infiltration tests were conducted, coupled with real-time soil moisture and matric potential measurements using sensors. Sensor data facilitated assessment and cross-verification of $SWCC_w$ indirectly determined from MDI measurements. The indirect estimation involved inverse analysis and optimization of $SWCC_w$ parameters (α and n of the van Genuchten model) based on measured cumulative infiltration (CI) -versus-time response along with the knowledge of final volumetric water content (VWC_f). The optimized $SWCC_w$ from MDI-infiltration matched the sensor-measured $SWCC_w$ reasonably well. The statistical tests using ANOVA proved that the CI measurements from MDI, together with VWC_f information, are reliable input for inverse estimation of $SWCC_w$ and its parameters. Based on a realistic wetting process in the unsaturated zone beneath the disc infiltrometer, this study demonstrates the utility of a compact MDI for a quick, non-destructive measurement of $SWCC_w$.

1 Introduction

The relationship between soil moisture and matric potential, designated as the soil-water characteristics curve (SWCC), is crucial for studying unsaturated soil behaviour. The SWCC relation that corresponds to a wetting process (e.g., infiltration, capillary rise) is known as the wetting soil water characteristic curve ($SWCC_w$). The knowledge of $SWCC_w$ is central for analysing the flow processes pertaining to infiltration of rainwater, irrigated water, seepage loss, slope stability, and deformation in soils [1, 2]. In addition, the $SWCC_w$ are essential inputs for modelling the transport of solutes, chemicals, and contaminants in the unsaturated zone.

It should be noted that the direct determination of $SWCC_w$ is a time-consuming process. Additionally, it involves intrusive sensor installation and destructive sampling. Moreover, the soil moisture and matric potential sensors must be installed carefully; otherwise, the wetting process may not be recorded adequately. To overcome these limitations, an indirect approach is presented in this study for estimating $SWCC_w$ based on the infiltration measurements from a compact and portable disc infiltrometer called the mini disc infiltrometer (MDI) (manufactured by METER Group, USA). An inherent relationship is stated to exist between $SWCC_w$ and soil infiltration characteristics [3]. With the help of this study, a non-intrusive and rapid method for measurements of $SWCC_w$, based on MDI infiltration measurements, is demonstrated. The method used in this study is simple and can be applied to both laboratory and in-situ soils.

2 Methodology

MDI is a miniature version of the tension disc infiltrometer with a disc diameter of 4.5 cm, a total height of 32.7 cm, and a variable suction range of 0.5 to 7cm [4]. The compact features and small size of the device allow to use it conveniently for laboratory scale infiltration studies, unlike larger diameter disc infiltrometers. Moreover, the suction provision in the device permits a slow, regulated entry of water into the soil, thus, enabling a gradual wetting process. Such gradual wetting can be easily captured using soil moisture and matric potential sensors to generate $SWCC_w$.

A flow chart of the methodology used in this study is provided in Figure 1. It involves conducting infiltration tests using MDI in soil columns pre-installed with sensors. While MDI allows tracking of the infiltration process on the surface level, the re-distribution of infiltrated water is tracked with the help of the sensors installed at a certain depth. From MDI infiltration tests, the cumulative infiltration measurements (CI) and final volumetric water content (VWC_f) after termination of the experiments are recorded. These measurements are analysed using

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inverse modelling and optimization techniques to generate the $SWCC_w$ and corresponding van Genuchten retention parameters, α and n [5]. The accuracy of the modelled results is verified using statistical analysis by comparing them with the directly measured results from sensors.

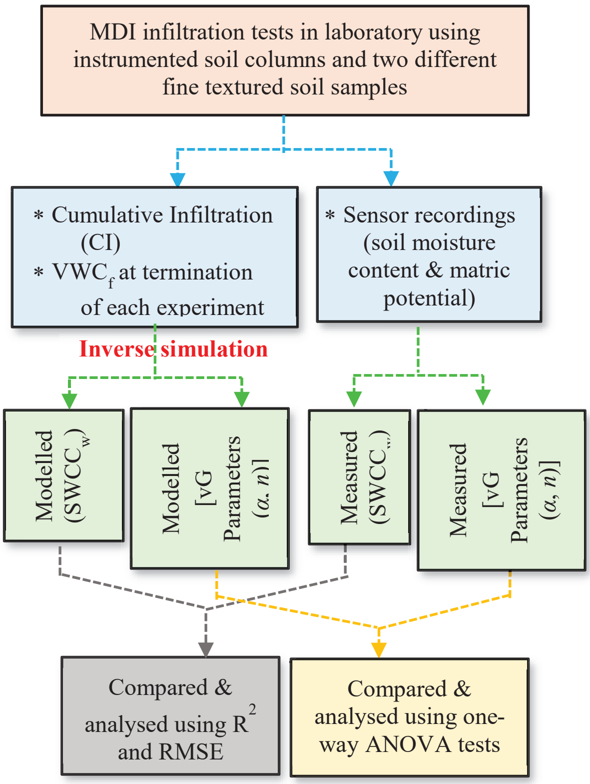

Fig. 1. Flowchart of the methodology used in this study

2.1 Laboratory tests

The factors affecting the infiltration characteristics of a soil (e.g., initial soil moisture, soil density, pore structure, and heterogeneity) may also influence its measured $SWCC_w$ and retention parameters. To avoid the influence of such factors on the analysis of $SWCC_w$, laboratory tests in this study were conducted using homogenous soil samples and regulated initial conditions. Two different soil samples (S-1 and S-2) (locally available) were collected in sufficient quantity and cleaned for the presence of debris, dead leaves, and plant roots. The soils were oven-dried for 24 hours to remove any extra water and then kept open to the atmosphere to allow hygroscopic water absorption. These steps were taken to maintain uniform initial moisture conditions for all the measurements. Both the soils were fine textured, with S-1 being cohesive and S-2 non-cohesive. Using standard procedures [6], S-1 and S-2 were characterized for grain size distribution (% sand, silt, clay). The particle size analysis results were 37% sand, 44% silt, and 19% clay for S-1 and 32% sand, 62% silt, and 6% clay for S-2. Based on the USDA soil classification system, S-1 and S-2 were classified as loam and silt loam textures, respectively.

Figure 2 shows a schematic illustration of the laboratory experimental set-up used in this study. Cylindrical columns with diameter of 0.3 m and volume of 0.017 m^3 were used. The soil columns were carefully filled to maintain uniform and homogenous soil conditions. The initial soil moisture (VWC_i) and compaction density were maintained closely uniform for all the measurements and repetitions. One 5TM sensor (for soil moisture recording) and one TEROS 21 sensor (for soil matric potential recording) (manufactured by METER Group, USA) were installed diagonally opposite to each other (oriented horizontally) at a depth of 5 cm from the surface of the soil column. The sensors were kept logged to dataloggers and computers for continuous monitoring of changes in soil moisture and matric potential during the wetting front migration from MDI infiltration. For each soil, five repetitions of MDI infiltration tests were conducted. From each of these experiments, measured-$SWCC_w$ were generated. Each $SWCC_w$ was then fitted to the van Genuchten retention model [5] to determine measured-α and n parameters (refer Figure 1).

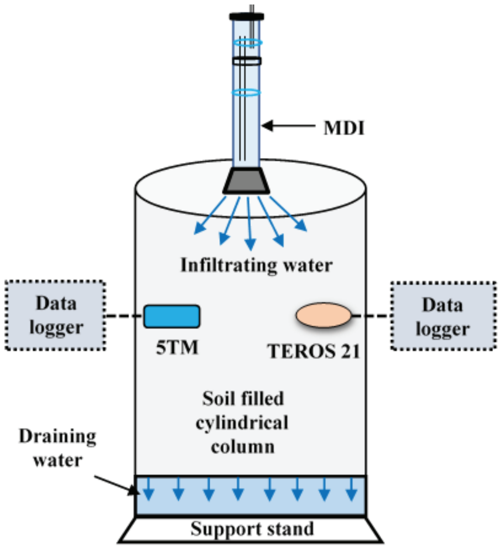

Fig. 2. Schematic diagram of laboratory experimental set-up

2.2 Numerical modelling

The measured CI data and VWC_f (Figure 1) from each experiment are used as input to determine $SWCC_w$ and van Genuchten-α and n using the numerical inversion technique. The inverse simulations (IS) were carried out using HYDRUS software [7] by solving the Richards flow equation given by [8] and van Genuchten-Mualem [5, 9] soil hydraulic conductivity model. The inverse parameter optimization involves minimizing an objective function that calculates the difference between the measured and modelled parameters. The details about the equations involved and optimization techniques are provided in the literature [3, 10].

To simulate the wetting process, a 2-D axisymmetric domain was designed. The radius was kept equal to 0.15m, and the height was kept depending on the depth of soil filled inside the cylinder. The initial conditions (IC) and boundary conditions (BC) were maintained similar to that of the laboratory experiments. The VWC_i

data measured before the start of each experiment were used as IC. The BCs were kept as free drainage at the bottom boundary and no flow conditions on the side boundaries. At the top, a constant head (= 0.06 m) condition was used at the location where MDI was placed, and the remaining portion was kept as no flow BC [11]. The values of the various parameters in the van Genuchten-Mualem model (e.g. saturated and residual soil moisture content, saturated hydraulic conductivity) during IS were taken from the literature [12] based on soil texture. The same values are readily available in the HYDRUS software, and the values of parameters α and n are also provided in MDI's user manual. For each experiment, multiple runs of IS were carried out by slightly varying the initial α and n. This was done till the optimized α and n converged to nearly the same values [10, 11]. The optimized and measured- α and n from five repetitions of each soil were then compared using statistical tests (one-way ANOVA). Similarly, the modelled and measured CI and $SWCC_w$ were evaluated for accuracy using the coefficient of determination (R^2) and root mean squared error (RMSE) values.

3 Results and discussion

3.1 Comparison of infiltration and $SWCC_w$ measurements

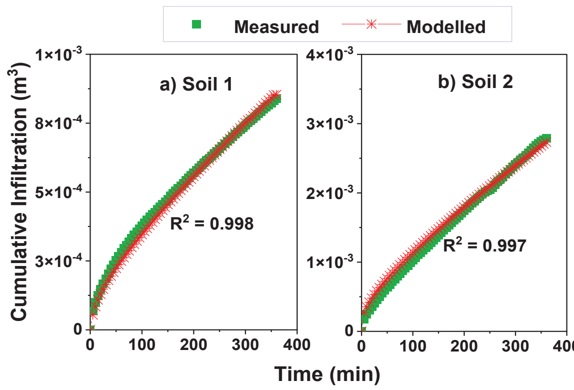

Fig. 3. Comparison of measured and modelled cumulative infiltration measurements for soils (a) S-l and (b) S-2

Figure 3a and b present the comparison between the measured and modelled CI response obtained from a single experiment of S-1 and S-2, respectively. The measured CI were obtained directly from MDI, and the modelled results were obtained from IS of MDI measurements. As seen from the figure, both modelled and measured results showed an excellent match, with R^2=0.998 for S-1 and 0.997 for S-2. The calculated RMSE were less, with the values being 1.99 × 10^{-5} m^3 for S-1 and 8.41 × 10^{-5} m^3 for S-2. Similar matching between the measured and modelled CI response (evaluated by high R^2 and low RMSE) was also observed in the case of other repetitions for both soil textures. For all these experiments, the modelled and measured $SWCC_w$ (refer Figure 1) were also assessed for similarity with the help of R^2 and RMSE. A plot showing the comparison between the two $SWCC_w$ measurements from a single experiment is given in Figure 4. As seen in the figure, the modelled $SWCC_w$ determined from IS of MDI-infiltration measurements were highly comparable with the sensor-recorded $SWCC_w$ for both soil textures. For the remaining four repetitions of each soil, the results were similar and, therefore, not provided for the sake of conciseness. It was noted that for all the cases, the R^2 values were > 0.95, and RMSE was > 1.0 × 10^{-3} m^3/m^3. These observations show that CI measurements from MDI, along with VWC_f information, were successfully able to produce accurate $SWCC_w$ results using the inverse optimization technique.

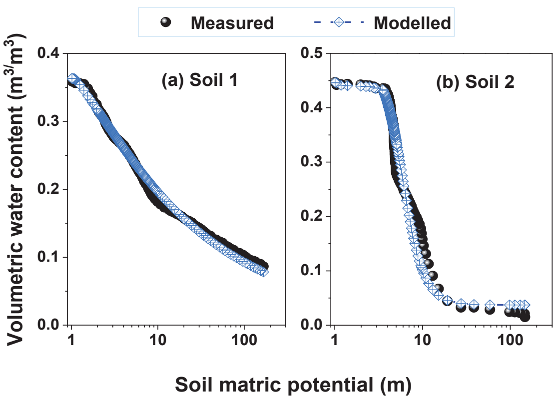

Fig. 4. Comparison between measured and modelled $SWCC_w$ for the two soils (a) S-l and (b) S-2

3.2 Comparison of van Genuchten retention parameters

The optimized/modelled $SWCC_w$ parameters (α and n) from all the repetitions of MDI measurements were also checked for accuracy by comparing them with the corresponding measured α and n (obtained by fitting the van Genuchten model to sensor-measured $SWCC_w$). Statistical analysis of the modelled and measured α and n for both soils were carried out with the help of one-way ANOVA tests. The results showed that the significance value (p) was > 0.05 in all four cases, as listed in Table 1. This implied that the difference between the group means was statistically insignificant or the modelled parameters matched fairly well with the measured parameters in all those cases.

Table 1. List of p-values from ANOVA tests obtained between the modelled and measured parameters for the two soils

Modelled versus Measured	
	***p*-value**
S-1-α	0.22
S-1-n	0.98
S-2-α	0.81
S-2-n	0.90

For further comparison, the mean (± standard deviation) values of α and n are calculated from the five repetitions of each soil. The calculated mean α and n for the measured and modelled parameters, along with their corresponding standard deviations (as error bars), are presented in Figure 5. A comparison between the measured and modelled parameters is also plotted in Figure 6. A 1:1 line and deviations of ± 10% and 25% are additionally provided for a better comparison of the results.

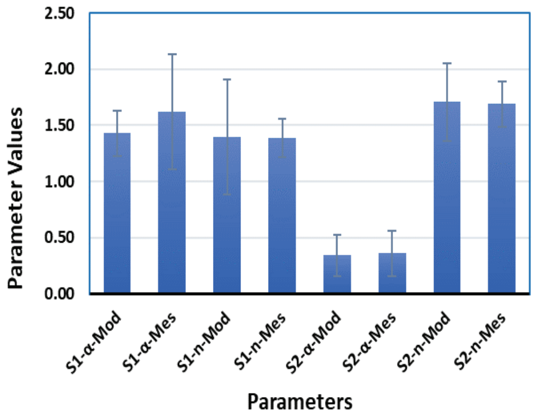

Fig. 5. The mean values of measured and modelled α and n [5] obtained from various experimental repetitions (S1- Soil 1, S2- Soil 2, Mes- Measured, Mod- Modelled)

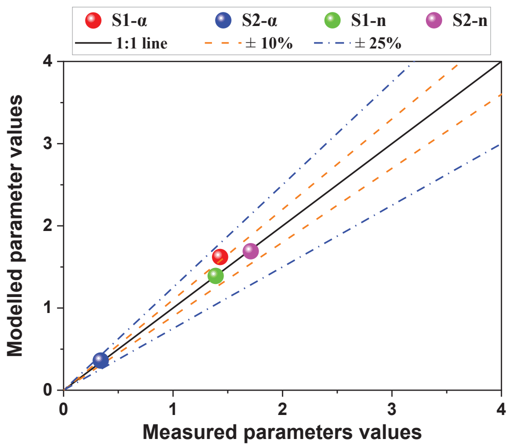

Fig. 6. Comparison between parameters α and n [5] obtained from the modelled $SWCC_w$ using inverse modelling of MDI infiltration and measured $SWCC_w$ recorded directly from sensors for the two soil textures (S-1 and S-2).

It is noted from the figures that for both the soils, the modelled mean α and n were significantly comparable with the measured mean α and n. The standard deviation values were also marginal, stating that the experimental repetitions were able to produce consistent results. The parameter values from all the cases were close to the 1:1 line and showed a maximum deviation of ±25%, as seen in Figure 6. The results from this study clearly endorse the applicability of MDI infiltration measurements to accurately quantify the $SWCC_w$ and its parameters with the help of the numerical inversion technique.

4 Conclusion

This study has carried out an investigation based on the realistic wetting process in the unsaturated zone beneath a mini disc infiltrometer (MDI) with the help of laboratory infiltration tests. The efficiency of a compact MDI in determining wetting soil water characteristics curve ($SWCC_w$) and its shape parameters (α and n) was demonstrated with the help of infiltration measurements using two fine-textured soils. Infiltration tests were conducted under regulated initial conditions using instrumented soil columns with provision for sensor placements at a suitable depth. An indirect method that involves inverse modelling and parameter optimization of the MDI infiltration measurements was suggested to analyse the results.

The accuracy of the inverse modelling results ($SWCC_w$ and the parameters α and n) was cross-verified by comparing it with the measured results obtained from sensor measurements. Based on the statistical comparison, an excellent match was reported between the modelled and measured $SWCC_w$, and α and n. The observations from this study proved that the cumulative infiltration measurements from MDI, along with final VWC information, can be used as a reliable input for inverse estimation of $SWCC_w$ and its parameters.

The findings from this study demonstrate the utility of a compact MDI for a quick and non-destructive measurement of $SWCC_w$. The advantage is that this method can be conveniently applied for both laboratory and field measurements.

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