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DIVISION S-1—NOTES

A MODIFIED UPWARD INFILTRATION METHOD FOR CHARACTERIZING SOIL HYDRAULIC PROPERTIES

M. H. Young*, A. Karagunduz, J. Šimůnek, and K. D. Pennell

Abstract

This note describes a modified upward infiltration method (UIM), which combines laboratory experiments and inverse parameter estimation for determining soil hydraulic properties in the wetting direction. The laboratory method used a Mariotte system to impose a constant head boundary condition on the bottom of a soil column, allowing water to be taken up by the soil material under negative pressure head. Tensiometers installed along the column measured the change in soil pressure head before and after wetting front arrival. The HYDRUS-1D code was used to obtain an optimal set of van Genuchten parameters, using pressure head and cumulative flux data as auxiliary variables in the objective function. Two soil types (a fine sand and a sandy loam) were tested in triplicate in uniformly-packed soil columns. The results of the uniform column experiments were repeatable, and showed excellent fits between observed and predicted data. Fitted parameters were used in forward simulations to independently predict water flow behavior in layered columns of the same soil material. The forward simulations successfully predicted water flow for sand-over-loam and loam-over-sand combinations in layered columns. The relative simplicity of the experimental procedure and the availability of appropriate numerical models renders the modified upward infiltration method an alternative for determining wetting hydraulic properties of soils.

The measurement of soil hydraulic properties, specifically soil water content (θ)—soil water pressure head (ψ) and hydraulic conductivity (K)—water content (θ) functions, is needed to predict the direction and rate of water movement in unsaturated soils. However, the paired values of $\theta(\psi)$ and $K(\theta)$ are dependent upon the direction of wetting or drying (Dane and Wierenga, 1975; Hillel, 1998). Experimentation required to establish the functions in wetting and drying directions, and their intermediate values, often require specialized laboratory setups, which is why often times only the drying functions are determined (Hillel, 1998).

In the past few decades, several transient methods have been proposed for characterizing soil hydraulic properties, including one-step outflow (Parker et al., 1985), multi-step outflow (Eching and Hopmans, 1993; van Dam et al., 1994), and evaporation (Wind, 1968; Šimůnek et al., 1998a). Each of these methods use the change in column weight to infer changes in soil water content, and with the exception of Parker et al. (1985) and van Dam et al. (1994), either one or more tensiometers placed along the column to measure change in soil water potential. A review of inverse estimation of hydraulic properties was done by Hopmans and Šimůnek (1999).

Experimental methods have been shown to work for a variety of soil textures undergoing drying. However, they do not yield hydraulic properties for soils undergoing wetting, and the transfer of drying curves to wetting curves is not trivial. The UIM is one of a few methods capable of obtaining wetting properties of soils. The UIM was originally described by Hudson et al. (1996), who showed that the method was robust for uniform, sandy-textured soil samples. Wyckoff (1997) applied the method to a variety of clayey-textured soils, including those with swelling clays. Both studies used constant flux bottom boundary conditions, which reduces the usefulness of the flux as an optimization parameter because the flux is independent of the soil properties (Šimůnek and van Genuchten, 1997).

Other researchers have used variations of the UIM. For example, Karkare and Fort (1993) and Demond et al. (1994) used standard Tempe cells, and reversed the gradient in a series of equilibrium pressure steps, so that test solution in a graduated burette would be taken up spontaneously into the soil. In these cases, soil water pressure head was not measured, so gradients could have existed in the column at the end of the step, yielding noncorresponding values of θ (inside the column) and ψ (at the bottom boundary).

Controlling water intake by setting the bottom boundary pressure, coupled with intensive soil data collection could improve on these methods. Recently, Šimůnek et al. (2000) suggested using a tension-based UIM for

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Abbreviations: UIM, upward infiltration method.

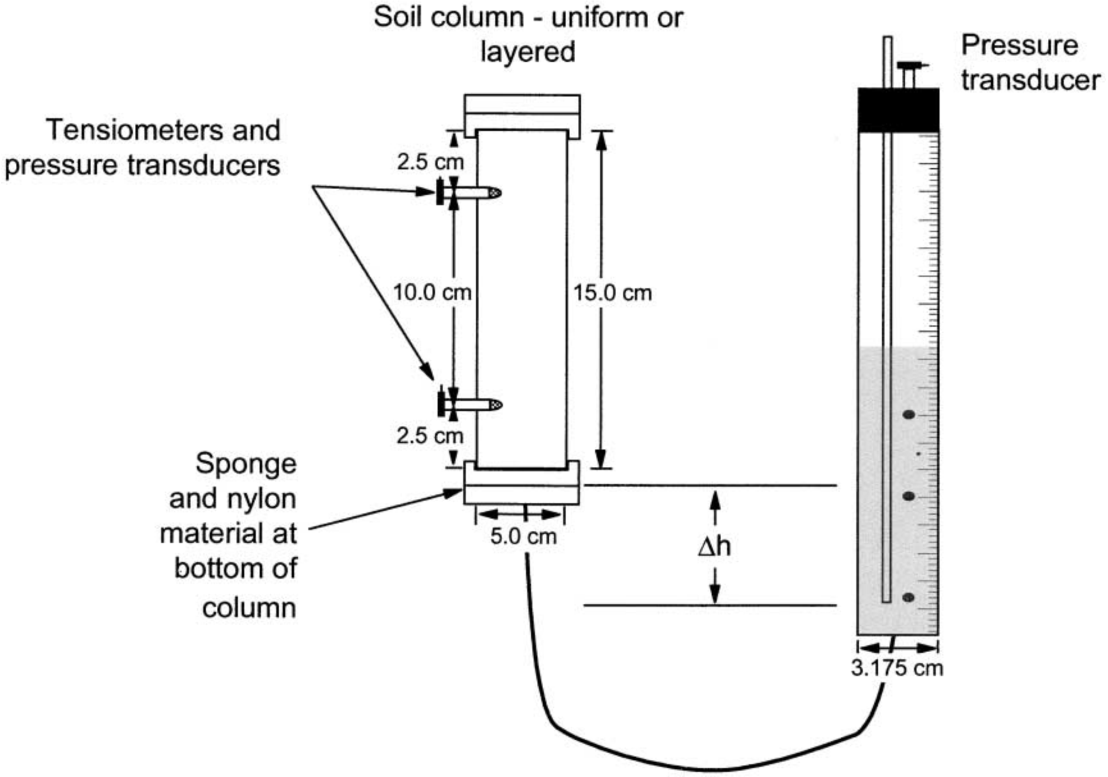

Fig. 1. Schematic of experimental setup.

evaluating nonequilibrium flow features in structured soils. Zurmühl (1998) described a fairly complex laboratory setup to reverse flow into and out of the soil column, using a pump and two pressure valves, all controlled by a personal computer. As will be described below, our experiments use only a Mariotte system to control the bottom boundary.

The purpose of this research was to characterize the wetting hydraulic properties of soils using a constant head bottom boundary. We (i) use the modified UIM to characterize disturbed soil samples, (ii) optimize the van Genuchten parameters with HYDRUS-1D to match experimental results, and (iii) use globally-fitted hydraulic properties to predict water flow into layered columns.

Materials and Methods

Laboratory Procedures

Soils of two textures were used for this research: (i) Vinton fine sand (sandy, mixed thermic Typic Torrifluvent) collected at the Campus Agricultural Center, Tucson, Arizona, and (ii) Appling sandy loam (clayey, fine, kaolinitic thermic Typic Hapludult), collected near the J. Phil Campbell, Senior, Natural Resource Conservation Center (USDA–ARS), Watkinsville, GA. Particle-size analyses for the Vinton and Appling soils showed percentage distributions of 96/3/1 and 77/14/9 for sand/silt/clay, respectively.

All column experiments were conducted using polycarbonate columns (15-cm long and 5-cm i.d.), outfitted with two threaded access ports through which tensiometers were inserted. Soil was retained using acrylic end plates (model CL-021, Soil Measurement Systems, Tucson, AZ). The interface between the soil and inlet end plate was equipped with sponge cloth (Spontex, Columbia, TN) cut into a circular discs (diam. = 6.2 cm) and placed inside the end plate. The sponge was used because the material allowed rapid water uptake, slow gravity drainage, and very little resistance to flow. A porous nylon filter (diam. = 7.4 cm; model R99SP04700, Osmonics, Inc, Minnetonka, MN), was then placed above the sponge and in direct contact with the soil. The sponge cloth was weighed before and after the flow experiment so that an accurate mass balance of water that entered the column could be ascertained.

Tensiometers (model CL-029, Soil Measurement Systems, Tucson, AZ), used to measure soil water pressure head, were inserted through the column wall at 2.5 and 12.5 cm above the bottom of the column and held in place using compression fittings. The bottom location was chosen after observations of Šimůnek et al. (1998a), who suggested monitoring as close as possible to the input-output boundary. The top tensiometer location was chosen close to the upper boundary to maximize the amount of soil subjected to wetting before the wetting front reached the top of the column. After calibrating the pressure sensors (model 136PC15G2, MicroSwitch, Richardson, TX), they were sealed to the open end of the tensiometer body. Standard errors obtained from calibration were consistently close to ±0.7 cm. A data logger (model CR-23X, Campbell Scientific, Inc., Logan, UT) was used to collect and store pressure readings.

A Mariotte system was used to control water input to the column. The water reservoir was 3.175-cm i.d. Using a pressure sensor (model 136PC01G2, MicroSwitch) to monitor change in water level and hence the volume of water flowing into the soil column, a measurement error of ± 0.34 cm^3 water was achieved. Test fluid consisted of deionized water containing 0.005 M $CaCl_2$. Two head levels were set for most of the laboratory experiments, with the initial value close to -0.8 kPa (-8 cm H_2O) and the final value set at ~ -0.3 kPa (-3 cm H_2O). Head levels were set by placing the bubbling tube below the bottom boundary of the soil column. Flow was initiated

Table 1. Experimental conditions for laboratory experiments.

Soil	Replicate	Bulk density	Initial vol. water content	Final vol. water content
		Mg m^{-3}	m^3 m^{-3}	
Vinton	**1**	**1.52**	**0.027**	**0.280**
Vinton	**2**	**1.49**	**0.027**	**0.320**
Vinton	**3**	**1.51**	**0.033**	**0.310**
Appling	**1**	**1.58**	**0.060**	**0.250**
Appling	**2**	**1.56**	**0.056**	**0.261**
Appling	**3**	**1.57**	**0.066**	**0.249**
Appling/Vinton†	**1**	**1.52 (1.56/1.44)**	**0.049**	**0.281**
Appling/Vinton	**2**	**1.52 (1.56/1.44)**	**0.049**	**0.277**
Appling/Vinton	**3**	**1.52 (1.54/1.48)**	**0.048**	**0.243**
Vinton/Appling	**1**	**1.52 (1.47/1.56)**	**0.044**	**0.283**
Vinton/Appling	**2**	**1.52 (1.48/1.57)**	**0.044**	**0.280**
Vinton/Appling	**3**	**1.52 (1.45/1.55)**	**0.048**	**0.276**

† First soil type listed indicates upper layer, and second soil type indicated bottom layer.

by placing the upper soil boundary under vacuum (~ −0.1 to −1.0 kPa) with a syringe for 1 to 5 s or until the sponge material began absorbing water. Flow was then sustained in virtually all cases. A schematic of the experimental setup is shown in Fig. 1.

Column experiments were run with uniform and layered soil configurations. Experiments were conducted in triplicate for uniform material for each of two soils, and for layered columns, with Vinton soil placed above Appling soil (i.e., Vinton/Appling), and vice versa (i.e., Appling/Vinton). Each layer was 7.5-cm thick. Repacked columns were used to better observe the wetting behavior in the soil, without potential uncertainties introduced by nonequilibrium flow into aggregates. Table 1 lists the soil bulk densities, and initial and final water contents for each experiment.

Analytical Procedures

Data were analyzed using the HYDRUS-1D code (Šimůnek et al., 1998b), which numerically solves Richards' equation for water flow in variably-saturated porous media. The governing flow equation is solved using Galerkin linear finite element schemes for time-dependent or time-independent boundary conditions. Richards' equation for one-dimensional flow is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\psi)\left(\frac{\partial \psi}{\partial z} + 1\right)\right) \quad [1]$$

where t is time, θ is volumetric water content (L^3 L^{-3}), ψ is the soil pressure head (L), and z is the spatial coordinate (L), positive upward. Initial and boundary conditions are, respectively:

$$\psi(z) = \psi_i \qquad \text{for } t = 0,\ 0 \leq z \leq L \quad [2]$$

$$q = \left[K(\psi)\frac{\partial \psi}{\partial z} + K(\psi)\right] = 0 \qquad \text{for } t > 0,\ z = L \quad [3]$$

$$h = h_1 \qquad \text{for } 0 < t \leq t_1,\ z = 0$$

$$h = h_2 \qquad \text{for } t_1 < t \leq t_2,\ z = 0 \quad [4]$$

where ψ_i is the initial soil water pressure head (L), q is the Darcy flux (L T^{-1}), and h is the head imposed at the bottom boundary (L).

Several representations of retention curves are available, and we expect that any reasonable representation of retention can be applied to this laboratory method. However, we used the van Genuchten (1980) relationship, because it is commonly used in the soils community, and because it seems to represent the $\theta(\psi)$ and $K(\theta)$ functions for most soils. The relationship is:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + (\alpha\,\psi)^n)^m} \quad [5]$$

where Θ is the relative volumetric water saturation; subscripts r and s refer to residual and saturated volumetric water contents, respectively; α (L^{-1}) and n (–) are empirical fitting parameters; and $m = (1 - 1/n)$. The Mualem–van Genuchten function (Mualem, 1976; van Genuchten, 1980) was used to represent hydraulic conductivity, $K(\theta)$:

$$K(\theta) = K_s\,\Theta^{1/2}(1 - (1 - \Theta^{1/m})^m)^2 \quad [6]$$

where K_s is the saturated hydraulic conductivity (L T^{-1}), and $0 < m < 1$ (van Genuchten, 1980).

Using Eq. [5] and [6], as many as five parameters can be fitted: θ_r, θ_s, α, n, and K_s. HYDRUS-1D simulates water flow using assigned initial and boundary conditions, compares the modeling results with observed data, and reinitializes the simulation using updated parameters. After each simulation, the program calculates an objective function (called SSQ in HYDRUS) that compares the simulated versus observed space-time (auxiliary) variables (see Šimůnek et al. (1998b) for a complete description). For this work, the auxiliary variables were soil water pressure head at two locations and cumulative flux. Weighting coefficients were calculated as the inverse product of the measurement variance and the number of observations for each auxiliary variable (Clausnitzer and Hopmans, 1995), which causes the objective function to become the average weighted squared deviation normalized by the measurement variances. Parameter estimation uses the Marquardt (1963) nonlinear optimization routine.

To reduce the number of fitting parameters, we chose to assign θ_r as the air-dry water content. Other parameters were based on educated guesses as starting points for the optimization. The parameters were then sequentially fitted, beginning with those found to be most sensitive, and finishing with those found to be least sensitive. The optimized parameter values were used as starting points in subsequent simulations, so that four parameters were fitted in the final simulation.

An average retention curve for each soil type was obtained by simultaneously fitting paired ψ-θ values, obtained using the optimized van Genuchten parameters for the three replicates, with the RETC code (v1.0, van Genuchten et al., 1991). The resulting *global* set of parameters represent the average soil hydraulic properties. To evaluate whether these parameters are representative of the soil, they were used in HYDRUS-1D in forward mode to predict water flow behavior in the layered soil column experiments. These predictions were evaluated against observed experimental data. Thus, if the numerical simulation accurately predicts water flow behavior in a soil column when the boundary conditions and soil layering are known, this would be evidence that the global parameter set, when used in the van Genuchten relationship, can be used for predictive purposes.

Table 2. Experimental results for soil columns containing no layering.

Soil	Replicate	Initial/final bottom tension	Cumulative infiltration	Arrival time-top tensiometer
		cm	cm (mL)	min
Vinton	**1**	**−8.55/−3.56**	**3.99 (80.87)**	**34.83**
Vinton	**2**	**−8.50/−3.65**	**4.74 (96.07)**	**29.50**
Vinton	**3**	**−8.60/−3.70**	**4.06 (82.29)**	**40.17**
Appling	**1**	**−8.20/−2.70**	**3.60 (72.97)**	**361.50**
Appling	**2**	**−8.40/−2.55**	**3.47 (70.33)**	**216.50**
Appling	**3**	**−8.60/−3.20**	**3.39 (68.71)**	**203.50**

Results and Discussion

Uniform Soil and Inverse Modeling

Table 2 summarizes the results of the experiments for uniformily-packed soil columns. Slight differences in the bottom pressure and soil bulk density led to some differences in the cumulative infiltration and the wetting front arrival. The largest difference in cumulative flux between replicates (e.g., Vinton Rep 1 versus Rep 2) was 15.20 mL of water (18.8%), but differences were normally close to 2 to 4 mL. Average front velocities for Vinton and Appling soils were 0.287 cm min^{-1} and 0.038 cm min^{-1}. Front velocities were significantly slower in the clayey-textured, Appling soil, because of the decrease in soil water diffusivity. Wetting front arrival at the lower tensiometer varied between 1.17 and 3.33 min for the Vinton soil and between 3.00 and 16.00 min for the Appling soil. Though the range in arrival

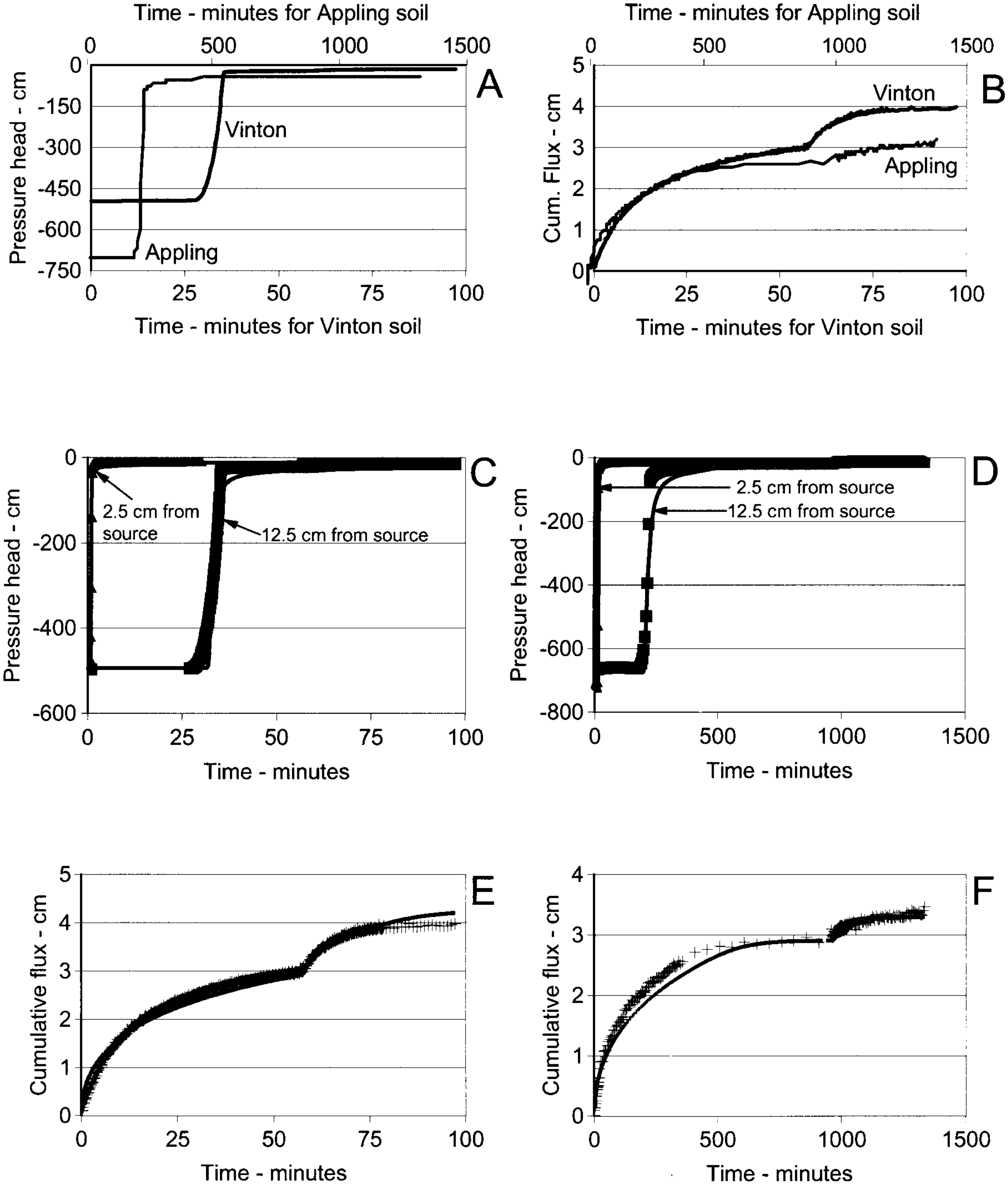

Fig. 2. Observed pressure head (A) and cumulative flux (B) for uniformily-packed Vinton (Rep 1) and Appling (Rep 2) soils. Observed (symbols) and predicted (line) pressure head (C and D) and cumulative fluxes (E and F) are shown for same replicates for Vinton and Appling soils, respectively. Predicted line may be hidden by symbols. Note different scales for abscissa for A and B.

times is wider for the Appling soil, the coefficient of variation (CV = Std. Dev./Mean) was virtually identical between the two soil types (53.9% for Vinton versus 54.5% for Appling).

Figures 2A and 2B show the pressure head at the upper tensiometer and cumulative fluxes for the uniformily-packed Vinton (Rep 1) and Appling (Rep 2) experiments (results from all experiments are not graphically shown). Though the pressure heads recorded prior to wetting front arrival were near the upper end of functionality of the tensiometer method itself and therefore may not be accurate, the wetting front arrival was detected unambiguously in each case, and provided accurate data for the inversion modeling. The final pressure heads at the bottom tensiometer were almost identical to the pressure head applied at the bottom boundary, indicating insignificant head loss through the sponge and nylon materials. Final pressure heads at the top tensiometer were typically ~10 cm lower (more negative) than heads at the bottom tensiometer, reflecting the increased height above the water source. Fluid applied with the Mariotte system exhibited some noise because of growth of air bubbles at the base of the bubbling tube, and possibly because of changes in air temperatures in the laboratory, but generally the signals were quite strong.

Results of the numerical simulations are presented in Table 3, and in Fig. 2C to 2F. Results in Fig. 2A and 2B for pressure head and cumulative flux are simulated in Fig. 2C and 2D, and in Fig. 2E and 2F, respectively. Pressure head data for the lower tensiometer is somewhat obscured by the *y*-axis, but the simulated pressure head at the upper tensiometer was closely simulated by HYDRUS-1D, indicating that the VG (van Genuchten) parameter set represented the behavior of the soil. Tensiometer responses tended, in most cases, to show more diffuse arrivals of wetting fronts, due mainly to the spatial averaging in the tensiometers. Using the final θ(ψ) conditions in the objective function, as recommended by Šimůnek et al. (1998c) did not improve overall fit to the tensiometer and flux data.

Table 3. Final parameter values for Upward infiltration method UIM experiments.

Soil	Replicate	θ_r	θ_s	α	n	K_s	r^2	SSQ†
		— $m^3\ m^{-3}$ —		cm^{-1}		cm/min		
Vinton	1	0.007	*0.359*	*0.062*	*2.507*	*0.339*	0.983	0.103
Vinton	2	0.007	*0.395*	*0.053*	*2.223*	*0.353*	0.909	0.352
Vinton	3	0.007	*0.360*	*0.060*	*2.319*	*0.279*	0.990	0.196
Vinton-global		0.007	0.372	*0.059*	*2.324*	*0.324*	0.990	–
Appling	1	0.0285	0.410‡	*0.171*	*1.387*	*0.561*	0.985	0.049
Appling	2	0.0285	*0.398*	*0.093*	*1.315*	*0.243*	0.972	0.059
Appling	3	0.0285	*0.414*	*0.165*	*1.370*	*0.945*	0.995	0.030
Appling global		0.0285	*0.409*	*0.162*	*1.328*	*0.583*	0.980	–

† Sum of squares.
‡ Held constant for this experiment only.

Correlation existed between some fitted parameter pairs. Specifically, θ_s and K_s showed the highest positively correlation, and θ_s and n showed the highest negative correlation of parameter pairs considered. Though high correlation among parameters does not inhibit convergence of the fitting procedure (Durner et al., 1999), it does slow down the convergence rate and lead to questions about the independence of the parameters. Also, some discrepancy was noted between observed and predicted pressure heads corresponding to the initial water content (e.g., observed $\theta(\psi) = 0.027\ m^3\ m^{-3}$ (-500 cm) versus fitted $\theta(\psi) = 0.027\ m^3\ m^{-3}$ (-196 cm) for the Vinton soils). Experience indicated that the air-dry water content was consistently close to 0.007 $m^3\ m^{-3}$, so this was chosen as the fixed value of θ_r. Given that large changes in pressure head translate to small changes in water content on the dry end of the retention curve, the discrepancy could be caused either by error

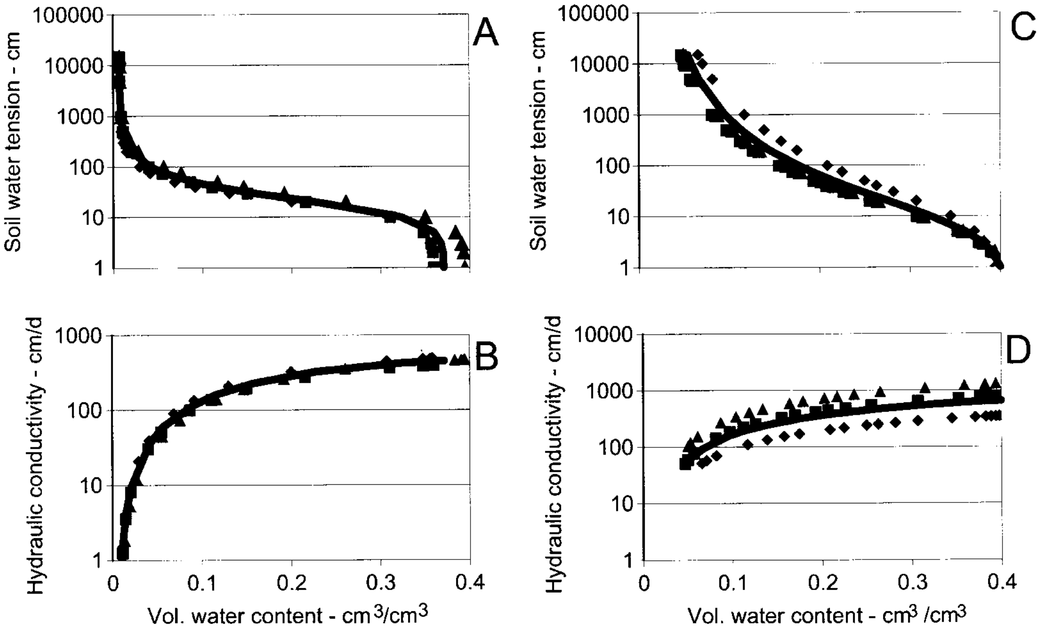

Fig. 3. Fitted (symbols) and global (line) soil water retention (A and C) and hydraulic conductivity functions (B and D) for Vinton and Appling soils, respectively. Squares, diamonds, and triangles correspond to Replicates 1 to 3, respectively.

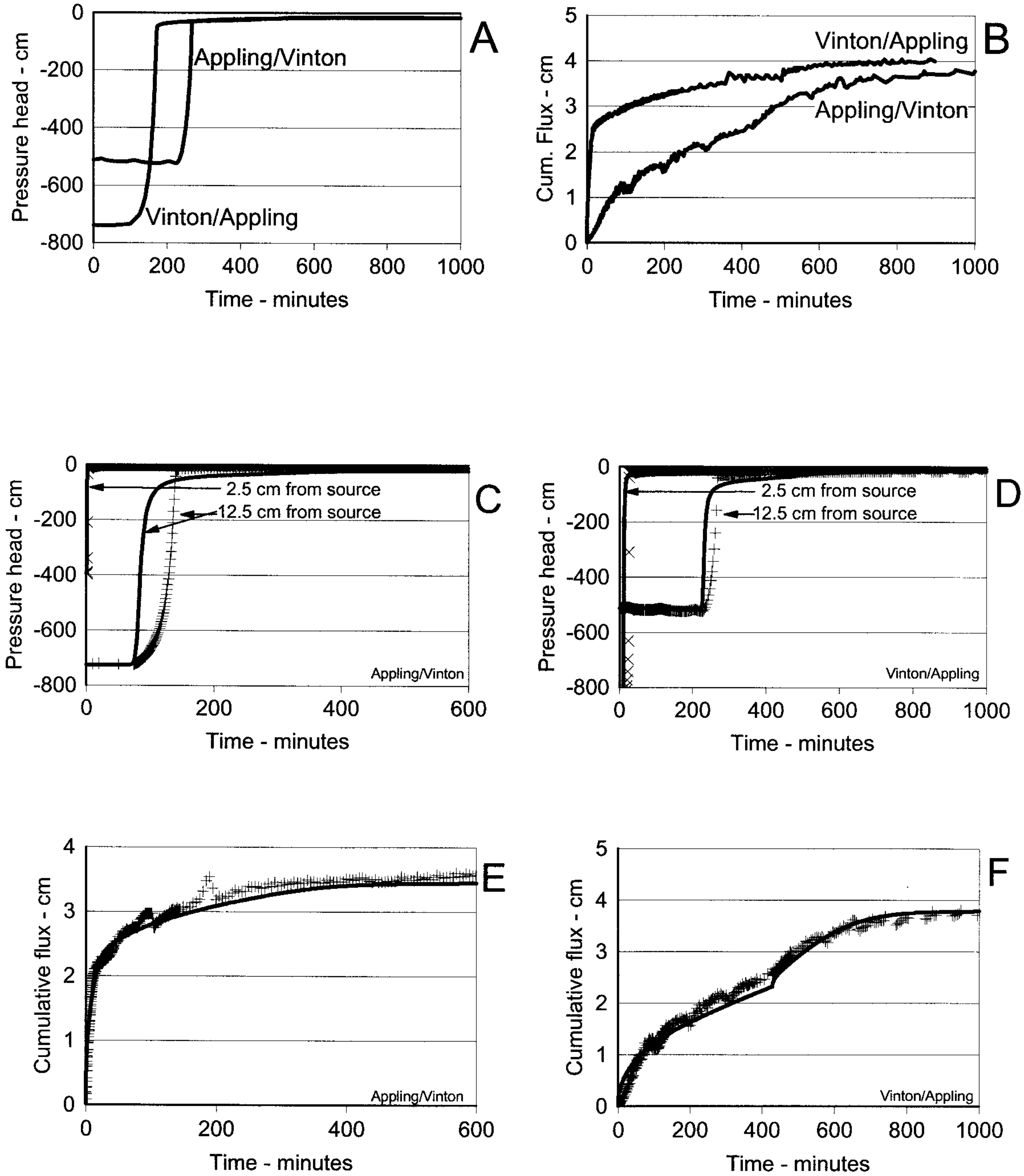

Fig. 4. Observed pressure head (A) and cumulative flux (B) for Appling/Vinton (Rep 3) and Vinton/Appling (Rep 1). Observed (symbols) and predicted (line) pressure head (C and D) and cumulative fluxes (E and F) are shown for same replicates.

in the pressure head measurement or model prediction, the use of the VG equation to represent soil water retention, or a combination of these.

Global hydraulic properties, obtained by simultaneously fitting individual paired ψ-θ data using RETC, are listed on Table 3. The measured parameters are in close agreement to the arithmetic average of those values individually obtained using the HYDRUS-1D model. Figure 3 shows the retention and conductivity functions (replicates and global) for Vinton and Appling soils. Retention curves were highly reproducible. Differences in the conductivity function were mainly from uncertainties in the fitted value of K_s, which was affected by the need to extrapolate beyond the conditions setup in the experiment. An independently measured K_s could reduce this uncertainty.

Layered Soil and Forward Modeling

Figure 4 shows the observed and predicted pressure head and cumulative flux for two of the six layered soil column experiments (replicate numbers are listed in the figure caption). Overall, the parameter estimates obtained from the uniform column experiments described the hydraulic behavior of the soil material, such that forward predictions were quite accurate. However,

Table 4. Experimental and numerical results obtained for layered soil columns.

Soil	Replicate	Cumulative flux		Wetting front arrival	
		cm		min	
		Observed	Predicted	Observed	Predicted
Appling/Vinton†	**1**	**3.75**	**3.45**	**87.67**	**81.47**
Appling/Vinton	**2**	**3.70**	**3.50**	**98.00**	**82.97**
Appling/Vinton	**3**	**4.00**	**3.94**	**98.83**	**84.27**
Vinton/Appling	**1**	**3.99**	**3.79**	**231.67**	**229.10**
Vinton/Appling	**2**	**4.05**	**3.76**	**228.70**	**233.10**
Vinton/Appling	**3**	**4.01**	**3.76**	**321.00**	**237.40**

† First soil type listed indicates upper layer, and second soil type indicates bottom layer.

some differences existed between observed and simulated responses. For example, simulated cumulative fluxes were underestimated by ~0.2 to 0.3 cm (Table 4), a relatively small amount (~5–7%) considering that the predictions used only the globally-fitted parameters and the known boundary conditions. Average differences in the wetting front arrival times between the replicates were 15 and 13% for Appling/Vinton and Vinton/Appling, respectively. In one case (Vinton/Appling Rep 3), the observed wetting front traveled slowly and was not modeled very well (difference = 83.6 min or 35.2%).

Toward the drier range, uncertainty increases because of a need to extrapolate beyond the tensiometer range. For example, in the cases presented here, θ_r was assumed equal to air-dry water content, and pressure head measurements were limited values of greater than ~ −700 cm. Neither situation supports the estimate of hydraulic properties in the very dry range. Independent verification of the soil hydraulic properties in the wetting direction were not available. However, a recent study by Zou et al. (2001) using the Vinton soil during a controlled infiltration experiment, produced a set of hydraulic parameters ($\alpha = 0.048$–$0.061\ \mathrm{cm}^{-1}$, $n = 2.47$–2.66, $K_s = 0.106$–$0.113\ \mathrm{cm\ min}^{-1}$), the range of values determined at different depths. Their results are very similar to those listed in Table 3, with the exception of K_s, which was found to be smaller.

Conclusions

A modified UIM procedure was used to characterize soil hydraulic properties in the wetting direction during transient water flow, rather than in the drying direction, as obtained through outflow methods. The procedure relies on a constant head bottom boundary condition, rather than a constant flux boundary condition, allowing the cumulative flux data to be included as an auxiliary variable in the objective function. The simplicity and rapidness of the modified UIM experimental procedure, its reproducibility, and its ability to capture the soil parameters in the wetting direction makes the method attractive for characterizing soil hydraulic properties. The method is generally applicable to both disturbed and undisturbed soil.

The utility of the method was demonstrated through the repeatability of experimental results and the numerical output. The globally-fitted hydraulic parameters derived from uniform soil columns were then independently used to predict soil water flow in layered soil columns. A comparison of observed and predicted responses to water addition showed an average deviation in cumulative flux of 5.91%. The method will be most useful in the wetter range of the retention and conductivity functions, where the bulk of data are typically collected.

Acknowledgments

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IMPROVED DESIGN FOR AN AUTOMATED TENSION INFILTROMETER

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Abstract

Automated measurements of water infiltration rates are commonly done using two gage transducers to measure water level changes in the reservoir of an infiltrometer. Previous studies have evaluated and described in detail infiltrometers automated with two gage-transducers and have shown that measurement precision and accuracy of soil hydraulic properties are improved. A previous study has also suggested the use of a single differential transducer to automate an infiltrometer to eliminate measurement error associated with air bubbles in the infiltrometer reservoir. In this study, the automation of a tension infiltrometer using a differential transducer was developed, evaluated, and applied. A single differential transducer was installed at the bottom of an infiltrometer reservoir and the other end was connected by tubing to the head-space in the reservoir. Calibration of the reservoir height measurements vs. transducer voltage output was simplified over previous methods and was even demonstrated in situ. Measurement precision was also improved by two orders of magnitude over previous methods. Measurements were also done to demonstrated the use of the single differential transducer set-up to obtain field measurements of unsaturated hydraulic conductivity and sorptivity. Unlike previous methods though, this method does not allow for the determination of the imposed potential at the soil surface unless adaptations are made.

Automated measurements of marriotte reservoir water levels were first introduced by Constanz and Murphy (1987), who used a single gage transducer. This improvement lead to faster measurements of a large range of fluxes and higher accuracy in outflow measurements from the reservoir; however, the single gage transducer measurements of water height were not precise because of bubbling-induced variability. Ankeny et al. (1988) developed a method to automate water height measurements in the reservoir of a tension infiltrometer that minimized bubble-induced variability and improved measurement precision. A tension infiltrometer (Fig. 1) is a device that measures unsaturated infiltration rates, and the improvement by Ankeny et al. (1988) increased the reliability of soil hydraulic properties such as sorptivity, unsaturated hydraulic conductivity, and macroporosity. The Ankeny et al. (1988) improvement uses two gage transducers, one at the top and the other at the bottom of the infiltrometer reservoir.

The use of two transducers improves infiltration measurement precision; however, there is still some error in the precision of the measurements due to bubbling-induced variability, synchronization of the two gage transducer measurements, and accuracy of the gage transducer calibrations. Ankeny et al. (1988) suggests the use of a differential transducer to improve the measurement precision. The use of a differential transducer would also eliminate the need for extensive calibrations required by the two gage transducer method. The purpose of this research was to automate a tension infiltrometer using a single differential transducer and provide a description, evaluation, and application of this set-up.

Materials and Methods

The infiltrometer that was used in this study was a Soil Measurement System[1] model SW-080B, which has a 20-cm diam. baseplate that was separate from the water tower. The water tower was comprised of a reservoir (inside diam. = 5.1 cm, length = 81 cm) and bubbling tower (inside diam. = 2.54 cm). The bubbling pressure of the membrane covering the baseplate was 2.9 kPa. The air entry ports of the bubbling tower could be changed to supply infiltration tensions ranging from 2 to 50 cm of water.

The manufacturer automates the infiltrometer as Ankeny et al. (1988) describes, using two Series PX-136 four-wire full-bridge gage transducers (Omega Engineering, Stanford, CT). Rather, in this study, a single Series PX26-001DV differential transducer (Omega Engineering, Stanford, CT) was used to automate the infiltrometer. A schematic of the differential transducer installation is shown in Fig. 1, where one port was installed at the bottom position on the reservoir and the other port was connected, using tubing, to the head-space of the reservoir. To automate the water height measurements, the four pins of the differential transducer were connected to a

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[1] Mention of trade name or company does not constitute endorsement by North Dakota State University.