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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.

Campbell 21X data logger (Campbell Scientific, Inc., Logan, UT). This automation was modeled after the single transducer set-up described by Constanz and Murphy (1987).

The voltage output from the transducer has a direct linear relation to the difference between head-space tension and the height of water in the reservoir (Constanz and Murphy, 1987; Ankeny et al., 1988); however, transducer calibrations still need to be developed. Laboratory and in situ transducer calibrations were done by determining the linear relationship between the water height in the reservoir vs. the differential pressure transducer output voltage. To do this in the laboratory, the differential transducer was connected to the reservoir, and the voltage outputs were recorded as water was incrementally drained from the reservoir. Calibration of the transducer was also demonstrated in situ during an actual infiltration experiment, where water level and voltage outputs were recorded simultaneously.

The precision of the water height measurements as it was affected by the bubbling-induced variance was tested in the laboratory and was the same demonstration described by Ankeny et al. (1988). This was done by closing the connection to the infiltrometer baseplate, opening an air entry port (tension = 15 cm), and evacuating the air from the head space at the top of the reservoir using a hand pump. Suction was continuously applied with a hand pump so that large air bubbles flowed through the reservoir rapidly and vigorously while transducer voltage was logged. During this experiment, no water left the reservoir and the water height was ≈24 mm from the top.

Lastly, a field infiltration experiment was done to demonstrate the differential transducer configuration. The experiment took place near Galesburg, ND, and the soil was classified as a Glyndon loam (coarse-silty, mixed, superactive, frigid Aeric Calciaquoll). Soil was sampled for antecedent water content measurements, then infiltration began at a tension of 5 cm. Water height in the reservoir was recorded every second for 600 s then switched to record every 40 s until the end of the experiment. The method for calculating both hydraulic conductivity and sorptivity was based on the Haverkamp et al. (1994) analysis for transient unconfined three-dimensional infiltration out of a disk infiltrometer of a 200 mm radius. The simplified explicit infiltration equation is given by Angulo-Jaramillo et al. (1996):

$$I = S_o \sqrt{t} + \left[K_n + \frac{\gamma\, S_o^2}{r_d(\theta_o - \gamma_n)} + \frac{1}{3}(K_o - K_n)(2 - \beta)\right] t, \qquad [1]$$

where I is the cumulative infiltration [mm], t is the time [s], S is sorptivity [mm s$^{-1/2}$], K is the hydraulic conductivity [mm s^{-1}], and θ is volumetric water content [cm^3 cm^{-3}]. The subscripts o and n stand for the tension imposed by the infiltrometer and the antecedent pressure potential of the soil. The parameters γ and β are related to the soil physical properties and to the initial and boundary conditions. Assuming $K_n \ll K_o$, $0.7 < \gamma < 0.8$, and $0 < \beta < 1$ (Angulo-Jaramillo et al., 1996) values of γ, β, K_o, and S_o were identified by fitting Eq. [1] to the experimental data using a nonlinear, least-squares approximation. This inverse method for obtaining the fitted parameters is described in detail by Kool et al. (1985), who determined soil hydraulic properties from one-step outflow experiments.

Results and Discussion

Calibration

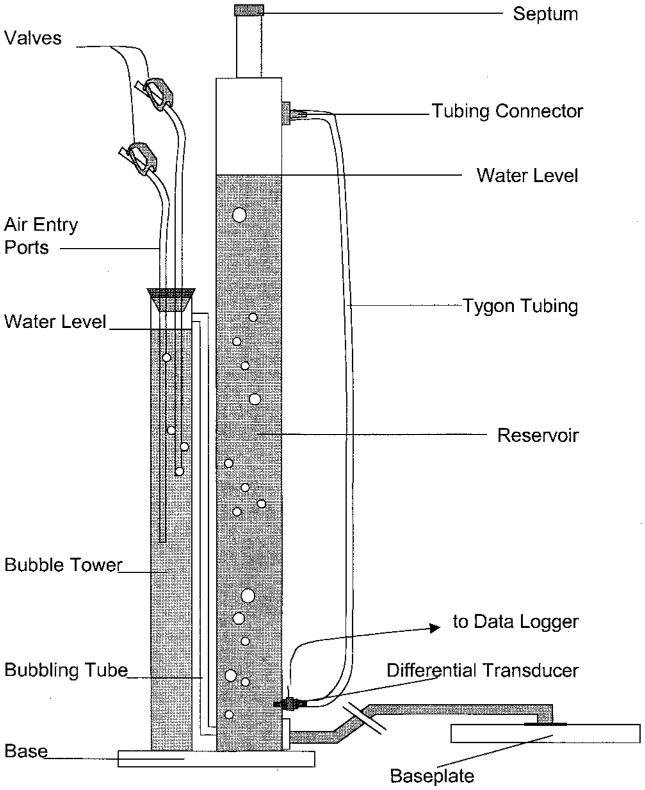

Fig. 1. Schematic of the tension infiltrometer configured with a single differential transducer.

As expected, the voltage output from the transducer had a direct linear relation to the difference between head-space tension and the height of water in the reservoir ($r^2 \geq 0.999$ for 68 measurement points). The transducer manufacturer specified the linearity between voltage output and pressure as ±0.25%, which corresponded directly to a linear relationship between the height of the water in the reservoir and the transducer voltage output. Calibration of the differential transducer was simple, and was even done in situ ($r^2 \geq 0.999$ for 8 measurement points). Ankeny (1992) noted that the intercept of the calibration line may drift, but the slope is constant; nonetheless, determining the infiltration rate is a difference method, so the intercept is not important.

The calibration of the differential transducer was an improvement over the two gage transducer method of Ankeny et al. (1988) because it was less involved and there was less inherent error. The two gage transducer infiltrometer set-up requires that tension vs. voltage relationships be developed by connecting the gage transducer to a manometer and recording the voltage output at specified tensions (Ankeny, 1992). Then the relation between the difference in the pressures between the two gage transducers and the water height in the reservoir needs to be established. These calibration steps were eliminated when one differential transducer was used; furthermore, some errors associated with the calibration of gage transducers were eliminated. Ankeny (1992) noted these calibration errors may include leaks in the manometer connections, recording exact height

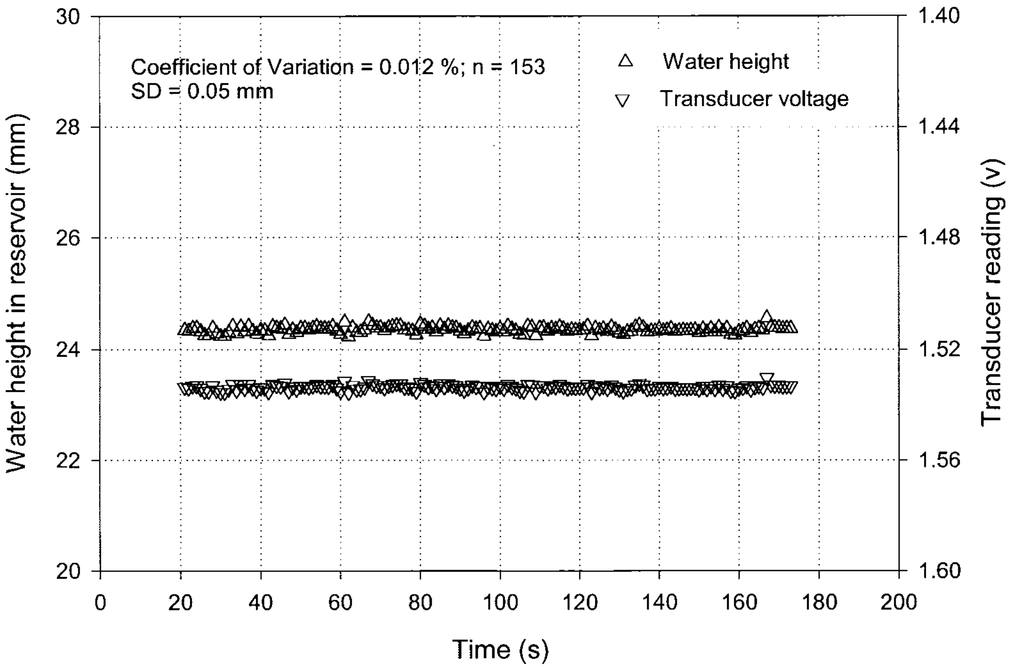

Fig. 2. Water height and transducer voltage output variations in the infiltrometer reservoir through time caused by bubbling without outflow and measured using one differential transducer.

of water column on both sides of the manometer, using the same electrical leads to connect transducers, and using the same time measurement intervals similar to those of the intended field use.

A disadvantage of the single differential transducer calibration was that the specified infiltrometer tension could not be checked against measurement data. With a two gage transducer set-up, the bottom transducer measurement is directly related to the imposed potential at the soil surface (Ankeny, 1992). It was possible to measure the potential at the soil surface using a differential transducer, but the slope and intercept of voltage vs. tension must be established. Also, the tube connecting the head space in the bubbling tower with the differential transducer must be closed for a short period of time during an infiltration experiment in order to measure the imposed potential.

Evaluation

To test the bubbling-induced variability, air was pulled through the infiltrometer while it sat on the bench top,

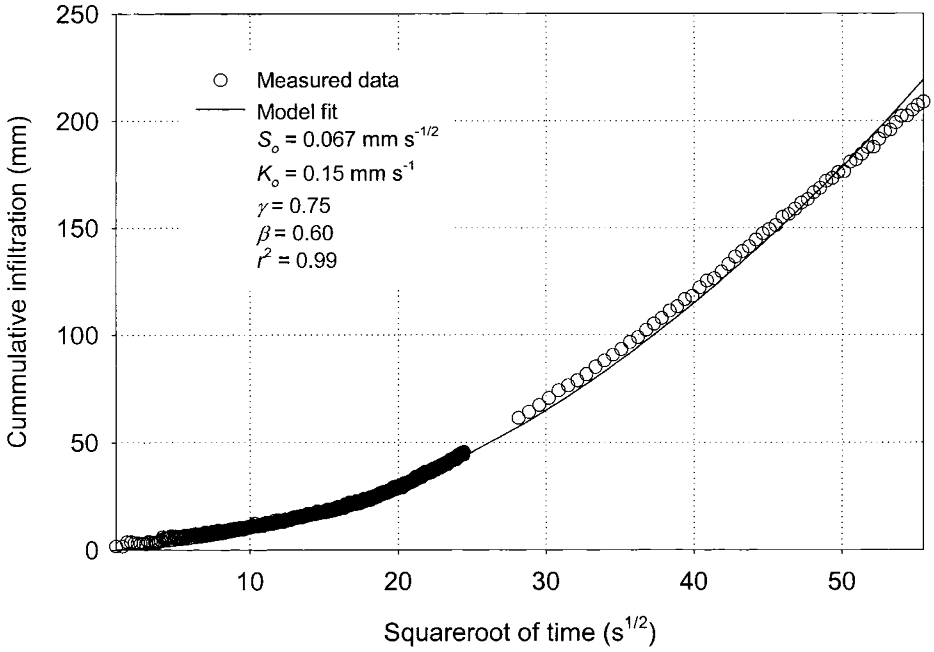

Fig. 3. Cumulative infiltration at 5-cm tension vs. square-root of time measured in situ with the differential transducer configuration. Equation [1] was fitted to the measured data.

and there was no water flow into or out of the reservoir. This experiment was identical to the experiment done by Ankeny et al. (1988). Figure 2 shows the water height measured by the differential transducer through time during this demonstration. The coefficient of variation for 153 measured points was 0.012%, which indicated a very low variability in the water height measurement. The precision that Ankeny et al. (1988) reported for the use of two gage transducers (SD = 2.2 mm) was an improvement over the precision for just one gage transducer (SD = 6.2 mm). When one differential transducer was used, the precision of the water height measurement was further improved (SD = 0.05 mm). Ankeny et al. (1988) noted that bubble detachment that occurs between gage transducer readings can cause measurement outliers and result in higher standard deviations. Ankeny et al. (1988) further noted that these outliers are easily identified and eliminated if a differential transducer is used.

Application

Lastly, the differential transducer automated set-up was used to obtain field infiltration measurements, which were used to calculate soil hydraulic properties (Fig. 3). Equation [1] described the data well, which was indicated by a high r^2 value of 0.99. The calculated K and S were 0.15 mm s^{-1} and 0.067 mm $s^{-1/2}$, respectively. The improved measurement precision from using the differential transducer would not have resulted in significant improvements of the calculated soil hydraulic properties. However, the differential transducer improvement made it easy to obtain early infiltration rate measurements so that S could be accurately determined. The improved measurement precision may be most beneficial for infiltration models that use a piece-wise linear (Ankeny et al., 1991; Reynolds and Elrick, 1991) or exponential (Logsdon and Jaynes, 1993) relationships between steady flow rate and tension to calculate hydraulic properties. The improved precision can increase the accuracy of the steady flow rate measurements at different tension and improve the piece-wise linear or exponential fits of these models.

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