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ESTIMATING SOIL HYDRAULIC PROPERTIES USING TENSION INFILTROMETERS WITH VARYING DISK DIAMETERS

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Tension infiltrometers have become a popular instrument for field determination of soil hydraulic properties, such as hydraulic conductivity (K_S) of saturated soil and the parameter (α) used in exponential expressions of the hydraulic conductivity function. However, results different from other independent field or laboratory measurements are often obtained using the steady-state approximate solutions. This is likely caused by the variable sizes of the infiltrometer disk used for the infiltration measurement and/or the limitations of steady-state solutions for small disk dimensions. To determine the effect of disk sizes on parameter estimation, we measured infiltration in two soils (Arlington sandy loam and Sparta sand) with tension infiltrometers of several disk diameters (5.5–34.5 cm). For each disk size, the infiltration was repeated at multiple supply potentials and continued until steady-state so that replicated parameter estimates were obtained for each disk size. Results indicate that estimated values of K_S and α appeared to vary with the size of the infiltrometer disk used. Variations in estimated K_S and α values for different disk sizes or for different potential increments for the same disk were greater than the potential overestimation with the steady-state solution when compared with an improved solution for small disk sizes. Discrepancies between tension infiltrometer and other methods in practice are probably caused by variability within each method, such as soil heterogeneity or simplifying the hydraulic conductivity function to the exponential expression, rather than by limitations in the steady-state solution for small tension infiltrometer disk sizes. (Soil Science 1998;163:356–361)

Key words: Tension infiltrometer, saturated hydraulic conductivity, parameter estimation, variable disk diameters.

PARAMETERS that are representative of *in-situ* soil hydraulic properties are very important for describing the dynamic processes of water and solute transport in the soil accurately. Direct measurements of the hydraulic parameters can be made with either standardized laboratory procedures using small soil cores taken from the field, or *in-situ* with specially designed instruments (Klute 1986). Most of these conventional methods are difficult to use, and they are often very time consuming.

Tension disk infiltrometers (Ankeny et al. 1988; Perroux and White 1988) are designed to offer a simple and fast means of estimating soil hydraulic properties and structural characteristics based on infiltration measurements at the soil surface. Water flow from a tension infiltrometer disk to the underlying soil follows a three-dimensional flow process. Temporal changes in soil water content can be described with the Richards' equation using initial and boundary conditions defined for geometric and hydraulic parameters specific to the infiltrometer. Because there is no exact analytical solution to such a transient three-dimensional flow problem, numerical inversion has been used to solve for hydraulic parameters based on known flow variables such as transient water content or infiltration rate (Simunek and van Genuchten 1996, 1997). From a practical standpoint, the most widely used method for parameter estimation based on tension disk infiltrometer measurement

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is to use an approximate analytical solution for steady-state water flow from a surface pond introduced by Wooding (1968). Other methods of data analysis from tension disk infiltrometer measurement often require the determination of transient water flow characteristics, such as the sorptivity and macroscopic capillary length method noted by White and Sully (1987). The steady-state approach using Wooding's approximate solution remains attractive because only steady-state infiltration rates are needed for the parameter estimation. However, the accuracy of soil hydraulic parameters estimated with Wooding's approximate solution may be in question because of large variations or discrepancies reported in the literature when comparing results with other methods. For example, estimated values of the saturated hydraulic conductivity were found to be within 5 to 300% of the mean using numerical simulations or other laboratory procedures (Reynolds and Elrick 1991; White and Perroux 1989; Ankeny et al. 1991). In addition to the spatial variability in soil hydraulic properties, one possible source of error with the Wooding's method is its limitations for relatively small disk sizes. After carefully re-examing Wooding's solutions for water infiltration from small shallow ponds, Weir (1987) provided a refinement of Wooding's solution for small disk diameters. The inadequacy of Wooding's solution for small disk sizes was also recognized by Warrick (1992), who provided a comparison with numerical simulations.

The objective of this study was to determine the effect of disk size on the estimation of soil hydraulic parameters using either the traditional Wooding's solution or the refinement solution by Weir (1987). The study will also provide an assessment of the practicality of using tension infiltrometers with a small disk and potential errors in the estimated hydraulic parameters using the simple form of Wooding's approximate solution.

MATERIALS AND METHODS

The rate of water and solute transport in an unsaturated soil is affected greatly by the hydraulic conductivity relationship, $K(h)$ (L T^{-1}) under a given soil matric potential, h (L). Many forms have been proposed for $K(h)$, including those by Childs and Collis-George (1950), Mualem (1976), and van Genuchten (1980). A simple alternative approach for $K(h)$ was introduced by Gardner (1958) using an exponential expression

$$K(h) = K_S \exp(\alpha h) \tag{1}$$

where K_S is the hydraulic conductivity of a saturated soil (L T^{-1}), and α (L^{-1}) is an empirical fitting parameter.

Wooding's Method

Under steady-state, Wooding (1968) solved for the infiltration rate from a shallow circular pond of radius r (L), based on Gardner's exponential hydraulic conductivity function, and found the following approximate solution

$$Q(h_o) = \pi r^2 K_S \exp(\alpha h_o)\left(1+\frac{4}{\pi r\alpha}\right) \tag{2}$$

where $Q(h_o)$ is the steady-state flow rate (L^3T^{-1}) under a given supply potential h_o (L). Because the only unknowns in this equation are K_S and α, they can be solved by making measurements with a fixed disk radius at multiple supply potentials or at a fixed potential with disks having variable radii. Detailed procedures of solving the equation for K_S and α can be found in Hussen and Warrick (1993).

Weir's Refinement for Small Disks

For water flow from a small surface source such as a small tension infiltrometer disk, Weir (1987) found that Wooding's approximate solution was inaccurate. If we normalize the flow rate $Q(h_o)$ and the infiltrometer disk radius r into the following dimensionless forms

$$Q^* = \frac{\alpha}{rK_S \exp(\alpha h_o)} Q(h_o) \tag{3}$$

$$r^* = \frac{1}{2} \alpha r \tag{4}$$

Wooding's relationship can be simplified to

$$Q^* = 4 + 2\pi r^* \tag{5}$$

For $r^* < 0.4$, Weir (1987) found that Eq. (5) was no longer accurate and provided the following alternative approximation for Q^*

$$Q^* = \frac{4\pi \sin^2(r^*)}{r^* \pi \sin(r^*) \cos(r^*) + 2r^* \sin^2(r^*) \ln(r^*) - 1.073(r^*)^3} \tag{6}$$

The empirical fitting parameter (α) should be generic to both the Wooding's and Weir's solutions and may be found by measuring the steady-state flow rate at two different supply potentials (such as h_1 and h_2) for the same disk radius and solving either Eq. (2) or (3) to obtain

$$\alpha = \frac{\ln[Q(h_2) / Q(h_1]}{h_2 - h_1} \tag{7}$$

The saturated hydraulic conductivity, however, will be found to be different by substituting α into either the Wooding's Eq. (2)

$$K_S = \frac{Q(h_1)}{\pi r^2 \exp(\alpha h_1)\left(1+\frac{4}{\pi r\alpha}\right)} \qquad (8)$$

or into the Weir's Eqs. (3) and (6)

$$K_S = \frac{\alpha}{r}\exp(-\alpha h_1)\,\frac{Q(h_1)}{Q^*} \qquad (9)$$

Field Measurements with Tension Infiltrometers of Different Disk Sizes and a Guelph Permeameter

Water infiltration was measured with tension infiltrometers of different disk diameters in two different soils. The first soil is an Arlington fine sandy loam (coarse-loamy, mixed, thermic, Haplic Durixeralf) with an Ap horizon for the surface 10 cm. At this depth, the particle size distribution consists of 63% sand, 30% silt, and 7% clay. Soil bulk density at this depth is 1.53 ± 0.03 (g cm^{-3}). Because no definable structure can be observed, the soil is considered massive. The second soil is a Sparta sand (mesic, uncoated, Typic Quartzipsamment) and consists of approximately 95% sand, 3% silt, and 2% clay in the surface layer. Soil bulk density near the surface is 1.50 ± 0.08 (g cm^{-3}). The structure of the soil is considered to be subangular blocky (Wang et al. 1994).

At the Arlington fine sandy loam, the tension infiltration measurements were made with four disk diameters: 5.5, 10, 15, and 20 cm. For each disk size, the measurements were repeated under eight supply potentials: 0, −1, −3, −5, −7, −10, −15, and −20 cm, which provided 28 estimates of α and K_S for each disk diameter. A layer of about 1 mm of no. 60 silica sand (diameter ~ 250 mm; K_S ~ 0.33 cm s^{-1}; water entry ~ 22 cm) was used between the disk membrane and the smoothed soil surface to improve hydraulic contact. At the Sparta sand site, the measurements were made with three disk diameters: 6.4, 8.7, and 34.5 cm, and the measurements were repeated under five supply potentials: 0, −1, −3, −6, and −12 cm for each disk size. This provided 10 estimates of α and K_S values for each disk diameter. Because of the large sand fraction and relatively smooth soil surface, we did not use any contact material for this soil.

To obtain additional estimates of soil hydraulic conductivity for the two soils that would be independent of the tension infiltrometer method, six bore holes, each 15 cm in depth from the soil surface, were used for replicated Guelph permeameter measurements in areas next to the infiltrometer measurements. Soil K_S values were calculated from the Guelph permeameter measurements following procedures similar to that of Reynolds and Elrick (1985) and Elrick et al. (1990), and these were used as a comparison with the tension infiltrometer estimates.

RESULTS AND DISCUSSION

A comparison between the Wooding's and Weir's solutions for small disk sizes showed a consistent and significant difference in the predicted normalized flow rate, Q^* (Fig. 1). Because the refined solution by Weir (1987), or Eq. (6), has been verified with numerical simulations by Weir (1987) and Warrick (1992) to be more exact than the Wooding's solution for $r^* < 0.4$, the normalized flow rate could be underestimated by about 6% for $r^* = 0.1$ to 8% for $r^* = 0.4$ if the conventional Wooding's equation were used. The definition of a small infiltrometer disk radius depends not only on the physical dimension of the disk itself (i.e., r) but also on the properties of the soil. As defined in Eq. (4), the normalized disk radius could be considered small for one soil (with a small α number) but may not be small for a different soil (with a large α number) even though the physical radius of the infiltrometer disk remains the same). The parameter α often ranges from about 0.008 cm^{-1} for a fine-textured soil such as clay to about 0.145 cm^{-1} for a course

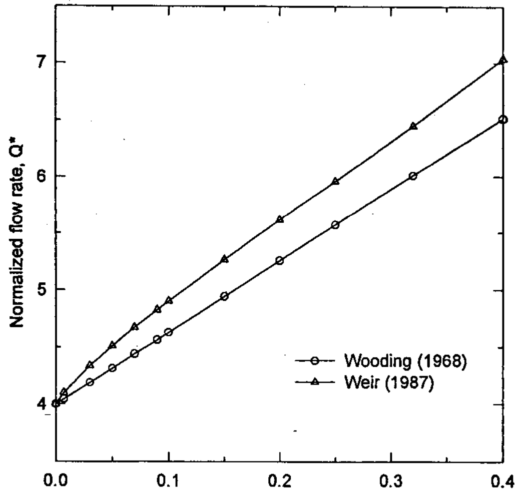

Fig. 1. Predicted water flow from small circular sources using analytical solutions of Wooding (1968) and Weir (1987).

soil such as sand (Carsel and Parrish 1988). To use Wooding's solution without the necessity of correcting for small disk sizes or $r^* < 0.4$, the minimum disk radius (r_{min}) should be 100 cm for clay and 5.52 cm for sand. It would be very impractical to construct and use an infiltrometer with a disk diameter of 2 m.

For each size of infiltrometer disk used in this study, measured steady-state infiltration rate decreased with decreasing supply potential (Figs. 2 and 3). In the Arlington sandy loam, the steady-state infiltration rate at zero potential was about 0.02 and 0.08 cm^3 s^{-1} for disk diameters of 5.5 and 10 cm, respectively. In the Sparta sand, the steady-state rate at zero potential reached about 0.21 and 0.35 cm^3 s^{-1} for the two comparable disk sizes (i.e., diameter = 6.4 and 8.7 cm). This is about an order of magnitude increase, which may indicate that under a normal infiltration event, such as rain or sprinkler irrigation where h_o can be considered as zero, the Sparta sand has a much larger infiltration capacity than the Arlington sandy loam. The steady-state infiltration rate at $h_o = -10$ cm, however, was 0.009 and 0.018 cm^3 s^{-1} for disk diameters of 5.5 and 10 cm at the Arlington sandy loam, and the steady-state rate for the Sparta sand at $h_o = -12$ cm was 0.011 and 0.021 cm^3 s^{-1} for disk diameters of 6.4 and 8.7 cm, respectively. The similar infiltration rates under lower supply potentials may indicate that most of the infiltration in the Sparta sand is attributed to gravity flow.

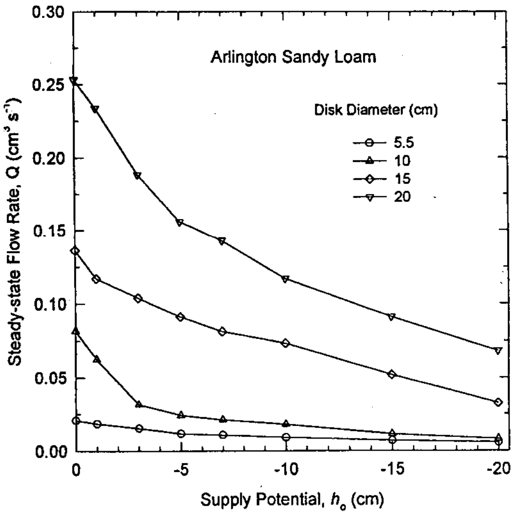

Fig. 2. Measured steady-state water flow using different infiltrometer disks and under variable supply potentials for the Arlington sandy loam.

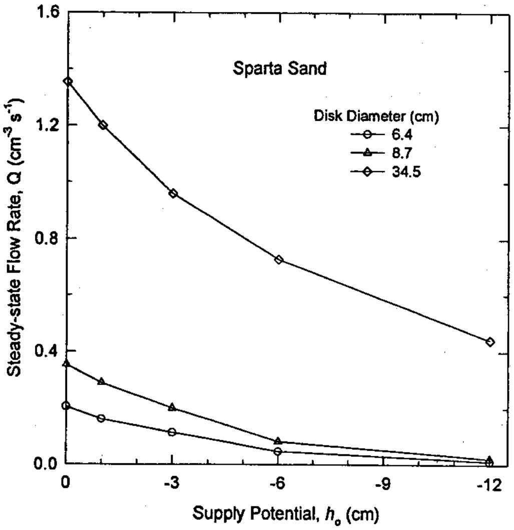

Fig. 3. Measured steady-state water flow using different infiltrometer disks and under variable supply potentials for the Sparta sand.

According to Eqs. (7) to (9), any combination of two supply potentials for each disk size would produce a pair of α and K_S estimates. The multiple measurements (i.e., $n > 2$) enabled us to use the nonlinear regression method (Logsdon and Jaynes 1993) to obtain estimates of α and K_S for each disk size. Shown in Table 1, the overall average of estimated α values was 0.086 ± 0.051 and 0.208 ± 0.055 cm^{-1} for the Arlington sandy loam and the Sparta sand, respectively. These values are reasonable compared with the overall mean: 0.075 ± 0.037 cm^{-1} ($n = 1183$) for sandy loam and 0.145 ± 0.029 cm^{-1} ($n = 246$) for sand, obtained from a much larger database by Carsel and Parrish (1988). According to the estimated α values, the normalized disk radius was less than 0.4 for all the disk sizes used in the Arlington sandy loam. This would imply that correction with Weir's refinement solution would be required to obtain more exact estimates of K_S. For the Sparta sand, however, only the $r = 3.2$ cm disk needed the correction for small disk sizes because the other two disk sizes had $r^* > 0.4$. It is clear that soil properties (i.e., α values) have contributed significantly to the determination of r^* since even a disk radius of 10 cm would be considered small and required a correction in the relatively fine-textured Arlington sandy loam.

With Wooding's method, estimated K_S values averaged $23.07 \pm 9.04 \times 10^{-5}$ cm s^{-1} for the Arlington sandy loam and $208.1 \pm 59.46 \times 10^{-5}$ cm s^{-1} for the Sparta sand. Measurements with the

TABLE 1

Measured soil hydraulic parameters†

Disk diameter (cm)	α (cm^{-1})	r^*	K_S Wooding (1968)	K_S Weir (1987)	K_S Guelph Permeameter
			$\times 10^{-5}$ ($cm\ s^{-1}$)		
Arlington Sandy Loam					
5.5	0.074±0.024	0.102±0.033	11.64±1.28	10.99±1.21	
10	0.134±0.079	0.334±0.197	31.38±9.66	29.23±9.00	
15	0.068±0.021	0.253±0.078	21.31±1.18	19.92±1.10	
20	0.071±0.017	0.353±0.084	27.94±1.98	25.99±1.84	
Average	0.086±0.051	0.260±0.099	23.07±9.04	21.53±8.37	25.49±19.63
Sparta Sand					
6.4	0.233±0.038	0.373±0.061	232.3±17.93	215.7±16.65	
8.7	0.233±0.008	0.508±0.017	258.8±7.30	234.6±6.61‡	
34.5	0.132±0.039	1.138±0.336	116.9±22.72	2.98±0.58‡	
Average	0.208±0.055	0.673±0.333	208.1±59.46	215.7±16.65	252.7±96.30

†Estimated parameters are mean ± standard deviation; $n = 28, 10$, and 6 for the Arlington sandy loam, Sparta sand, and the Guelph permeameter measurements; α = a fitting parameter; r^* = scaled disk radius; K_S = hydraulic conductivity of saturated soil.

‡Exceeding recommended maximum for disk size correction or $r^* > 0.4$.

Guelph permeameter produced K_S estimates of $25.49 \pm 19.63 \times 10^{-5}$ and $252.7 \pm 96.30 \times 10^{-5}$ cm s^{-1} for the two soils, respectively. A statistical mean comparison (with a t statistic for two population means with small sample sizes) indicated that the estimated K_S values were not significantly different (at $P = 0.05$) between the Wooding's method and the Guelph permeameter measurements. This implies that the infiltrometer-Wooding's approximation method can provide a good estimate of soil K_S under field conditions. Close examination also shows that the Guelph permeameter estimates had a larger variation than values obtained from the infiltrometer-Wooding's approximation method; therefore, the infiltrometer-Wooding's method may produce more repeatable K_S measurements than other field techniques such as the Guelph permeameter.

Correction with Weir's solution reduced the average K_S by 7.2% for the Arlington sandy loam. For the Sparta sand, a 7.7% reduction in estimated K_S was obtained for the 3.2-cm radius disk. Large variation was found in estimated α and K_S values between different disk sizes and for each disk size between different supply potentials. The coefficient of variation (CV) for α was 59.3% and 26.4% for the Arlington sandy loam and Sparta sand, respectively. For K_S, calculated CV was 39.2% between the four disk sizes for the Arlington sandy loam and 28.6% for the Sparta sand. These variations are clearly much greater than the potential inaccuracies that Wooding's approximate solution would produce. The large variation in estimated α and K_S values between different disk sizes is very likely caused by soil spatial heterogeneity inasmuch as soil hydraulic properties may change in a very short distance (Mohanty et al. 1994). The variation in estimated α and K_S values between different supply potentials, however, may be attributed to soil macropores. The presence of soil macropores may not be apparent visually but can be effective functionally only when the supply potential is greater than some threshold value when the macropores start to conduct water (Logsdon et al. 1993; Wang et al. 1996).

CONCLUSION

This study was conducted to determine the effect of tension infiltrometer disk sizes on the determination of soil hydraulic parameters using the traditional approximate solutions of water flow from a shallow pond by Wooding (1968). Infiltration in two soils (Arlington sandy loam and Sparta sand) was measured to steady-state with tension infiltrometers of several disk diameters, and the measurement was repeated at multiple supply potentials for each disk diameter. Soil saturated hydraulic conductivity (K_S) and the parameter (α) used in Gardner's exponential saturated-unsaturated hydraulic conductivity function were determined based on the infiltrometer measurements using the Wooding's method and a refinement solution for small disk sizes by Weir (1987). Variation of estimated values of K_S and α between different disk sizes or different supply potentials for the same disk was much greater than the potential overestimation with the Wooding's solution when compared with the Weir's refined solution for small disk sizes. Soil spatial variability and macropores may play a larger role than the physical sizes of the tension infiltrometer disk in the determination of soil hydraulic properties. Wooding's approximate solution should be sufficient for most disk sizes used for the tension infiltrometer measurements.

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