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**In situ Evaluation of Unsaturated Hydraulic Properties
Using Subsurface Points**

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 Variably saturated, permeameters, soil water, hydrology

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Publications & Patents Summary (following page)

Summary of Cooperation (following page)

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Publication Summary (numbers)

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Refereed (published, in press, accepted)	1	3		4
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Patent Summary (numbers)

	Israeli inventor only	US inventor only	Joint IS/US inventors	Total
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Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Visits/Meetings	1	2		3
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- **Cooperation**, briefly explain whether synergistic, complementary or supportive. All four of the P.L's met in Israel in May 1996 which proved a vital planning meeting and visit of Arava Research Station. Three of the P.L's (Or, Shani and Warrick) met at Utah State in August 1997. Runs were made using the Utah State devices in the laboratory. A final meeting of all four P.L's was in Arizona in May 1998.

ABSTRACT

In Situ Evaluation of Unsaturated Hydraulic Properties Using Subsurface Point Sources
(Warrick and Yitayew, University of Arizona; Shani, Arava Research Station and Hebrew University; Or, Utah State University.)

The primary information for accurately predicting water and solute movement and their impact on water quality is the characterization of soil hydraulic properties. This project was designed to develop methods for rapid and reliable estimates of unsaturated hydraulic properties of the soil. Particularly, in situ methodology is put forth, based on subsurface point sources. Devices were designed to allow introduction of water in subsurface settings at constant negative heads. The ability to operate at a negative head allows a direct method of finding unsaturated soil properties and a mechanism for eliminating extremely rapid preferential flow from the slow matrix flow. The project included field, laboratory and modeling components. By coupling the measurements and the modeling together, a wider range of designs can be examined, while at the same time realistic performance is assured. The developed methodology greatly expands the possibilities for evaluating hydraulic properties in place, especially for measurements in undisturbed soil within plant rooting zones.

The objectives of the project were (i) To develop methods for obtaining rapid and reliable estimates of unsaturated hydraulic properties in situ, based on water distribution from subsurface point sources. These can be operated with a constant flow or at a constant head; (ii) To develop methods for distinguishing between matrix and preferential flow using cavities/permeameters under tension; (iii) To evaluate auxiliary measurements such as soil water content or tensions near the operating cavities to improve reliability of results; and (iv) To develop numerical and analytical models for obtaining soil hydraulic properties based on measurements from buried-cavity sources and the auxiliary measurements.

The project began in July 1995 and was terminated in November 1998. All of the objectives were pursued. Three new subsurface point sources were designed and tested and two old types were also used. Two of the three new designs used a nylon cloth membrane (30 μm) arranged in a cylindrical geometry and operating at a negative water pressure (tension). A separate bladder arrangement allowed inflation under a positive pressure to maintain contact between the membrane and the soil cavity. The third new design used porous stainless steel (0.5 and 5 μm) arranged in six segments, each with its own water inlet, assembled to form a cylindrical supply surface when inflated in a borehole. The "old" types included an "off-the-shelf" porous cup as well as measurements from a subsurface drip emitter in a small subsurface cavity. Reasonable measurements were made with all systems. Sustained use of the cloth membrane devices were difficult because of leaks and plugging problems. All of the devices require careful consideration to assure contact with the soil system. Steady flow was established which simplified the analysis (except for the drip emitter which used a transient analysis).

ACHIEVEMENTS

Significance of main scientific achievements or innovations

The vadose zone and near surface soil is positioned literally at the center of most problems dealing with water resources and water quality in terrestrial systems. In order to make meaningful predictions of the water regime, recharge and transport of solutes and contaminants, the soil hydraulic properties are needed. This is true in arid regions, such as the American Southwest and Israel, and in humid regions. Still, to date, most of the measurement technology is focused on either the saturated properties only (hydraulic conductivity and transmissivity) or on laboratory measurements. This project presents methodology for measurements of unsaturated properties, in situ and adaptable for subsurface determinations. This is part of a difficult scenario in order that measurements can be made in situ, below the ground surface and for water under tension. This requires innovation in terms of the design of appropriate devices and in development of analytical techniques to get the needed parameters.

The new devices developed were of two porous materials chosen in order to maintain water flow without air leakage between the source and the soil system. Porous cloth was used as the first membrane material, and put together over a cylindrical framework and designed to inflate against the soil from within a cylindrical bore—while maintaining the water under tension. This device was tested in soil tanks in the laboratory and in the field in both Utah and Arizona. The major difficulties are with respect to initializing the system to assure no air is present, preventing leaks and preventing plugging of the membrane. A second device was constructed using porous stainless steel (0.5 and 5 μm) as the supply surfaces. Six segments or reservoirs, each with its own water inlet, were assembled to form a cylindrical supply surface when fully inflated within a borehole. Reasonable results were also obtained with the porous stainless steel device. This device is more robust than the cloth device and capable of operating under more severe conditions such as with small pebbles or sharp fragments. Other devices which were also used include an off-the-shelf ceramic cup and

subsurface drip emitters. The ceramic cup was found to be quite versatile when used as a infiltration device under tension, although a contact medium between the cup and finer soil materials is needed.

Analysis of the data was examined in the context of alternative forms of hydraulic functions, assumptions of gravity vs. without gravity and steady vs. unsteady states. Generally, the simplest analysis using steady-state conditions and ignoring gravity was acceptable. Choosing a hydraulic conductivity exponentially related to pressure head generally gave results acceptable for the sorptive number (or Gardner α) but in some cases gave saturated conductivity which tended to be too small. Use of a power relationship of saturated conductivity to pressure head (i.e., Brooks-Corey) tended to give more reliable results.

Potential for application, estimated economic benefits and impacts

The devices are usable in their present form, but probably remain primarily as a research tool, rather than a commercial apparatus. Of the devices, probably the porous cup is the easiest to use and is the least fragile. The operation is reliable and the results are repeatable. The problems of installing at deep depths have not been fully addressed, although, in principle, measurements a few meters below the soil surface should be attainable with similar devices. The new devices offer advantages over those using ponded water (i.e, borehole permeameters) in that flow can be limited to the soil matrix and flow in cracks or fissures can be avoided; they also offer advantage over disc-tension permeameters in that subsurface operation is practical. The analyses and background information should serve as a reference point for other in situ devices which will follow over the next decade.

The economic benefit and impacts are difficult to estimate. The gains in better prediction of subsurface hydrology is obviously of great importance, but the dollar amounts and percentage impacts are fuzzy at best.

Details of cooperation

All four of the P.I.'s met in Israel in May 1996. We visited the "Agritech International Exhibition" on Monday before meeting at Volcani on Tuesday to discuss details of the projects followed by visit and meetings at the Arava Research Station on Wednesday and Thursday. This allowed for an in-depth exchange of information among the P.I.'s as well as the other Israeli scientists involved with the project.

Three of the P.I.'s (Or, Shani and Warrick) met at Utah state in August 1997. Runs were made using the Utah State porous steel device in the laboratory. Plans were discussed for the third year of the project, including journal article preparation. A final meeting involving all four investigators was in Tucson in May 1998. This included a field run of all of the permeameters. Later in the summer, a UA student Doug Holland, visited Utah State and did some field tests using the Arizona devices for the Utah soils.

IN SITU EVALUATION OF UNSATURATED HYDRAULIC PROPERTIES USING SUBSURFACE POINT SOURCES

Investigators: A. W. Warrick and Muluneh Yitayew, University of Arizona
Uri Shani, Arava Research Station and Hebrew University
Dani Or, Utah State University

Background, scientific and agricultural relevance of the project

Characterizing and predicting phenomena in the vadose zone remain among the most difficult and challenging tasks dealing with water resources and water quality problems in both arid and humid regions. Agricultural production depends on maintaining favorable water conditions in the root zone and responsibilities include the prudent use of chemicals and minimization of water quality deterioration. Reliable methodology for obtaining necessary soil water transport properties are needed to make meaningful predictions of the water regime, recharge and transport of solutes and contaminants in the vadose and variably saturated zones. Still, to date, most of the measurement technology is focused on either the saturated properties only (hydraulic conductivity and transmissivity) or on laboratory measurements. This project addresses methodology for measurements of unsaturated properties, in situ and adaptable for subsurface determinations.

Methodologies, materials, results and discussion

The technical results of the project will be reported under four topical headings. The major thrust of the project is reported in two papers which have been submitted for publication and are Appendices 1 and 2:

Appendix 1. "Subsurface Tension Permeametry" by Or, Shani and Warrick which has been submitted to Water Resources Research

Appendix 2. "Measurement of subsurface unsaturated hydraulic conductivity" by Holland, Yitayew and Warrick which has been submitted to the Journal of Irrigation and Drainage Engineering (ASCE)

Additionally, results are included below and in Appendix 3 regarding an analysis of transient results and on the effects of source cavity shape on steady flow.

Subsurface tension permeametry

Appendix 1 (which follows in its entirety) describes several tension permeameter devices which were constructed and tested in four soils in both Utah (Millville silt loam and Kidman loamy sand) and Arizona (Gila sandy loam and Vinton fine sand). Both field and laboratory tests were used. The devices were constructed alternatively from porous cloth and a stainless steel arranged in segments which allow expansion to form contact with a cylindrical surface (See Figure 1). A theoretical analysis is also presented using steady state analyses based on the Gardner model (unsaturated hydraulic conductivity exponential decreasing with tension) and Brooks and Corey (power function relations of hydraulic conductivity with finite air-entry value). While the capillary length parameter values were generally consistent with previously measured values, the estimates for saturated hydraulic conductivity were, in some case, an order of magnitude lower than other previously reported values. An analysis based on the Brooks and Corey model seems to extend the useful range of parameters. Values determined for all four soils are given in Table 1. Details of the analysis, construction and testing is in Appendix 1.

Measurement of subsurface hydraulic conductivity

Appendix 2 (which follows in its entirety) describes a second porous cloth permeameter constructed at Arizona as well as use of an off-the-shelf porous ceramic cup to measure unsaturated hydraulic conductivity in situ. A sketch of the porous cloth device is given as

Figure 1. Cloth membrane device.

Table 1. Summary of hydraulic properties.

Soil type	Device	Philip [1986] Eq. (11)		Tensiometers Eq. (2) & (14a)		Brooks & Corey ($n=1$; $b=0.55$)	
		α [cm ⁻¹]	K_s [cm h ⁻¹]	α [cm ⁻¹]	K_s [cm h ⁻¹]	h_c [cm]	m
Millville sl Field 1997	SS 5.0 μ m	0.102	0.567				
	SS 0.5 μ m	0.043	0.102				
	Combined	0.058	0.184	0.037	0.037	-21.0	2.286
Millville sl Field 1998	SS 5.0 μ m	0.059	0.119				
	SS 0.5 μ m	0.047	0.042				
	Fabric 5.0 μ m	0.061	0.054				
	Combined	0.073	0.122	0.052	0.035	-14.8	2.286
Millville sl Lab. 1997	SS 5.0 μ m	0.135	3.26				
Kidman sand Lab. 1997	SS 5.0 μ m	0.145	12.39				
Gila Field 1998	Combined (SS)	0.078	0.234	0.069	0.11	-10.0	2.286
	Fabric 5.0 μ m	0.078	0.975				
Vinton sand Lab. 1998	Combined (SS+Fabric)	0.244	13.6	0.228	6.70

Figure 2. Sketch of the Arizona porous cloth permeameter

Figures 2 and 3. Some of the results are also given in the first paper above. The cloth permeameter was found to be more difficult to operate—primarily due to leaks and plugging. Both methods gave results for unsaturated K that were reasonable (see Table 2). Field testing of the ceramic cup was done using a layer of fine sand for contact between the cup and the soil.

In situ determination of subsurface unsaturated hydraulic conductivities by a single measurement

The steady flow analysis has been extended based on the transient behavior of an infiltration event. The modified procedures are for two types of infiltration experiments: (i) infiltration

Table 2. Comparison of results for the porous cloth and porous cup permeameters.

Soil	Vinton Fine Sand		Gila Loam
Parameter	Porous cloth	Porous cup	Porous cup
Gardner's α (cm^{-1})	0.22	0.20	0.043
K_s (cm/h)	90	57	0.23
Range of h (cm)	-7 to -18	-20 to -32	-10 to -30

Figure 3. Porous cloth permeameter design.

with a constant cavity discharge and pressure build-up; and (ii) constant water pressure in the cavity and variable discharge. Estimates based on the new procedures yielded hydraulic parameters that were in excellent agreement with estimates by the original method using positive pressures and may also be applied to the early stages using the devices above (in Papers 1 and 2). The real advantage is for cases where sampling efforts are limited to a single infiltration event at the depth of interest. This method is still under development. Details of the analysis and testing are in Appendix 3.

Effects of source-cavity shape on steady flow

The effect of source-cavity shape was developed for steady-state, Laplacian flow and published (Warrick and Rojano, 1999). The relevance to the project is that the analysis is valid for steady flow when gravity can be neglected. It is relevant to many potential flow problems including ground water flow, gas flow, heat conduction and other analogs. Gravity is generally less important for small sources. (In Appendix 1, it is shown that for a spherical source, gravity becomes important when the radius divided by the capillary length is significant compared to 2; for other spheroids results are also given.) The shapes considered are given in Figure 4. The general strategy is to look at distances at which the

potential and flow field for the more complex geometries, such as the prolate spheroid, becomes identical to that for the simpler sphere. In addition to the prolate spheroid a finite-line source and “well interval” are considered as shown in the figure. The maximum relative difference (a value of $\delta_{\max} = 0.05$ corresponds to a 5% difference compared to a sphere) is given as Figure 4 for prolate spheroids whose vertical to horizontal axis ratios are $b/a = 5$ and $b/a = 2$. This can also be expressed as

$$\delta_{\max} \approx \frac{c^2}{3\rho^2} + \frac{c^4}{5\rho^4} \quad (1)$$

Figure 4. Alternative sources: (a) spherical, (b) line, (c) prolate spheroidal, and (d) finite borehole interval.

with an error of order of $(c/\rho)^6$, using $c^2 = a^2 - b^2$ with ρ the distance from the center of the source. For $b/a = 2$, the maximum difference is about 1% at a distance of about $5c$ from the source.

The relevance to the project is that the simplest analysis is for a sphere and when gravity can be ignored. This provides a framework applicable for all soil properties and is useful to judge more complex shape factors.

Scientific implications and potential impact on agriculture, industry, environment, policy, legislation

The devices and analysis which were developed provide a methodology for direct characterization of the vadose zone and lead to more reliable input for predicting ground

Figure 5. Maximum relative difference between potential for prolate spheroids with length to width aspects of 2 and 5 compared to sphere of aspect of 1.

water flow and transport. This allows better and more defensible environmental decisions to be made based on sound scientific principles. The interest of all members of society benefit, including agriculture, industry and the general population.

References and Publications

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APPENDIX 1. “Subsurface Tension Permeametry” by Or, Shani and Warrick which has been submitted to Water Resources Research.

Subsurface Tension Permeametry

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ABSTRACT

A new method for determining subsurface unsaturated hydraulic conductivity in-situ was developed. Steady state flow conditions were established from spheroidal cavities under sub-atmospheric pressure. Several borehole tension permeameter devices were constructed and field tested in four different soils. While the capillary length parameter (α) values were generally consistent with previously reported values, the estimates for saturated hydraulic conductivity (K_s) were, in some cases, one order of magnitude lower than reported values for the test soils. In part, this can be traced to the rigid log-linear shape of conductivity to pressure head used by the Gardner model which produces overly small intercept values ($K(0)=K_s$) when measured for drier conditions. Transformation of the estimated parameters to the Brooks and Corey model seems to extend the useful range of the parameters. A potential combination of near-saturation measurements [Shani and Or, 1995] with the proposed method could lead to improved characterization of subsurface $K(h)$.

1. INTRODUCTION

Prevention of groundwater pollution has become a primary concern for many land users, sparking considerable interest in the study of pollutant pathways in the vadose zone. Transport through this zone of variably-saturated porous material is a critical link in understanding transport processes between the soil surface and the groundwater. This is true both for humid and arid regions, however, the thickness of the vadose zone tends to be greater for arid environments. Quantitative models and predictions of transport processes through porous media require the characterization of media hydraulic properties. Such an undertaking is laborious, expensive and time-consuming. The most common approach is characterization through core samples which are removed from the field and taken to the laboratory for evaluation. The determination of hydraulic properties in-situ is considered more reliable and representative of actual field conditions. In-situ methods have emphasized measurements near the surface, such as with tension infiltrometers [Clothier and White, 1981; White and Sully, 1987; Smettem and Clothier, 1989, Hussen and Warrick, 1993] and analysis of one-dimensional infiltration processes.

Unlike the measurement of near-surface hydraulic properties, subsurface measurement presents additional difficulties due to limited accessibility, the lack of well-defined boundaries (limiting the applicability and extension of surface-based methods), and adverse effects of invasive sampling on the properties of interest. Therefore, the need for simple, cost-effective, and physically-sound methods for subsurface hydraulic characterization is widely recognized [Tseng and Jury, 1993; Shan and Stephens,

1993]. Borehole infiltration tests ("packer" tests) have been conducted to considerable depths, however, they nearly always aimed at measurement of saturated hydraulic conductivity only [Stephens and Neuman, 1982]. Other borehole permeameter designs have been proposed such as the Guelph permeameter [Reynolds et al., 1985] for in-situ characterization of subsurface unsaturated hydraulic conductivity. Originally, the method was designed for near-surface measurements but the apparatus can be adapted to obtain measurements to depths of 2-4 m [Amoozegar, 1989]. Unfortunately, it has been recognized that the method can be unreliable leading to physically impossible values of the soil parameters of interest [Elrick and Reynolds, 1992; Heinen and Raats, 1990]. Shan and Stephens [1993] have proposed to use Philip's [1968] solution to the distribution of matric potential, h [length], about a buried point source under steady-state flow conditions as a means for estimating the saturated hydraulic conductivity, K_s [length time⁻¹] and the slope of log unsaturated hydraulic conductivity vs. the matric potential, α [length⁻¹]. Shan and Stephens assume that matric potential measurements can be made at known distances from a fixed-discharge injection source. Consequently, they suggest using these measurements to infer K_s and α in a piecewise linear fashion (i.e., multiple values of K_s and α for various ranges of h). Although Shan and Stephens' method has not yet been tested, their approach implies using a solution which does not satisfy Richards' equation other than within a given step. We foresee several limitations to its routine field application (e.g., difficulties in placing tensiometers to great depths at prescribed distances from a source, and low measurement resolution due to relatively wet conditions at large depths).

Shani and Or [1995] have used Philip's [1992] analysis for the onset of positive pressures about buried point sources as a means for developing a new measurement method for subsurface unsaturated hydraulic conductivity, $K(h)$ [length time⁻¹]. Preliminary field tests of their subsurface confined cavity method yielded estimates of hydraulic properties that are in agreement with other well-established surface-based methods. In soils with substantial amounts of macropores or in highly fissured geologic formations, maintaining a positive cavity pressure is virtually impossible. Furthermore, the results are heavily biased by the presence of such preferential pathways [Wu et al., 1993]. To circumvent the problem we propose in this study to maintain sub-atmospheric water pressures in the cavity, or supply the water under tension through the cavity walls, in order to reduce the role of the presumably empty macropores and fissures on matrix flow. This requires a special apparatus and analysis techniques as will be outlined shortly.

Borehole methods based on analytical solutions to steady flows from subterranean cavities involve certain simplifying assumptions and approximations. These include the simplistic exponential representation of the unsaturated hydraulic conductivity function (required for linearization of the governing flow equation), geometrical approximations to actual boundary conditions, and experimental difficulties in assessing attainment of steady state conditions. Limitations of analytically-based borehole techniques led some researchers [Gribb, 1996; Simunek and van Genuchten, 1997; Hayashi et al., 1997; Timlin and Pachepsky, 1998] to consider application of numerical "inverse" techniques to transient flow experiments. Although numerical methods are capable of accommodating more realistic initial and boundary conditions,

steady state-based analytical methods offer a distinct advantage in a direct linkage between imposed experimental conditions and the hydraulic parameters governing system response.

The specific objectives of this study were: (i) to propose a new field method for obtaining rapid estimates of unsaturated hydraulic conductivity from measurements of tension flow from subsurface cavities; (ii) to present a newly-developed tension permeameter and measurement protocol for field application of the methodology; and (iii) to present results from laboratory and field tests of the proposed method and permeameters in four soils.

2. THEORETICAL CONSIDERATIONS

The analyses of Philip [1986, 1989] offer an analytical framework for estimating soil hydraulic parameters from measurements of steady flow rates from spheroidal cavities under controlled water pressure conditions. These solutions take into consideration the influence of gravity, which enters the calculations through the shape and size of the cavity.

2.1 Analytical Solution for Steady Infiltration from Spheroidal Cavities

Philip [1986] employed the scattering analog methodology [Waechter and Philip, 1985; Philip 1989] to obtain solutions for steady unsaturated infiltration from spheroidal cavity of arbitrary aspect ratio into isotropic soils. Considering a cavity with equatorial (horizontal) radius r_0 , and a vertical semiaxis of symmetry ωr_0 , the spheroidal aspect

ratio is ω . For prolate spheroids $\omega > 1$, for spheres $\omega = 1$, and for oblate spheroids $\omega < 1$.

The idealized geometry of the tension borehole permeameter considered in this study is represented by a prolate spheroid ($\omega > 1$).

Philip [1986] obtained a solution for the total (steady) cavity discharge $Q^*(\omega; s)$ [length³ time⁻¹] as:

$$Q^*(\omega; s) = \frac{8\pi}{\alpha} \Phi_0 \mathcal{L}(\omega; s) \quad (1)$$

where α is the soil sorptive number, a soil parameter defining the slope of $\ln K(h)$ vs. the soil matric potential, h , in the exponential model of unsaturated hydraulic conductivity $K(h)$ proposed by Gardner [1958]:

$$K(h) = K_s e^{\alpha h} \quad (2)$$

with K_s as the saturated hydraulic conductivity; Φ_0 [length² time⁻¹] is the Kirchoff potential (or the matric flux potential) at the cavity surface:

$$\Phi_0 = \int_{-\infty}^{h_0} K(h) dh \quad (3)$$

Other parameters include h_0 the matric potential at the cavity surface, s a dimensionless parameter representing the influences of cavity size and soil capillary behavior defined as: $s = \alpha r_0/2$. The function $\mathcal{L}(\omega; s)$ is the wetting function introduced by Philip [1985b]. A specific form of $\mathcal{L}(\omega; s)$ for prolate spheroids ($\omega > 1$) is provided as eq. (28) in Philip [1986]. The practical usefulness of eq. (1) for hydraulic parameter

estimation hinges on availability of simple approximations for the complex function $\mathcal{Q}(\omega;s)$.

Philip [1986] developed expansions for small and large s values. The cavity aspect ratio ω (Note that ω in this study is identical to that in Philip [1986] for an isotropic soil) is used to define the quantity, τ :

$$\tau = \frac{(\omega^2 - 1)^{1/2}}{\ln[\omega + (\omega^2 - 1)^{1/2}]} \quad (4)$$

Note that the special case of $\omega=1$ (spherical cavity) yields $\tau=1$. This quantity is used to derive approximations for the dimensionless cavity discharge,

$$Q(\omega;s) = \frac{\alpha Q^*(\omega;s)}{8\pi\phi_0 s} \quad (5)$$

for small and large values of s as:

$$\begin{aligned} Q(\omega;s) &= \tau + \tau^2 s + A(\omega) s^2 & ; \quad 0 \leq s \leq \tau^{-1} \\ Q(\omega;s) &= \frac{s}{2} + 0.99615319 \omega^{2/3} s^{1/3} + B(\omega) s^{-1/3} & ; \quad \tau^{-1} < s \leq \infty \end{aligned} \quad (6)$$

A matching procedure employed by Philip [1986] for obtaining approximations for $Q(\omega;s)$ accurate for small and large s values yields the following $A(\omega)$ and $B(\omega)$ coefficients at the matching point $s=\tau^{-1}$:

$$\begin{aligned} A(\omega) &= -\frac{2\tau}{7} (2.5\tau^2 - 0.99615319 \omega^{2/3} \tau^{2/3} + 1) \\ B(\omega) &= \frac{5\tau^{-4/3}}{7} (1.8\tau^2 - 0.99615319 \omega^{2/3} \tau^{2/3} - 0.3) \end{aligned} \quad (7)$$

Philip [1986] stated that eqs. (6) and (7) yield useful estimates for $Q(\omega;s)$ for all $0 \leq s < \infty$, and for cavity aspect ratios in the range $0 < \omega \leq 20$. However, this wide range of

applicability is only given here for completeness; in most practical applications, borehole radii are on the order of a few cm (<5 cm), and α for most soils is the range $0.002 \leq \alpha \leq 0.2 \text{ cm}^{-1}$ [Philip, 1989]. Consequently, the expected range of s is small ($s < 0.5$), and an even simpler approximation based on the two leading terms in the small- s approximation for $Q(\omega; s)$ in Eq. (6) is sufficient. The resulting working equation for relating steady state discharge from spheroidal cavity to soil hydraulic properties is thus:

$$Q^*(\omega; s) = \frac{8\pi\Phi_0 s}{\alpha} (\tau + \tau^2 s) = \frac{4\pi r_0 K(h_0)}{\alpha} \left(\tau + \frac{\alpha r_0 \tau^2}{2} \right) \quad (8)$$

where a substitution of the exponential function for hydraulic conductivity (eq. 2) was introduced into eq. (3), and dry soil conditions are assumed at the fringes of the flow field ($h = -\infty$) to yield: $\Phi_0 = K(h_0)/\alpha$. It is interesting to note that the approximate solution in eq. (8) is identical to an earlier solution for infiltration from spherical cavities (i.e., for $\tau = 1$) obtained by means of separation of variables method [Philip, 1984].

Taking the ratio of two steady state discharge measurements obtained at two different cavity pressures h_{01} and h_{02} , inserted in eq. (8) as:

$$\frac{Q_1^*}{Q_2^*} = \frac{K(h_{01})}{K(h_{02})} = e^{\alpha(h_{01} - h_{02})} \quad (9)$$

results in an explicit expression for estimation of α :

$$\alpha = \frac{\ln[Q_1^*/Q_2^*]}{(h_{01} - h_{02})} \quad (10)$$

The estimated parameter α is then used in eq. (8) to obtain an estimate for the other soil hydraulic parameter K_s :

$$K_s = \frac{\alpha Q_i^* e^{-\alpha h_{0i}}}{2\pi r_0 (2\tau + \tau^2 \alpha r_0)} \quad (11)$$

Either of $\{Q_i^*; h_{0i}\}$ pairs may be used for the estimation of K_s .

Alternatively, for multiple h - Q^* measurements, eq. (8), with $K(h)$ expressed by eq. (2), yields the following linear relationships for estimating K_s and α .

$$h = \frac{1}{\alpha} \left[\ln Q^* + \ln \left(\frac{\alpha}{2\pi r_0 K_s (2\tau + \tau^2 \alpha r_0)} \right) \right] \quad (12)$$

The slope of the regression line between h and $\ln(Q^*)$ equals α^{-1} ; whereas K_s is extracted from the intercept of the linear equation (eq. 12). The expressions in eqs. (10) to (12) form the basis for an analytically-based method for estimating unsaturated soil hydraulic conductivity using two or more measurements of the borehole tension permeameter outlined next.

3. EXPERIMENTAL METHODS

3.1 Design of Inflatable Borehole Tension Permeameter (IBTP)

The primary design considerations for an inflatable borehole tension permeameter (IBTP) were (1) to control the supply tension of water at cavity surface; (2) to ensure hydraulic contact between the permeameter supply surface and the soil cavity walls; and (3) to measure cavity discharge rates. Preliminary experiments with various IBTP prototypes revealed that maintaining permeameter-cavity contact is of crucial importance for obtaining reliable measurements. To ensure consistent contact

with the porous media some have used a rigid-wall permeameter design inserted (or forced) into a slightly under-sized borehole [Gribb, 1996; Kodesova et al., 1998; Hayashi et al., 1997]. Others [Holland et al., 1999] have used fine-sand as contact material between the permeameter and the borehole walls. We opted for an alternative approach based on inflatable permeameters (such as illustrated in Fig. 1) designed to be inserted into slightly over-sized boreholes and inflated in place.

In the basis of the proposed IBTP design, water supply surfaces made of porous materials (to prevent air bubbling into the water supply cavity) are brought into contact with cavity walls by means of an inflatable bladder. The first prototype design (Fig. 1a) was based on a porous membrane made of a finely-woven nylon fabric (Gilson Company Inc., Worthington, OH) with two pore grades of 5 and 30 μm . A thick pad of coarse porous plastic material (e.g., a ScotchBrite pad) was inserted between the rubber bladder and the flexible nylon mesh to ensure free water path. The nylon fabric IBTP geometry. Properties are summarized in Table 1 and Fig. 1 a for the 5 μm fabric. The flexible nylon fabric design was designed for measurements in soft soils and similar geological materials due to its ability to conform to borehole surface irregularities often found in such media. We had many difficulties preventing air from bubbling through the 30 μm nylon fabric, hence only the 5 μm fabric IBTP became operational and will be further discussed.

For a second prototype design we used porous stainless steel at the supply surfaces of the IBTP. Six segments or reservoirs, each with its own water inlet, were assembled to form a cylindrical supply surface when the IBTP is fully inflated within the borehole (Fig. 1b). An additional hemispherical bottom segment was mounted as

illustrated in Fig. 1b to supply water through the bottom of the borehole. Corrugated stainless steel plates were soldered to the back of each porous stainless steel segment to form a gap for water flow. Individual water inlets provided water supply from the IBTP's central stem to each segment unit (Fig. 1b). Two different stainless steel porous materials were used for construction (dimensions and material properties for the two prototypes are listed in Table 1). The air entry values reported in Table 1 pertain to averages over individual segments. These were measured by connecting each segment to a hanging water column and lowering the head until air bubbled through the porous stainless steel (a similar procedure was used for the fabric IBTP). Water tension within the IBTPs was monitored automatically by means of pressure transducers connected to a data logger.

3.2 Measurement System and Procedure

The measurement system consisted of a water supply reservoir equipped with a high resolution pressure transducer for automatic recording of water flow rates connected to the IBTP. The water is supplied to the IBTP under negative (sub-atmospheric) pressure created by a series of Mariotte towers as depicted in Fig. 2. The water height in "tension" columns is used to offset the positive height above the IBTP (denoted by h_3 in Fig. 2), and sets the target value for cavity pressure, h_0 (i.e., $h_0 = h_3 - h_1 - h_2$). As water is drawn from the (Mariotte) water supply reservoir, negative pressure develops at the head space and air bubbles in through the "tension" towers only when the head space pressure equals h_0 (hence a constant sub-atmospheric pressure is maintained at the cavity during the infiltration experiment).

The water level in the reservoir was automatically recorded and converted to volumetric flux into the porous medium ($Q^*=a \, dh/dt$, where dh/dt is the rate reservoir water level change, and a is reservoir cross-sectional area).

In most laboratory and field tests we installed two tensiometers equipped with pressure transducers at distances of 1 and 4 cm from the cavity surface (with their porous cups aligned with the center of cavity). The tensiometers were used to monitor changes in matric potential with time to assess attainment of steady state conditions, and provided data for independent estimation of unsaturated hydraulic conductivity.

The pressure in the inflatable rubber bladder was also monitored: (a) to attain controlled and repeatable contact pressure; and (b) to verify constant contact throughout the duration of the experiment. Typical values of air pressure maintained in the bladder were in the range of 30 to 40 kPa.

To ensure consistent performance of the permeameters, a priming procedure was developed. Prior to each test, air was evacuated from the IBTPs by complete immersion of the porous supply surfaces in a water-filled chamber, and evacuation of chamber's head space with a vacuum pump. The water used in the experiments (especially the SS 0.5 μm) was filtered through a 0.2 μm filter. Prior to each experiment a standard flow test was performed by measuring the flow rate through the IBTP immersed in water for a standard pressure head (usually 10 cm). This procedure was instrumental in identifying potential problems due to pore clogging and air entrapment (especially within the fabric IBTP).

3.3 Experiments and Soils Studied

Initial tests of the IBTPs and the proposed method were conducted in large lysimeters (diameter=0.38 m; height=60 cm) filled with one of the following test soils (Table 2): Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxerolls), Kidman loamy sand (coarse-loamy, mixed, mesic Calcic Haploxerolls), and Vinton fine sand (sandy, mixed, thermic Typic Torrifluvents). A standard 2" hollow stem auger (Giddings Company, Ft. Collins, CO) driven by a sliding hammer was used to create the borehole in the laboratory and in the field. A 2" wire brush was used to gently smooth wall surfaces at the bottom of the borehole (the permeameter location), and to remove any smeared soil layer formed by the auger.

Field tests were conducted at the Greenville farm (located 3 miles north of the Utah State University campus in Logan, UT) in Millville soil and a limited number of tests were performed in Gila sandy loam (coarse-loamy, mixed, calcareous, thermic Typic Torrifluvents) (Table 2) at the University of Arizona Campus Agricultural Center (Tucson, AZ). To simplify installation of IBTP and tensiometers, and for ease of monitoring, most of the field tests were conducted at relatively shallow depths of 30 to 60 cm.

4. RESULTS AND DISCUSSION

4.1 Performance of Inflatable Borehole Tension Permeameters (IBTP)

As indicated earlier, good contact is crucial for reliable measurement, interpretation, and inference of soil hydraulic parameters. Visual inspection of inflated

IBTPs in transparent tubes of similar diameter as the borehole revealed that, in most cases, the flexible fabric IBTP resulted in very good and nearly complete contact. In contrast, the relatively rigid stainless steel (SS) permeameter suffered from incomplete contact, either due to improper alignment of the radial segments upon inflation of the IBTP, or in slightly over-sized boreholes resulting in gaps between adjacent segments. To circumvent these difficulties, we fitted the permeameter with a fabric sleeve (cylindrical+bottom) made of thick felt to serve as soft contact material. This also resulted in more homogeneous hydraulic contact with borehole walls (especially whenever small gaps between segments form). The introduction of a contact "sleeve" reduced contact problems with the SS-IBTPs to a minimum.

Response time and head drop across the porous stainless steel IBTPs was tested by attaching a tensiometer directly onto 5.0 and 0.5 μm porous SS supply segments. The test pairs were placed in Millville soil with the back side of the tensiometer shielded from contact with the soil. The water pressure within the SS segment was varied by means of a Mariotte flask, and was monitored in the tensiometer and within the supply SS segment by pressure transducers. The results show very little head drop across the SS surface ($\Delta h=0.5$ to 2 cm depending on flow rate) in accordance with material properties. Additionally, tensiometer response to changes in segment internal pressure was instantaneous.

4.2 Attainment of Steady State Flow Conditions

Some of the analyses and data interpretation methods assume attainment of steady state flow conditions within the soil volume of interest. In most cases this

condition is assessed by monitoring flux leaving a permeameter and declaring steady state conditions when the flux attains a constant value for some time. Warrick [1992] and others have pointed out that this may take considerably longer than what is commonly reported in the literature. The matric head measurements obtained by the two tensiometers adjacent to the IBTPs highlight another aspect of steady state attainment related to the different soil volumes involved. To illustrate this aspect we show in Fig. 3 typical field measurement results using 0.5 μm SS- IBTP in Millville soil. The top part (Fig. 3a) depicts the changes in cavity pressure and water supply level with time (changes in supply reservoir water level are used for flux calculations). The corresponding tensiometer readings at distances of 1 and 4 cm from the cavity are shown in Fig. 3b. The results clearly show that steady state flow occurs much sooner than for the matric head at 1 cm away from the IBTP. This means that constant flux criteria may involve only a very small volume of soil in contact with the permeameter. Typically, it required more than 2 hours to attain steady state conditions at 1 cm from the cavity, and more than 10 hours for a distance of 4 cm (in Millville soil).

4.2 Estimation of Soil Hydraulic Properties - Results and Comparisons

4.2.1 Millville Silt Loam - Field Measurements

A summary of field measurements collected during the summer of 1997 and 1998 are shown in Fig. 4a and 4b, respectively. The system was set up to collect data automatically (Fig. 2), and typical measurement period for acquiring a Q^*-h data pair took between 4 and 12 hours (in some instances the system was left running overnight). The data in Fig. 4 represent measurements obtained by the SS-IBTPs from

many locations in the field. Despite the large scatter, the relationships between steady state flow rate and cavity pressure show a clear trend. Estimates of the hydraulic parameters α and K_s (Eq. 12) were obtained from individual IBTP measurements, as well as for the pooled data (Table 3). The resulting parameters from field measurements were: $\alpha=0.058 \text{ cm}^{-1}$ and $K_s=0.184 \text{ cm h}^{-1}$ for the 1997 data set, and $\alpha=0.073 \text{ cm}^{-1}$ and $K_s=0.122 \text{ cm h}^{-1}$ for the 1998 season.

The values for the α parameter are within the range of previously measured values in the same field by surface-based methods (e.g., $\alpha=0.075 \text{ cm}^{-1}$ [Shani et al., 1987], and $\alpha=0.057 \text{ cm}^{-1}$ [Or, 1996]). The estimated value of K_s , however, is about one order of magnitude smaller than previously measured saturated hydraulic conductivity in the same field ($K_s=2.56 \text{ cm h}^{-1}$ [Shani et al., 1987], and $K_s=2.30 \text{ cm h}^{-1}$ [Or, 1996]). One possible explanation for the low K_s estimates is due to the unsaturated conditions that exclude large pores that contribute significantly to K_s in the other surface methods where the soil surface is fully saturated (this will be elaborated shortly). The potential for permeameter conductivity limiting the flow was investigated and ruled out (in all cases the flux was much lower than the porous membrane "capacity" for the flow conditions). Moreover, measurements with the same IBTPs in other soils resulted in much higher K_s values (cf., sandy soils in Table 3).

Steady state tensiometer measurements near the cavity (1 cm) were coupled with flux information to calculate the unsaturated hydraulic conductivity at mid-distance, assuming radial-horizontal flow, and using the Buckingham-Darcy equation [$Q^*/(4\pi r^2) = -K dh/dr$] The resulting discrete $K(h)$ values plotted against mean matric head (mean of cavity head and steady state tensiometer value) are denoted as "Darcy" in Fig. 5. The

dashed line denoted as “Eq. (12)” is based on parameters estimated from Eq. (12) for the Gardner [1958] unsaturated hydraulic conductivity function (see Table 3) .

4.2.2 Alternative Analyses Using Tensiometric Measurements

A different approximation was employed for obtaining another estimate for the parameters α and K_s based on tensiometer soil matric head measurements. First, we assume that flow from an IBTP can be approximated by flow from a spherical cavity ignoring exact shape and gravity (Note a recent study by Warrick and Rojano [1999] provides solutions for a wide range of cavity shapes), resulting in the following radial flow equation which can be integrated between cavity surface and tensiometer radial positions:

$$\int_{r_0}^{r_1} \frac{Q}{4\pi r^2} dr = \int_{h_0}^{h_1} -K(h) dh \quad (13)$$

where r_1 and h_1 are the tensiometer radial distance and (steady state) matric head reading, respectively, r_0 and h_0 are the cavity radius and pressure head, and Q is the steady total discharge. Substitution of eq. (2) for $K(h)$ into Eq. (13) and integration yields an analytical expression

$$\left(\frac{1}{r_0} - \frac{1}{r_1} \right) \frac{\alpha Q^*}{4\pi K_s} = \exp(\alpha h_0) - \exp(\alpha h_1) \quad (14)$$

It is then a relatively simple matter to introduce a correction due to IBTP shape and effects of gravity similar to the RHS of Eq. (8) [see discussion and Fig. 1 in Philip, 1984]:

$$\left(\frac{1}{r_0} - \frac{1}{r_1} \right) \frac{\alpha Q^*}{2\pi K_s} \frac{1}{(2\tau + \tau^2 \alpha r_0)} = \exp(\alpha h_0) - \exp(\alpha h_1) \quad (14a)$$

The parameters α and K_s are then estimated from observed Q^* , h_0 , h_1 by parameter estimation routines found in most modern computer spreadsheets [Wraith and Or, 1998]. The resulting α and K_s parameters are denoted in Table 3 as “Tensiometers eq.(2) & (14a)”, and the corresponding line is plotted in Fig. 5 (dash-dot) and denoted as “Eq. (14a)”. In general, we found very good agreement between $K(h)$ based on parameters estimated by this method (Eq. 14a) with estimates by Eq. (11) and data points from direct “Darcy-based” estimates of $K(h)$. We note, however, that availability of this type of information in routine applications will be dependent on ability to place tensiometers at fixed (short) distances from the cavity at large depths of interest (a nontrivial undertaking).

The results in Fig. 5 clearly illustrate the merits and limitations of unsaturated hydraulic conductivity representation based on the Gardner [1958] model (eq. 2). As expected, the match is best for data points at the wet end (high matric head), however, the log-linear relationship fails to capture the behavior for the lower (more negative) matric head. To circumvent this lack of flexibility we seek an alternative representation of $K(h)$ that is fully compatible with the estimated parameters (α and K_s). Warrick [1995] and Shani and Gordin-Katz [1998] developed a framework for relating parameters of different hydraulic models through expressions for the first moment of the diffusivity function. In particular, we are interested in using the simple Brooks and Corey [1964] model for unsaturated hydraulic conductivity:

$$\begin{aligned}
K(h) &= K_s \left(\frac{h_c}{h} \right)^{(n+2)\beta + 2} & h \leq h_c \leq 0 \\
K(h) &= K_s & h > h_c
\end{aligned} \tag{15}$$

where h_c is the air entry value of the matric head, n is a pore connectivity parameter, and β is a pore size distribution parameter. The details of Shani and Gordin-Katz [1998] derivations are beyond the scope of the work, hence only final results are presented here. We denote the exponent in Eq. (15) as $m=(n+2)\beta+2$, and assume reasonable values for shape parameter $b=0.55$ [Warrick and Boradbridge, 1992], and for $n=-1$. Defining $M=(1-b)/b$, Shani and Gordin-Katz [1998] derived the following explicit expression for m :

$$m = 1 + \frac{M}{M(n+3) - (n+2)} \tag{16}$$

For known m , the air entry value parameter (h_c) is estimated from α by: $h_c = 1/(\alpha(1-m))$. The m and h_c values for our measurements are reported in Table 3. The use of these parameters in the Brooks and Corey [1964] $K(h)$ model resulted in very good match with “Darcy-based” $K(h)$ measurements for the entire range of matric head as evidenced in Fig. 5.

Summarizing, matric head measurements in the vicinity of the IBTP provided an opportunity to explore other methods of analysis for estimation of $K(h)$. The parameters and $K(h)$ functions estimated by the three methods resulted in similar and consistent behavior (within their parametric representation limits). The results in Fig. 5 offer a partial explanation for the low K_s estimated from tension measurements. The exponential model of Gardner [1958] results in a straight line on the log-linear scale of

Fig. 5. The intercept of the line ($K(0)=K_s$) is dependent on the range of matric heads used for the measurements [Moldrup et al., 1989], and is expected to decrease as more negative matric head values are used. Hence, the K_s parameter estimated under tension should be viewed as an average “intercept” of the log-linear line (Eq. 2) which is characteristic of the range of matric heads used. This is different than the K_s parameter estimated near saturated conditions by the various surface methods. This observation also raises some concern regarding the indiscriminate use of K_s and α measured by saturation methods to predicted transport processes for dryer conditions.

A combination of methods such as the saturated confined cavity method of [Shani and Or, 1995] and tension methods discussed in this work may be needed to provide complementary information. The potential for converting the Gardner parameters to a more flexible model such as Brooks and Corey's [1964] as proposed by Shani and Gordin-Katz [1998] offers some remedy to the $K(h)$ representation problem over a wide range of h .

4.2.3 Millville Silt Loam - Laboratory Measurements

Measurements were conducted in a soil-filled lysimeter. The primary difference from field measurements was the disturbed state of the soil. Measurement results are depicted in Fig. 6 for a range of h down to -40 cm, with the parameters estimated from this set of measurements given in Table 3. The parameter values $\alpha=0.135 \text{ cm}^{-1}$ and $K_s=3.26 \text{ cm h}^{-1}$ are slightly higher than those obtained in the field, and are somewhat similar to those reported by Shani and Or [1995] for the same soil using saturated subsurface cavity method ($\alpha=0.143 \text{ cm}^{-1}$ and $K_s=5.0 \text{ cm h}^{-1}$). Because these

parameters were estimated from a set of measurements conducted at the same soil volume under different initial and boundary conditions, their significance for field soil is limited (unlike information from multiple locations obtained in the field).

4.2.4 Kidman Loamy Sand and Vinton Fine Sand - Laboratory Measurements

A similar set of measurements was obtained with a lysimeter-filled with Kidman loamy sand. The experiments were relatively simple to conduct due to lack of IBTP-soil contact problems in the sandy soil. Measurement results are depicted in Fig. 7a for a range of h down to -50 cm, and the parameters estimated from this set of measurements is given in Table 3. Parameter values from the IBTP method ($\alpha=0.145 \text{ cm}^{-1}$ and $K_s=12.39 \text{ cm h}^{-1}$) were similar to those obtained by disc permeameter method: $\alpha=0.156 \text{ cm}^{-1}$ and $K_s=21.9 \text{ cm h}^{-1}$ [Or, 1996 unpublished data].

Laboratory measurements were also conducted in Vinton fine sand as part of a collaborative study with the University of Arizona [Holland et al., 1999]. Cavity pressure vs. discharge rate relationships are depicted in Fig. 7b. The resulting $\alpha=0.244 \text{ cm}^{-1}$ is similar to the values of $\alpha=0.20$ to 0.22 cm^{-1} reported by [Holland et al., 1999]. The saturated hydraulic conductivity $K_s=13.6 \text{ cm h}^{-1}$ is lower than reported by Holland et al. ($K_s=90$ to 57 cm h^{-1}) possibly due to the lower range of matric heads ($<-20 \text{ cm}$) used in most of our measurements. However, it is in agreement with the value of $K_s=6.96 \text{ cm h}^{-1}$ reported by Young et al. [1998].

4.2.5 Gila Sandy Loam - Field Measurements

Results from a small number of field measurements conducted in Gila sandy loam (at the University of Arizona Campus Agricultural Center) are depicted in Fig. 8. Parameter values are generally consistent with those reported by Holland et al. [1999] ($\alpha=0.043 \text{ cm}^{-1}$ and $K_s=0.23 \text{ cm h}^{-1}$). Tensiometric measurements were used in similar fashion as described for Millville silt loam field measurements to obtain alternative estimates of $K(h)$. The $K(h)$ functions for the Gila data (Fig. 8b) show a similar trend as found for Millville silt loam soil (Fig. 5b).

5. SUMMARY AND CONCLUSIONS

In this study we developed a field method for estimation of subsurface unsaturated hydraulic conductivity of porous media by borehole tension permeametry. The basic analytical solution we use for inference of hydraulic parameters was derived by Philip [1986] for spheroidal-shaped permeameters of different sizes and aspect ratios. The size, aspect ratio, and the soil capillary length parameter (α) determine the effect of gravity (or the extent of distortion from spherical shape) in the resulting flow field around permeameters.

Two primary prototype borehole tension permeameters (IBTPs) were designed. One design was based on using flexible nylon fabric with small pores ($5 \text{ }\mu\text{m}$) as the porous supply surface. For the second design we used porous stainless steel for the IBTP supply surface. The experimental setup consisted of a Mariotte supply tower connected to a series of tension towers which controlled tension at the plane of the IBTP-soil interface. In addition to the monitoring of cavity pressure vs. flow rate which

are in the core of the measurement, measurements of matric head around the IBTP were collected. The information was gathered automatically from various pressure transducers connected to a data logger.

Field and laboratory tests of the IBTP and the interpretation method were conducted in four different soils: Millville silt loam, Kidman loamy sand, Gila sandy loam, and Vinton fine sand. Analyses based on observations of steady state discharge and cavity pressure only, resulted in estimates of α and K_s for the Gardner [1958] exponential $K(h)$ model. While the α values were generally consistent with previously reported values, the estimates for K_s were, in some cases, an order of magnitude lower than reported values for the test soils. Evidence implicates the linear shape (on a log-linear scale) of the Gardner $K(h)$ model which produces smaller values for the intercept ($K(0)=K_s$) as the matric head used for the measurement becomes more negative. The implications of this observation are that parameter values for the Gardner model may be used for $K(h)$ delineation within the range of their measurement only. For extended coverage, transformations to a more flexible model such the Brooks and Corey [1964] are possible and may improve the range of applicability of the estimated $K(h)$ function. Judicial use of measurements near saturation may be used to complement the unsaturated measurements and provide a more complete description.

A methodology for using auxiliary tensiometric measurements was presented and tested. The matric head information was also instrumental in assessing the relatively slow rate of steady state attainment, and the limited soil volume where such conditions prevail.

Although IBTP design and proposed methodology remain in their preliminary stages, the consistency of the results over a relatively wide range of conditions and soils is promising. The primary results of this study are: (i) the development of a practical methodology for in-situ characterization of subsurface unsaturated hydraulic conductivity; (ii) two prototype tension permeameters were designed and field tested along with a simple experimental setup and measurement protocol; and (iii) laboratory and field tests show the method to provide representative K_s and α estimates for characterization of the $K(h)$ function in-situ for a range of h values.

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Table 1: Specifications of the Borehole Tension Permeameters (IBTPs).

IBTP- Prototype	Porous Material (Manufacturer)	Diameter [mm]	Height [mm]	Material thickness [mm]	Surface area ^(a) [mm ²]	Bubbling pressure [kPa]	Ks (σ_{ks}) ^(b) [m/s]
Nylon fabric 5.0 μm	Woven nylon fabric (Gilson Company Inc., Worthington, OH)	50	100	~0.1	17300	-6.5	3.37×10^{-8} (8.35×10^{-9})
SS 0.5 μm	Porous stainless steel (Mott Metallurgical Corp., Farmington, CT)	54	80	1.5	15700	-34.0	1.17×10^{-7} (6.37×10^{-8})
SS 5.0 μm	Porous stainless steel (Mott Metallurgical Corp., Farmington, CT)	54	80	1.7	15700	-12.0 ^(c)	8.17×10^{-7} (3.54×10^{-7})

(a) total surface area of the inflated IBTP including bottom section.

(b) σ_{ks} is the standard deviation of IBTP-measured saturated hydraulic conductivity.

(c) bubbling pressure variations in the range of -9.5 to -14 kPa were observed among individual IBTP segments (reservoirs).

Table 2: Textural Properties and Porosities of Test Soils.

Soil	Sand (%)	Silt (%)	Clay (%)	Porosity
Millville silt loam	29	55	16	0.46
Kidman loamy sand	86	11	3	0.41
Gila sandy loam	59	32	9	0.43
Vinton fine sand	97	2	1	0.47

Table 3: Summary of hydraulic properties measured by the various IBTP's and analyzed by different methods.

Soil type	IBTP	Philip [1986] Eq. (11)		Tensiometers Eq. (2) & (14a)		Brooks & Corey ($n=-1$; $b=0.55$)	
		α [cm^{-1}]	K_s [cm h^{-1}]	α [cm^{-1}]	K_s [cm h^{-1}]	h_c [cm]	m
Millville sl Field 1997	SS 5.0 μm SS 0.5 μm	0.102 0.043	0.567 0.102				
	Combined	0.058	0.184	0.037	0.037	-21.0	2.286
Millville sl Field 1998	SS 5.0 μm SS 0.5 μm Fabric 5.0 μm	0.059 0.047 0.061	0.119 0.042 0.054				
	Combined	0.073	0.122	0.052	0.035	-14.8	2.286
Millville sl Lab. 1997	SS 5.0 μm	0.135	3.26				
Kidman sand Lab. 1997	SS 5.0 μm	0.145	12.39				
Gila Field 1998	Combined (SS)	0.078	0.234	0.069	0.11	-10.0	2.286
	Fabric 5.0 μm	0.078	0.975				
Vinton sand Lab. 1998	Combined (SS+Fabric)	0.244	13.6	0.228	6.70		

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Figure 1: A scheme of the borehole tension permeameter (IBTP) prototype designs with (a) nylon fabric design, and (b) the porous stainless steel design.

Figure 2: Illustration of the experimental measurement system used in laboratory and field tests. The transducers were connected to a data logger (not shown).

Figure 3: Typical response from the various experimental elements obtained from SS 0.5 μm IBTP measurement in Millville field soil with (a) temporal changes in cavity pressure head and water level in supply reservoir (the volumetric flux is calculated from the slope of the line); and (b) response of tensiometer readings to water application showing the relatively slow and limited attainment of steady state conditions.

Figure 4: Analyses of steady state cavity discharge vs. applied cavity tension (negative pressure head) obtained from different IBTP's for two sampling campaigns in Millville field soil with (a) measurements conducted during Summer of 1997, and (b) results for Summer of 1998. Symbols represent measured values by the respective IBTP prototype, and lines are predictions based on pooled data using eq. (12).

Figure 5: Unsaturated hydraulic conductivity functions for Millville field soil estimated from IBPT and tensiometer measurements during (a) Summer of 1997; and (b) Summer

of 1998. Symbols denote estimates based on Buckingham-Darcy equation using tensiometer data, lines represent different estimates as discussed in the text. Note that “eq. (12)” estimate makes no use of tensiometer information.

Figure 6: Analyses of steady state cavity discharge vs. applied cavity tension obtained in lysimeter filled with Millville soil using SS 5.0 μm IBTP. Symbols represent measured values by the IBTP, and lines are predictions based on pooled data using eq. (12).

Figure 7: Analyses of steady state cavity discharge vs. applied cavity tension obtained in lysimeters filled with (a) Kidman loamy sand, and (b) Vinton fine sand using various IBTP prototypes (see Table 3). Symbols represent measured values by the IBTP, and lines are predictions based on pooled data using eq. (12).

Figure 8: (a) Analyses of steady state cavity discharge vs. applied cavity tension measured in Gila field soil using various IBTPs, with symbols representing measured values by the IBTP, and lines are predictions based on pooled data using eq. (12); and (b) unsaturated hydraulic conductivity functions for Gila field soil estimated from IBTP and tensiometer measurements (see Fig. 5).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

APPENDIX 2. “Measurement of subsurface unsaturated hydraulic conductivity” by Holland, Yitayew and Warrick which has been submitted to the Journal of Irrigation and Drainage Engineering (ASCE).

MEASUREMENT OF SUBSURFACE UNSATURATED HYDRAULIC CONDUCTIVITY

D. F. Holland,¹ M. Yitayew,² Member, ASCE, and A.W. Warrick³

ABSTRACT: Measurement of unsaturated hydraulic conductivity is needed for precise control of water and solutes in the vadose zone. Because of the spatial variation of soils, a large number of surface and subsurface measurements are needed to characterize a field. In this work, permeameters were developed and tested for estimating subsurface unsaturated hydraulic conductivity. The permeameters apply water under a tension and are easy to use and have adequate accuracy. Unsaturated hydraulic conductivity was determined by measuring the steady flow rates for various values of negative pressure. Tests using a soil of known hydraulic conductivity showed that the permeameters provided valid measurements. Two types were used, a porous cloth model which was inflated against the soil and a porous ceramic cup which was rigid. The field testing determined that a rigid design using a ceramic cup coupled to the soil by a layer of fine sand was easier to use, reliable and provided good results.

Keywords. Water flow, Hydraulic conductivity, Vadose zone, Unsaturated water flow

INTRODUCTION

A knowledge of unsaturated hydraulic conductivity is needed to understand water and solute movement under microirrigation, and also has application to drainage and surface irrigation where flow in the vadose zone can be important. Surface and subsurface microirrigation systems are capable of delivering water directly to plant roots, minimizing losses due to evaporation or runoff. This feature is particularly important for the application of chemicals to plants where pollution control is an important concern. Because of the spatial variability of the hydraulic properties in soil, a large number of measurements are needed. Thus, this work was directed at developing a permeameter for measuring subsurface unsaturated hydraulic conductivity that is easy to use and has adequate accuracy.

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Field measurement of hydraulic conductivity can be performed by introducing a monitored source of water either at a positive or negative pressure and observing the resulting flow of water into the soil although negative pressures are very much harder to maintain and operate. The theoretical basis for this flow is well established for many source shapes. Philip (1968) provided the analytical basis for steady flow from a point source under the influence of gravitational and matric forces. In a later paper, Philip (1992) provided simple analytical expressions that described the flow near a point source. Philip (1985) also developed the relation of flow to shape of spheroidal cavities when gravitational forces can be neglected. Warrick and Rojano (1999) developed additional relationships for varied shapes of source cavities and reviewed earlier work using well tests and auger-hole tests. Shan and Stephens (1993) extended the approach of Philip to more complex relations between conductivity and matric potential.

Field measurement methods differ in the geometry of the water source, whether they operate at positive or negative pressure, or whether there are time transients or flow is steady. Shani et al. (1987) used a surface drip system to establish a water source. The borehole or constant well head permeameter and cylindrical sources, have been widely used. They are typically operated at a positive pressure, thus producing a saturated zone around the source. The Guelph Permeameter described by Reynolds and Elrick (1986) is based on this approach and has been widely used in field work with good results.

Shani and Or (1995) used a small subsurface source to provide a quasi-point source operating at a positive pressure.

Operating at a positive pressure results in formation of a region of saturated soil around the source. Water moves into the soil is through this saturated region and then into the unsaturated region. Operating at negative pressure eliminates the saturated region since flow is directly from the source into the unsaturated soil. This could provide a more reliable measurement since flow is less influenced by macro pores. Disc permeameters operate at negative pressure to measure the unsaturated hydraulic conductivity on the surface and the agreement with known unsaturated soil properties was good (e.g., Smettem and Clothier (1989)). Hayashi et. al. (1997) measured subsurface unsaturated conductivity by using a tensiometer in a transient mode.

Although the theoretical understanding is advanced, the field techniques for measurement of unsaturated hydraulic conductivity are still in the investigative stage. This paper reports work that extends the limited methods for field measurement at negative pressure and, in addition, is a first effort to measure the subsurface hydraulic conductivity with a permeameter operating at negative pressure. Although this has the advantages cited above, the low flow rates at negative pressure have presented difficulties in measurement and interpretation.

THEORY

The subsurface permeameter operates at negative pressure. Measurements are made at or near steady flow conditions. In the following, a relationship is developed that uses steady state flow rates at various pressures as a means to determine an approximate expression for the unsaturated conductivity. Flow in soils can be characterized by Darcy's law.

$$J = -K\nabla(-z + h) \quad (1)$$

where $-z + h$ is the hydraulic head, z is the depth, h the matric potential, K is the hydraulic conductivity and J is the Darcian flux of water.

At distances close to the probe under unsaturated conditions, the effects of gravitational forces are small although Philip (1968) provided an approximate solution for flow from a spherical cavity with gravity. When gravity is neglected, the flow from a point source is radial and the equal-potential surfaces are spherical. Neglecting gravity, the following relation holds for steady flow:

$$J = \frac{q}{4\pi r^2} = -K(h) \frac{dh}{dr} \quad (2)$$

where q is the steady water flow rate. Solving this equation for the surface of a spherical probe gives:

$$\frac{q}{4\pi r_o} = \int_{h_\infty}^{h_o} K(h) dh \quad (3)$$

where h_o is the matric potential at the soil interface of a spherical probe of radius r_o and h_∞ is the initial matric potential of the soil in the region of the probe. The matric potential at the interface (h_o) is equal to the pressure of the probe. Equation 4 shows Philip's modification of Equation 3 to include an approximation for gravity.

$$q = \frac{4\pi r_o}{1 - 0.5\alpha r_o} \int_{h_\infty}^{h_o} K(h) dh \quad (4)$$

where α is a constant that depends on soil texture. Equation 4 is valid for $0.5\alpha r_o < 0.2$

The Gardner model was used for the unsaturated hydraulic conductivity since it directly relates the unsaturated hydraulic conductivity to the soil potential and this form can be easily integrated. The hydraulic conductivity relation with the matric potential can be fit to the Gardner model given in Equation 5 within the range of interest for the matric potential

$$K(h) = K_s e^{ah} \quad (5)$$

where K_s is the saturated hydraulic conductivity.

Substituting Equation 5 into Equation 4 and integrating gives the following result:

$$q = \frac{4\pi r_o K_s}{\alpha(1 - 0.5\alpha r_o)} (e^{\alpha h_o} - e^{\alpha h_\infty}) \quad (6)$$

When the initial matric potential is much lower than the operating pressure (dry soil),

$e^{\alpha h_\infty}$ is negligible and the results become

$$\ln q = \ln\left(\frac{4\pi r_o K_s}{\alpha(1 - 0.5\alpha r_o)}\right) + \alpha h_o \quad (7)$$

The slope and intercept of this expression lead to α and K_s .

Since Equation 4 is for a spherical probe, an equivalent sphere must be found that best fits the actual shape of the permeameter. Permeameters with two different shapes were tested, one using porous cloth and one using a ceramic cup. The surface of the porous cloth is that of a cylinder with no flow at the ends. Warrick and Rojano (1999) have developed tables that give the equivalent spherical radius for various ratios of the radius and height of the cylindrical surface. For the porous cloth permeameters used in this work, with a height of 7 cm and a radius of 4 cm, the equivalent spherical radius is 3.1 cm.

The geometry of the porous cup differs in that much of the flow area is in the spheroidal end of the cup. To relate the flow in this geometry to spherical flow, a spheroidal shape is assumed. Philip (1985) studied flow for spheroids where the length of the axis of revolution b is varied relative to the symmetry axis a . He showed that if the volume is held constant, the change in flow for $0.5 < b/a < 2$ is very small compared to a sphere ($b/a = 1$). Therefore, by designing the probe with a height to diameter ratio less than two, the cylinder approximates a sphere. Philip showed that the radius of the equivalent sphere r_o is best determined by equating the volume of the equivalent sphere to that of the probe. Equation 8 provides the equivalent radius for the porous cup

$$r_o = \left[\frac{3d^2s}{16} + \frac{d^3}{16} \right]^{1/3} \quad (8)$$

where d is the cup diameter and s the length of the cylindrical part not including the hemispherical end.

For the cup used in this work, the diameter was 4.4 cm and the length of the cylindrical part including the hemispherical end was 6 cm. These dimensions resulted in an equivalent spherical radius of 2.7 cm. In the field, sand is packed in the space between the cup and the walls of the bore hole. For a 3-inch diameter hole, the diameter would

then be 3 inches or 7.6 cm. Based on Equation 8, the effective spherical radius would then be 4.0 cm.

MATERIALS AND METHODS

The permeameter includes a probe that is placed in contact with the soil. The probe is connected to a monitored supply of water at negative pressure. Figure 1 shows a drawing of the porous cup permeameter as it is used in the field. Fine sand is packed between the cup and the soil to provide the conduction pathway. In laboratory tests, the sand is not needed since the soft soil can be packed directly against the porous material. The soil draws the water from the permeameter through the porous material. In a typical operation, the pressure is held constant at a sub-atmospheric value and the water flowing through the porous material into the soil is measured as a function of time. The matric potential of the soil at the probe interface is equal to the negative pressure of the water source which is maintained by the Mariotte flask. The steady state flow rate at various pressures are then used to determine the hydraulic conductivity at that range of matric potential.

As water is drawn from the flask, negative air pressure will develop above the water in the flask and air will enter the tube near the bottom. This point of air entry is at atmospheric pressure and serves as the reference for establishing the desired pressure. In the field, a small pit is prepared for the flask about 0.5 m from the probe location

with sufficient depth to provide the pressure head required for the tests. The flask is raised or lowered relative to the permeameter to change the operating pressure. Some pressure drops may occur in the line between the flask and the permeameter, so the pressure in the permeameter is measured by a pressure sensor immediately above it (on the right of Figure 1).

The total amount of water that has flowed through the permeameter is indicated by the pressure sensor on the Mariotte flask shown on the left of Figure 1. This pressure sensor determines the water depth by measuring the differential pressure between the air space over the water and the water pressure near the bottom of the flask. The flow rate during a time increment is the change in volume divided by the increment of time.

Tensiometers were used to measure the matric potential in the soil around the permeameter. In laboratory tests, two were placed on the same level as the permeameter to measure the horizontal water movement and one was placed at a depth greater than the permeameter to measure the downward water movement. These tensiometers are equipped with pressure sensors to determine the matric potential. To avoid fracturing the soil, tensiometers could not be placed near the probe in the field tests and thus their readings were not of use.

All measurements and time were recorded on a Campbell Scientific 21X data logger. The input values were averaged over five minutes and the average value was recorded. A computer was used to program the data logger, monitor the sensors, and retrieve the data from the data logger after the completion of the test.

The porous cloth design is shown in Figure 2. Water flows into the region behind the porous cloth and then through the cloth into the soil. The pressure sensor measures the negative pressure at the probe location. The porous cloth was acquired from Gilson Company, Inc., P.O. Box 677, Worthington, OH 43085-0677. A finely woven nylon mesh forms this material. Cloth with pore sizes of 5 and 15 μm were tested. The air entry pressure for the porous cloth determines the maximum negative pressure for which the permeameter can operate. The air entry pressure was measured by placing the cloth in a flat-bottom funnel and attaching a hanging water column. The height of this hanging column is increased until air entry occurs. For the 5 μm and 15 μm cloth, air entry occurred at a pressure head of about -80 cm and -50 cm of water respectively. Below that pressure, leakage increased over a range indicating a range of pore sizes. The 5 μm cloth was used for the permeameter.

Initial tests with the cloth resulted in air entry at pressures much higher than expected (i.e., small pressure differences across the material). The cause appeared to result from air pockets trapped inside the probe at the inner surface of the cloth. The apparatus

shown in Figure 3 was used to fill the porous cloth permeameter to eliminate these air pockets inside the probe. The probe was placed in the container and the air removed. When the pressure was as low as attainable with the vacuum pump, the valve to the pump was closed and the other valve, connected by a tube to a source of water, was opened. To measure pressure drop across the porous cloth from flowing water during a test, the probe was placed in water and connected to an elevated source of water. The measured pressure drop at the highest flows expected during any test were not significant.

The second design used a high-flow porous ceramic cup. The pressure sensor was mounted outside the probe using a tee at the top as shown in Figure 1. The probe is filled with water when operating. The porous cup was manufactured by Soilmoisture Equipment Corporation, P.O. Box 30025 Santa Barbara, CA 93105. The specification for the bubbling pressure was 0.5 bar and the hydraulic conductivity was 3.11×10^{-5} cm/s. To check the specified hydraulic conductivity, the pressure drop was measured across the porous cup by partially filling the probe while the external surface of the porous cup was submerged in water. Tests were conducted before and after exposure to soil for several hours. The pressure drop was proportional to the flow rate, but varied about 10 percent during repeat trials and increased slightly after the soil exposure. The pressure drop agreed well with the calculation from the material conductivity and thickness. The temperature variation agreed well with the expected variation due to the

change in viscosity. For the temperature range during tests reported here, the variation would be less than 10 percent. The pressure drop was approximately 2 cm of water head per unit of flow in cm^3/min . The pressure outside the cup at the soil interface was then determined from the probe pressure by subtracting this pressure drop.

To improve repeatability, test procedures were developed for both the porous cloth and porous cup permeameters based on the initial operating experience. After repeated use of the cloth, the conductivity was reduced by buildup of deposits and was unusable. These deposits may have been biological in origin so water with 2 ppm of bleach was used in all tests. Also, the cloth was changed when it showed indications of reduced conductivity and the outside of the porous cup was cleaned with fine sandpaper before each test. Filling procedures were developed for the porous cup to minimize air trapped inside during filling with water. Water was de-aired by putting it under vacuum prior to use to reduce bubble collection on the inner porous surface that could reduce flow.

For both the porous cloth and porous cup permeameters, a series of tests were performed to determine repeatability. For each test, the operating pressure was varied in steps starting from the lowest tension. For each step, the flow rate was monitored and the pressure was maintained constant until a steady flow was achieved. The pressure, volume of water in the flask, and the three tensiometer's readings were recorded using 5-minute averaged values.

RESULTS AND DISCUSSION

Laboratory Tests

A well-characterized soil, Vinton Fine Sand(sandy, mixed thermic Typil Torriflrvnt), was selected for laboratory testing. This soil is 97% sand, 2% silt, and 1% clay. The unsaturated hydraulic conductivity for this soil was determined by infiltration experiments performed by Zou (1999). The results were matched to the van Genuchten (1980) parameters given by :

$$h = \frac{1}{\alpha} \left(\left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{-1/m} - 1 \right)^{1/n} \quad (9)$$

Where h is the soil water pressure head, θ_s is saturated moisture content, θ_r is the residual moisture content, and α , n, and m are emperical parameters describing the shape of the soil water retention curve. Zou (1999) arrived at the following values:

α	0.0417 cm ⁻¹	θ_s	0.47 volume fraction
n	2.554	θ_r	0.0303 volume fraction
K_s	167 cm/d		

(Note that the α defined by van Genuchten is not the same as that used in the exponential parameterization in Equation 5).

Equation 3 was integrated using the van Genuchten parameters to predict the approximate flow rate for the porous cloth and porous cup designs. The spatial integration was from $r = \infty$ to the effective radius. The effective radius for the porous cloth was 3.1 cm and the effective radius for the porous cup was 2.7 cm. The integration of the matric potential was from $h = -\infty$ to the negative pressure of the probe. This prediction does not include the gravity effect. The predicted flow rates for the two permeameters are shown in Figure 4.

A series of tests were conducted at the University of Arizona Campus Agricultural Center(CAC) using the porous cloth permeameter. The soil at the site is a loam or sandy loam designated Gila Loam. The soil's characteristic curve has been determined previously. Van Genuchten parameters were derived by fitting to the characteristic curve resulting $\alpha = 0.015$, $\theta_s = 0.43$, $\theta_r = 0.1$ and $n = 2$. For the test shown in Figure 5, the tensiometers were placed as follows:

- T1 11 cm horizontal distance from the probe at mid-plane
- T2 3.5 cm horizontal distance from the probe at mid-plane
- T3 5 cm horizontal distance from the probe and 10 cm below the mid-plane

The response of the tensiometers as the wetting front passes these locations can be seen in Figure 5.

After the test, soil was excavated to determine the location of the wetting front. The dimensions of the wetted bulb were 24 cm from the probe center at mid-plane and 33 cm from the probe center at the bottom. This profile is characteristic of unsaturated flow with gravity confirming that the predictions shown in Figure 4 are only approximate.

For the porous cloth tests, Figure 4 compares the natural log of flow to the flow predicted by the van Genuchten parameterization by Zou (1999).

Although these values are in fairly good agreement with the van Genuchten parameterization determined by Zou (1999) in lysimeter tests, the flow rate near saturation is significantly higher. However, the extrapolation of these measured values to saturated conditions results in a saturated hydraulic conductivity that is in good agreement with the measured saturated hydraulic conductivity for the soil used in these tests. The difference between these results and Zou (1999) likely results from the relative light packing used in the tests relative to the lysimeter tests.

A straight line fit, shown in Figure 6, is used for the porous cloth to determine the Gardner parameterization. Using Equation 7, the slope $\alpha = 0.22 \text{ cm}^{-1}$ and based on the intercept with the Y-axis, $K_s = 90 \text{ cm/hr}$.

A second series of tests using the Vinton Fine Sand was conducted with the porous cup permeameter. A typical flow record using the porous cup is shown in Figure 7

For this test, the tensiometers were located as follows:

- T1 4 cm horizontal distance from the probe at mid-plane
- T2 3 cm horizontal distance from the probe at mid-plane
- T3 1 cm horizontal distance from the probe and 4 cm below the cup.

The response of the tensiometers indicates the advance of the wetting front. At the end of the test, the flow was stopped with the cup still in place and the probe acts as a tensiometer. The resulting pressure rise can be seen in the figure. Even though the permeameter without flow would behave as a tensiometer, its pressure differs from the tensiometer readings. This is consistent with the results from the porous cloth permeameter. Since the flow has been stopped, the pressure difference between the probe and the tensiometer is not the result of flow resistance. Some air did diffuse into the head space over the tensiometers and could have contributed to transient effects but whether this could cause the small difference in readings could not be confirmed.

Figure 4 shows the measured flow rates for the porous cup tests compared to the van Genuchten curve derived from the parameters determined by Zou (1999) scaled to the

size of the cup. The operating potential has been adjusted for the pressure drop across the porous cup. The flow rates are comparable to those predicted using the data of Zou (1999) and show agreement with the trend in the porous cloth data towards lower values at lower soil potential. To determine the value of α and the saturated hydraulic conductivity, a straight line was fit to a plot of the natural log of the flow versus the pressure adjusted for the pressure drop in the porous material. The results are shown in Figure 8. Using Equation 7,

$$\alpha = 0.20 \text{ cm}^{-1} \text{ and } K_s = 57 \text{ cm/hr.}$$

Field Tests

Field tests were conducted at the University of Arizona Campus Agricultural Center (CAC) Tucson, Arizona. The purpose of these tests was to evaluate the performance under field conditions. The soil at the site is a loam or sandy loam designated Gila Loam. A hole was prepared with a 37.6 cm auger and the sides were brushed to remove any compressed soil. The gap between permeameter and soil was filled with Vinton Fine Sand that was firmly packed.

The pressure at the soil interface is the probe pressure plus pressure drops across the porous cup and the sand. The pressure drop across the porous material in the cup was discussed previously. The pressure drop in the sand layer Δh can be calculated based on

the previously measured values of unsaturated hydraulic conductivity for the Vinton Fine Sand. As shown in Equation 9, Equation 3 is integrated for the sand layer

$$\int_{r_b}^{r_o} \frac{q}{4\pi r^2} dr = - \int_{h_o + \Delta h}^{h_o} K_s e^{\alpha h} dh \quad (10)$$

where r_o and r_b are the radii of the probe and bore hole respectively, K_s and α are for the Vinton Fine Sand, and h_o is the probe pressure. Rearranging the terms in the solution of the integration give the pressure drop.

$$\Delta h = \frac{1}{\alpha} \ln \left[1 - \frac{\alpha q}{4\pi K_s e^{\alpha h_o}} \left(\frac{1}{r_o} - \frac{1}{r_b} \right) \right] \quad (11)$$

Note that values of h_o and Δh are negative. The presence of the sand extends the effective radius from r_o to r_b .

The porous cup design provided fewer operational and reliability problems and therefore was selected for the field tests. A typical flow history for the porous cup permeameter is shown in Figure 9. Although time averaging filtered out the short transients of period less than 5 minutes, the 60 minute transients for flow changes are clearly seen in Figure 10. A summary of all measurements using the porous cup is

given in Figure 10. The soil pressure has been adjusted for the pressure drop across the porous wall of the cup and the sand.

Based on Equation 7, the Gardner parameters are $\alpha = 0.043 \text{ cm}^{-1}$ and $K_s = 0.23 \text{ cm/hr}$.

These results are generally consistent with the laboratory measurement of the Gila loam soil. The saturated conductivity of the disturbed soil in the laboratory was higher but that would be expected since the packing is less than for field soil.

The validity of these measurements can be evaluated by comparison with the unsaturated hydraulic conductivity derived from the soil's characteristic curve using the method suggested by van Genuchten (1980). The relative conductivity (the ratio of the unsaturated hydraulic conductivity to the saturated conductivity) is shown in Figure 11. The two curves are close enough to indicate the validity of the measurements.

Table 1 summarizes the measured values of the Gardner parameters for the soils tested. The differences are well within the variability expected due to the different soil condition in each test.

Table 1, Comparison of results for the porous cloth and porous cup permeameters

Soil	Vinton Fine Sand		Gila Loam
Parameter	Porous cloth	Porous cup	Porous cup
Gardner's $\alpha(\text{cm}^{-1})$	0.22	0.20	0.043
$K_s(\text{cm/hr})$	90	57	0.23
Range of $h(\text{cm})$	-7 to -18	-20 to -32	-10 to -30

CONCLUSIONS

Two types of permeameters were developed for subsurface measurement of unsaturated hydraulic conductivity, one using nylon cloth and the other a ceramic cup. For laboratory tests with Vinton Fine Sand, the two permeameters agreed with each other. Within the range of soil potentials studied, the measurements of unsaturated hydraulic conductivity are comparable to previous work by Zou (1999) for Vinton Fine Sand but the trend is towards higher values near saturated soil conditions. The differences are probably due to the soil packing during measurement. Measurements by Zou are based on lysimeter tests in which the soil conditions differ from the disturbed soil used in these laboratory tests.

Laboratory tests using the porous cloth probe were limited to pressure above -20 cm because of air entry. However, testing of the porous cloth indicates that air entry should not occur until the pressure is below about -80 cm. The difference probably results from air collecting on the inside of the cloth allowing that portion of the cloth to drain. When water drains from that spot, air can penetrate through the cloth. A new probe design that reduces the potential for air pockets may be effective with this problem but air entry will probably limit this approach to pressures above -50 cm.

Laboratory tests of the porous cup showed some pressure loss occurred as the water flows through the ceramic cup. However, this loss was small and was factored into the

calculations. This pressure drop could be reduced by use of thinner porous material with lower flow resistance. Air entry in the porous cup was not a problem in our experiments. However, a greater surface area will be needed to measure flows at lower pressure.

Laboratory tests for both the porous cloth and porous cup permeameters showed some differences between the soil pressure measured by the tensiometers and derived from the soil moisture, compared with values predicted by the permeameter operating pressure. Since this difference persisted after the flow was stopped, the origin does not appear to be related to pressure drops between the probe and the soil. The good agreement with measured hydraulic conductivity based on the probe pressure indicates that differences between the probe pressure and the tensiometers does not affect measurement.

Field tests were performed to determine the suitability of the permeameters for field use. Operation of the porous cup was superior to the porous cloth design because of the higher air entry pressure and lower potential for air leaks. Field tests of the porous cup indicated that packing high conductivity sand between the porous cloth and the field soil is effective in establishing good contact. The pressure drop in the sand is small and can be calculated based on the soil properties for Vinton Fine Sand.

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Appendix II. Notation

The following symbols are used in this paper:

d	=	outer diameter of the porous cup;
h	=	matric potential;
h_o	=	matric potential at soil interface;
h_{∞}	=	initial matric potential of the soil in the region of the probe;
J	=	Darcian flux,
K	=	unsaturated hydraulic conductivity;
K_s	=	saturated hydraulic conductivity;
m, n	=	parameter in the van Genuchten parameterization;
q	=	water flow rate;
r	=	distance from the probe center;
r_o	=	equivalent radius of the probe;
r_b	=	equivalent radius of the bore hole;
s	=	height of the cylindrical portion of the porous cup
z	=	depth in soil;
α	=	parameter in Gardner or van Genuchten parameterization;
Δh	=	water head loss in the sand between the probe and soil;
θ_r	=	residual water content in the van Genuchten parameterization;
θ_s	=	saturated water content in the van Genuchten parameterization.

Figure 1. Permeameter system

Figure 2. Porous cloth permeameter design

Figure 3. Vacuum container for evacuation and filling of permeameter

Figure 4. Predicted flow rates for Vinton Fine Sand based on van Genuchten parameters

Figure 5. Porous cloth permeameter results for Vinton Fine Sand

Figure 6. Analysis of all tests on Vinton Fine Sand with the porous cloth

Figure 7. Porous cup permeameter results with Vinton Fine Sand

Figure 8. Analysis of results for porous cup in Vinton Fine Sand

Figure 9. Test results for Gila Loam using the porous cup.

Figure 10. Analysis of the results for the porous cup in Gila Loam

Figure 11. Comparison of measured unsaturated hydraulic conductivity to values derived from the characteristic curve

FIGURE CAPTIONS

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