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Geotechnical Site Characterization

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A new CPT method for estimating soil hydraulic properties

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ABSTRACT: Complete characterization of contaminated sites should include determination of soil hydraulic properties that describe behavior under unsaturated conditions. We present a new cone penetrometer test (CPT) method for estimating soil-moisture characteristic and hydraulic conductivity curves from in situ measurements. A modified cone penetrometer is used to inject water from a screen into the soil. The cumulative flow and pressure heads at two locations are recorded in time. The soil hydraulic properties are obtained via numerical inversion of Richards' equation. Here we discuss field-scale tests in a laboratory aquifer that demonstrate the device and solution technique. Results show that the saturated hydraulic conductivity is well estimated and the soil moisture characteristic curve lies between the wetting and drying curves obtained from other standard laboratory methods.

1 INTRODUCTION

Definition of the hydraulic properties of unsaturated soils is increasingly necessary for geotechnical applications. Knowledge of the soil-mositure characteristic and hydraulic conductivity curves, θ(h) and K(h), is particularly important for accurate numerical modeling of variably saturated flow and contaminant transport processes. While these soil properties can be determined in the laboratory, in situ methods are often preferred.

Direct measurement of point data on the soil-moisture characteristic curve, θ(h), and/or the hydraulic conductivity curve, K(h), may be obtained using instantaneous profile, crust, or infiltrometer methods, among others (Klute & Dirksen 1986; Benson & Gribb 1997). The Guelph permeameter and double ring infiltrometer are commonly used to obtain saturated hydraulic conductivity values (Reynolds 1993; Bouwer & Jackson 1974).

Parameter optimization is an indirect approach that makes it possible to obtain K(h) and θ(h) simultaneously from transient flow data (Kool et al. 1987). A flow event is modeled with an appropriate governing equation and analytical models of K(h) and θ(h). The unknown parameters of K(h) and θ(h) are obtained by minimization of an objective function describing the differences between some measured flow variables and those simulated with a model. This methodology was originally applied to one-step and multi-step column outflow data in the laboratory (see for example, Kool et al. 1985; Parker et al. 1985; van Dam et al. 1992, 1994; and Eching & Hopmans 1993). In the field, this method has been used with ponded infiltration (Bohne et al. 1992), tension disc infiltrometer (Šimůnek & van Genuchten 1996, 1997, and Šimůnek et al. 1997), and multi-step soil water extraction data (Inoue et al. 1997) obtained in the near surface.

Gribb (1993, 1996) proposed a new cone penetrometer tool (e.g., cone permeameter) and use of parameter optimization to estimate soil hydraulic properties at depth. The prototype was further developed by Leonard (1997) as shown in Figs. 1. and 2. The cone permeameter is pushed into the soil to the test depth, and a constant head is then applied to the 5-cm long screen. Cumulative inflow volume is determined from scale readings of the mass of water removed from a bottle. Pore water pressure increases are measured with tensiometer rings 5 and 9 cm above the screened section. An inverse solution method is used to predict the soil hydraulic

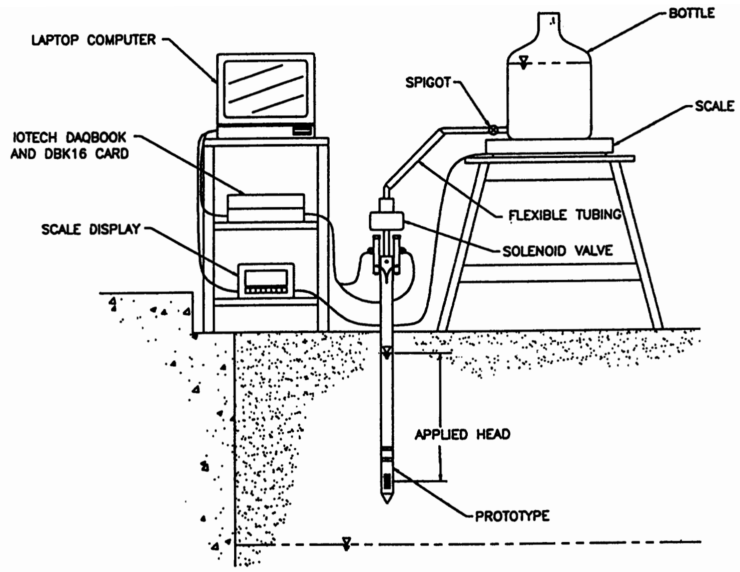

Fig. 1. Cone permeameter test set up (Leonard 1997).

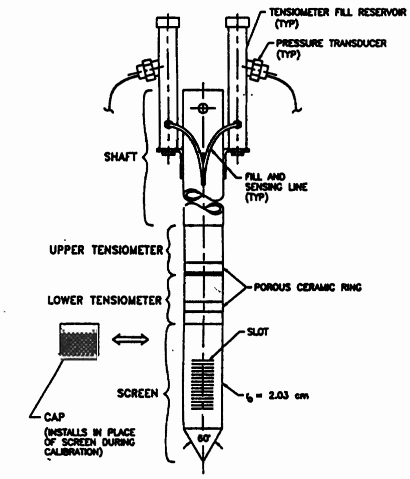

Fig. 2. Prototype cone permeameter (Leonard 1997).

properties. Here we present observed data and numerical analysis of tests performed by Leonard (1997) in a laboratory aquifer system under unsaturated conditions. Results are compared with independent measurements of the soil hydraulic properties to benchmark performance.

2 THEORY

HYDRUS-2D (Šimůnek et al. 1996) is used to simulate the cone permeameter test in unsaturated soil. The governing flow equation for radially symmetric, isothermal Darcian flow in an isotropic, rigid porous medium, assuming that the air phase plays an insignificant role in the liquid flow process is (Richards 1931):

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r K \frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right] = \frac{\partial \theta}{\partial t} \tag{1}$$

where r = radial coordinate, z = vertical coordinate positive upward, t = time, h = pore water pressure head, and K and θ = hydraulic conductivity and volumetric moisture content, respectively. The initial pressure head distribution in the domain is determined from initial tensiometer readings. A constant head boundary condition is applied to represent the source. Exterior boundaries are located far enough away from the source as not to influence the solution, and are defined as no-flow boundaries.

The van Genuchten (1980) expressions for the moisture content and hydraulic conductivity $\theta(h)$ and $K(\theta)$ are used in this work:

$$\theta_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^n\right)^m} \quad h < 0$$

$$\theta_e = 1, \quad h \geq 0 \qquad (2)$$

and

$$K(\theta) = K_s\, \theta_e^{0.5}\left[1 - \left(1 - \theta_e^{1/m}\right)^m\right]^2 \quad h < 0$$

$$K(\theta) = K_s \quad h \geq 0 \qquad (3)$$

where θ_e = effective moisture content, K_s = saturated hydraulic conductivity, θ_r and θ_s = residual and saturated moisture contents, respectively, α, n and m (= 1 - 1/n) = empirical parameters. The hydraulic characteristics defined by (2) and (3) contain five unknown parameters: K_s, θ_r, θ_s, α, and n.

To derive estimates of the hydraulic parameters using parameter optimization, an objective function, Φ, expressing the differences between flow responses measured with the prototype and those predicted by a numerical model with hydraulic parameter inputs, is minimized:

$$\Phi(\beta, q_k) = \sum_{j=1}^{k}\left[v_j \sum_{i=1}^{n_j} \left[q_j^*(t_i) - q_j(t_i, \beta)\right]^2 \right] \qquad (4)$$

where k = number of different sets of measurements, such as cumulative inflow volume, or the pressure head measurements, n_j = number of measurements in a particular set, $q_j^*(t_i)$ = specific measurements at time t_i for the jth measurement set, β = vector of optimized parameters (e.g., K_s, α, θ_s and n in this work), $q_j(t_i, \beta)$ = corresponding model predictions for the parameter vector, and v_j = weights associated with a particular measurement set. Minimization of the objective function Φ is accomplished using the optimization routine developed by Šimůnek & van Genuchten (1997).

3 METHODS

Prototype tests were conducted in a laboratory aquifer measuring 4.7 m x 4.7 m x 2.6 m. The aquifer material is a sandy soil with occasional kaolin pockets, underlain by 20 cm of gravel. A description of the aquifer and properties of the soil were previously presented by Gribb et al. (1997). The cone penetrometer was continuously pushed to a depth of 70 cm by a drill rig. Two representative tests were selected for presentation here. For a first test (Test A) a water pressure head of 30 cm was supplied to the center of the screen. The following day, a second test (Test B) was performed with a water pressure head of 50 cm. Flow data were electronically collected every 5 sec for 400 sec (Leonard, 1997).

Two inverse solutions for each test were performed. In the first case, Inverse Solution 1 yielded estimates of the unknown parameters, α, n, θ_s and K_s, for θ_r = 0.008 cm^3/cm^3. In the second case, Inverse Solution 2 yielded estimates of α, n and K_s, for θ_s = 0.35 cm^3/cm^3 and θ_r = 0.008 cm^3/cm^3.

4 RESULTS AND DISCUSSION

Results of the optimization processes and

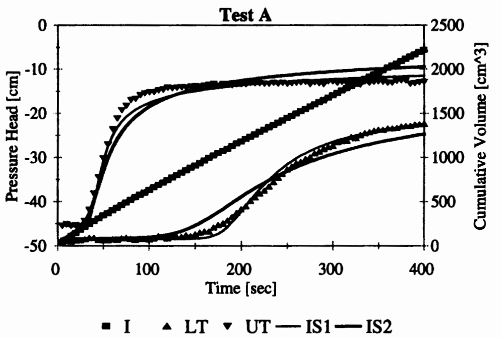

Fig. 3. Measured cumulative inflow (I), and pressure head data (LT = lower tensiometer, UT = upper tensiometer) and simulated flow responses (IS1 = Inverse Solution 1, IS2 = Inverse Solution 2) for Test A.

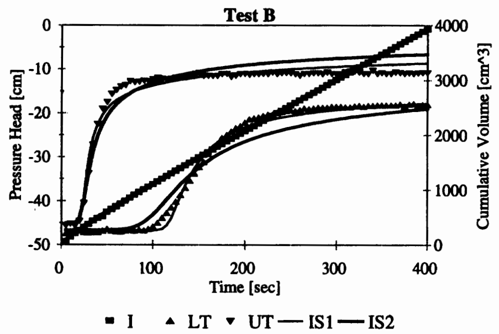

Fig. 4 Measured cumulative inflow (I), and pressure head data (LT = lower tensiometer, UT = upper tensiometer) and simulated flow responses (IS1 = Inverse Solution 1, IS2 = Inverse Solution 2) for Test B.

representative hydraulic property data obtained using standard techniques are shown in Figs. 3-5 and in Table 1. Measured and simulated cumulative flow and pressure head data in time from the two inverse solutions are plotted in Figs. 3-4 The estimated retention curves for solutions of the two cone permeameter tests, along with those independently determined with capillary rise and pressure plate tests (Singleton, 1997) are presented in Fig. 5. Table 1 shows the hydraulic parameters α, n, θ_s and K_s estimated via inverse modeling, hydraulic parameters α, n and θ_s of the retention curves obtained with the standard laboratory methods and the mean values of K_s determined from slug tests (Scaturo, 1993), Guelph permeameter tests (Scaturo, 1993) and laboratory constant head tests (Singleton, 1997).

The estimates of parameters α, n, θ_s and K_s obtained solely from the cone permeameter flow responses (Inverse Solution 1) provided a better fit of measured data for both numerical solutions. The resulting retention curves for both tests followed the same shape, but the estimated saturated moisture content θ_s was much smaller than that obtained from other test methods.

Nonuniqueness of θ_s values was anticipated by the results of earlier numerical experiments with error-free synthetic data. Gribb (1996) showed that an objective function similar to (4) was least sensitive to θ_s and n, and more sensitive to K_s and α. Since θ_s was not reliably estimated for this test, Inverse Solution 2 was performed to investigate the influence of θ_s. In this case, θ_s was set equal to 0.35 cm^3/cm^3, and K_s, n, and α were optimized. The simulated cumulative flow data fit the measured data very well, and the modeled pressure heads at the lower tensiometer position tracked closely to observed data. On the other hand, the simulated pressure heads at the upper tensiometer showed earlier, and more gradual, progressions of the wetting front when compared to the measured data. Comparison of soil hydraulic properties resulting from Inverse Solutions 1 and 2 shows that the optimized parameter K_s increased with the larger fixed value of θ_s for both tests. It is interesting to note that higher values of K_s were obtained for Test B. This test was performed with a higher applied pressure head, which resulted in larger pressure head increases in the soil than in the case of Test A. However, the values of K_s obtained were very close for both tests and solutions. Values of α and n decreased and the characteristic curves had more gradual slopes with the higher, fixed value of θ_s. The shapes of the curves obtained from both tests were similar for each solution.

Table 1. Hydraulic parameters obtained from laboratory tests and inverse solutions. CR = capillary rise, PP = pressure plate, ST = slug test, GP = Guelph permeameter, CH = constant head laboratory test, A, IS1 = Test A, Inverse Solution 1, B, IS2 = Test B, Inverse Solution 2, and so on.

Test	Hydraulic Parameters			
	α [cm^{-1}]	n [-]	θ_s [-]	K_s [cm/sec]
CR	0.086	3.60	0.33	-
PP	0.045	1.61	0.35	-
ST	-	-	-	0.0073
GP	-	-	-	0.0035
CH	-	-	-	0.0039
A, IS1	0.047	4.24	0.21	0.0032
A, IS2	0.040	2.12	0.35	0.0036
B, IS1	0.048	7.00	0.22	0.0039
B, IS2	0.036	2.57	0.35	0.0042

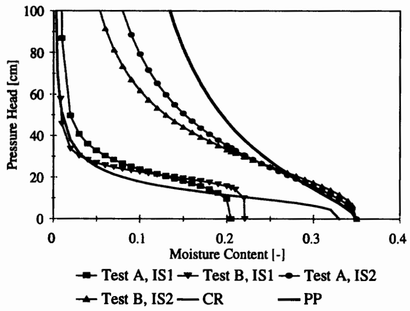

Fig. 5 Soil-moisture characteristic curves for the pressure plate (PP), capillary rise (CR) and inverse solutions for Tests A and B (IS1 and IS2).

Disturbance of the soil surrounding the cone occurs during placement. However, it seems that soil structure changes due to placement were not significant for this soil. This was evident from the results of the numerical inversions, which were within the range of hydraulic properties obtained with other standard techniques. Saturated hydraulic conductivity values were similar to those obtained with Guelph permeameter (Scaturo, 1993) and laboratory constant head tests (Singleton, 1997). The soil-moisture characteristic curves were most similar to the wetting retention curve determined with the capillary rise test. The curves for fixed θ_s = 0.35 were within the two limiting branches of the characteristic curves obtained with the capillary rise (wetting) and pressure plate (drying) tests. The shapes of the curves close to the limiting or scanning wetting branches of the soil-moisture characteristic curves were expected, because of the wetting character of the cone permeameter test.

5 CONCLUSIONS

We present here a new cone tool for simultaneous determination of the soil-moisture characteristic and hydraulic conductivity curves in unsaturated soil. Our results in a laboratory aquifer composed of sandy soil showed that the saturated hydraulic conductivity was well estimated. In addition, the soil-moisture characteristic curves obtained were between the wetting and drying curves obtained from other standard laboratory methods.

It is well known that the soil fabric is disturbed due to cone penetration; however, the results of these few tests in sandy soil show little effect of disturbance on the value of K_s returned from the optimization procedure. It is likely that disturbance effects will be more significant in other soil types. This will be studied further in the field.

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