HYDRAULIC PROPERTIES OF SOIL CORES FROM UNTRAFFICKED AND TRAFFICKED AREAS

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The hydraulic conductivity is an important soil parameter that is both difficult and time consuming to measure directly. Several methods have been proposed to estimate soil hydraulic conductivity indirectly. This paper focuses on one method of predicting hydraulic conductivity from knowledge of the soil water retention curve. Water retention curves were measured for 15 undisturbed soil cores. Unsaturated hydraulic conductivity of the same 15 soil cores also was determined directly by using unit gradient measurements. An equation was fitted to each of the retention curves, and a procedure using the fitting parameters was implemented to predict hydraulic conductivity of each core. Predicted and observed hydraulic conductivities are compared. The procedure describes hydraulic conductivity relationships better when observed values of unsaturated hydraulic conductivity are included in the curve fitting process, than when the saturated hydraulic conductivity alone is used as a matching point. Analysis of a data set taken from the literature indicates that observed air permeabilities may also be useful for estimating the unsaturated hydraulic conductivity.

INTRODUCTION

The hydraulic conductivity is an important property that affects the transport of water and solutes in soil. Most processes involving water flow in the rooting zone occur under unsaturated conditions. Several investigators have searched for alternative ways to estimate the unsaturated hydraulic conductivity because of difficulties associated with direct measurement of the hydraulic conductivity. Many methods have been proposed to estimate hydraulic conductivity indirectly from more easily measured soil properties. Attempts have been made to estimate hydraulic properties of soil by using data such as soil texture, organic matter content, and bulk density. *Clapp and Hornberger* [1978], for example, have estimated the exponent of a water retention power curve by using soil textural information. *Bloemen* [1980] used textural properties to estimate a parameter in the *Brooks and Corey* [1964] equation. *Schuh and Bauder* [1986] indicated that bulk density was not always a productive indicator of the unsaturated hydraulic conductivity because of ambiguities resulting from grain size and compaction. They also showed that organic matter related well to hydraulic conductivity only at high water contents, whereas water-filled porosity was significantly related to hydraulic conductivity at several water contents.

Much attention has been devoted to the use of pore-size distribution functions obtained from soil water retention curves (volumetric water content, θ, as a function of soil water pressure head, h) for predicting the hydraulic conductivity. Among the most popular methods have been *Millington and Quirk* [1961], *Brooks and Corey* [1964], *Campbell* [1974], and *van Genuchten* [1978, 1980]. The main objective of this study is to use the analytical function of *van Genuchten* [1980] to describe observed water retention data, and to predict the unsaturated hydraulic conductivity. Predicted hydraulic conductivities will be compared to measured values.

THEORY

The following equation was presented by *Mualem* [1976] to predict the relative hydraulic conductivity, K_r, by using information from the water retention curve

$$K_r = S_w^{1/2}\left[\frac{\int_0^{S_w}[h^{-1}(x)]dx}{\int_0^1[h^{-1}(x)]dx}\right]^2 \tag{1}$$

where h is the pressure head, which is a function of the dimensionless water content, S_w:

$$S_w = \frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{2}$$

in which θ_r is the residual water content, and θ_s is the saturated water content.

Van Genuchten [1980] proposed the following expression for the water retention relationship:

$$S_w = \frac{1}{\left[1+(\alpha h)^n\right]^m} \tag{3}$$

where α, n, and m are parameters that can be determined by curve fitting (3) to data.

Van Genuchten [1980] combined (3) and (1), set $m = 1\text{-}1/n$, and evaluated the integrals to find a closed-form equation for K_r:

$$K_r(S_w) = S_w^{1/2}[1-(1-S_w^{1/m})^m]^2 \tag{4}$$

where $m = 1\text{-}1/n$ is the same m as in (3). Thus, once (3) is fitted to water retention observations, the parameter n can be used in (4) to predict the unsaturated hydraulic conductivity.

The relative hydraulic conductivity also may be expressed in terms of the pressure head by substituting (3) into (4):

$$K_r(h) = \frac{\left(1-(\alpha h)^{n-1}[1+(\alpha h)^n]^{-m}\right)^2}{[1+(\alpha h)^n]^{m/2}} \tag{5}$$

To estimate the relative hydraulic conductivity from air permeability measurements, one can extend Mualem's model to the gas phase in a procedure similar to that of *Parker et al.* [1987] by using

$$S_a = 1 - S_w \tag{6}$$

where S_a is the reduced air content. Substitution of (6) into (1) gives

$$k_{ra}(S_w) = (1-S_w)^{1/2}(1-S_w^{1/m})^{2m} \tag{7}$$

where k_{ra} is the relative air permeability. By determining k_{ra} experimentally as a function of S_w [*Evans*, 1965], the parameter m in (7) can be determined. Substitution of m into (4) subsequently provides estimated values of K_r.

MATERIALS AND METHODS

Undisturbed soil cores 7.6 cm in diameter by 7.6 cm long were obtained with a Uhland core sampler [*Blake*, 1965] from depths of 5 to 15 cm in field plots established on a Muscatine soil (fine-silty mixed mesic Aquic Hapludolls) near Marshalltown, IA. Eight samples were taken from the middle of an interrow under wheel tracks and seven from the middle of an interrow with no wheel tracks.

Soil water retention values were determined, corresponding to soil water matric potentials of 0, -10, -20, -30, -50, -130, -200, -300, and -400 cm of water. Potentials were achieved by desorbing soil cores using compressed air and fritted glass plates sealed into Buchner funnels [*Hill et al.*, 1985]. Matric-potential values of -1 to -15 bars were obtained by using a pressure plate apparatus [*Richards*, 1965]. Cores were initially saturated overnight from the bottom under a small head of water. The water content at each pressure step was calculated from the volume of outflow between pressure steps and the weight of oven-dried cores.

Unit gradient laboratory measurements of the unsaturated hydraulic conductivity were made by using a device similar to that described by *Klute and Dirksen* [1986]. A Mariotte bottle controlled the tension at the upper soil surface, and a hanging water column controlled tension at the lower surface. A broadcloth-covered 400-mesh nylon filter (Spex Industries; Edison, NJ) was used as a porous membrane for hydraulic contact with the soil. To establish the tension boundary condition uniformly on both ends of the soil cores, sand was applied to provide a smoother contact surface. Unsaturated measurements at 3, 6, and 15 cm of water tension were made, followed by measurements of saturated hydraulic conductivity.

The nonlinear regression computer program RETC [*Leij et al.*, 1992] was used to fit analytical functions to observed retention and conductivity data, either independently or simultaneously. The residual water content, θ_r, was not used as an unknown parameter in the curve-fitting program, but was assigned the value of water content measured at a matric potential of -15 bars.

Table 1. Values of the Parameter n†

Sample no.	Retention	Conductivity	Simultaneous
		Untrafficked	
1	1.228	1.025	1.186
2	1.260	1.077	1.181
3	1.212	1.076	1.183
4	1.250	1.086	1.222
5	1.292	1.226	1.226
6	1.209	1.048	1.191
7	1.207	1.109	1.205
$\bar{X}$	1.237	1.092	1.199
		Trafficked	
8	1.280	1.672	1.397
9	1.226	1.042	1.194
10	1.203	1.013	1.263
11	1.204	1.195	1.195
12	1.204	1.013	1.252
13	1.249	1.170	1.179
14	1.208	1.292	1.235
15	1.245	1.359	1.273
$\bar{X}$	1.227	1.220	1.249

† Retention parameter means were obtained using (3) to fit retention data, conductivity means using (5) to fit conductivity data, and simultaneous means using both (3) and (5) to fit all data.

RESULTS AND DISCUSSION

Table 1 presents the n parameters obtained by fitting (3) and/or (5) to measured hydraulic data for each soil core. Because the parameter α does not appear in all of the equations that may be used for fitting the observed data, we discuss here only the parameter n.

Stephens and Rehfeldt [1985] pointed out that the slope of the $K_r(h)$ curve is determined almost exclusively by the parameter n. This parameter was determined in three different ways. First, (5) was fitted directly to measured unsaturated hydraulic conductivity data. Next, (3) was fitted to water-retention data. Finally, (3) and (5) were fitted simultaneously to the conductivity and retention data. The average values of n for wheel-tracked cores obtained by fitting conductivity, retention, and simultaneous data are 1.220, 1.227, and 1.249, respectively. The average values of n for untracked cores obtained by fitting conductivity, retention, and simultaneous data are 1.092, 1.237, and 1.199, respectively. The ranges of n values are quite small for both sets of soil cores, irrespective of the type of curve-fitting method used. The simultaneous curve-fitting method consistently (13 of 15 samples) provides n values that numerically range between the conductivity and retention n values. Thus, as expected, the simultaneous fit better describes the soil hydraulic conductivity than does fitting the retention data alone.

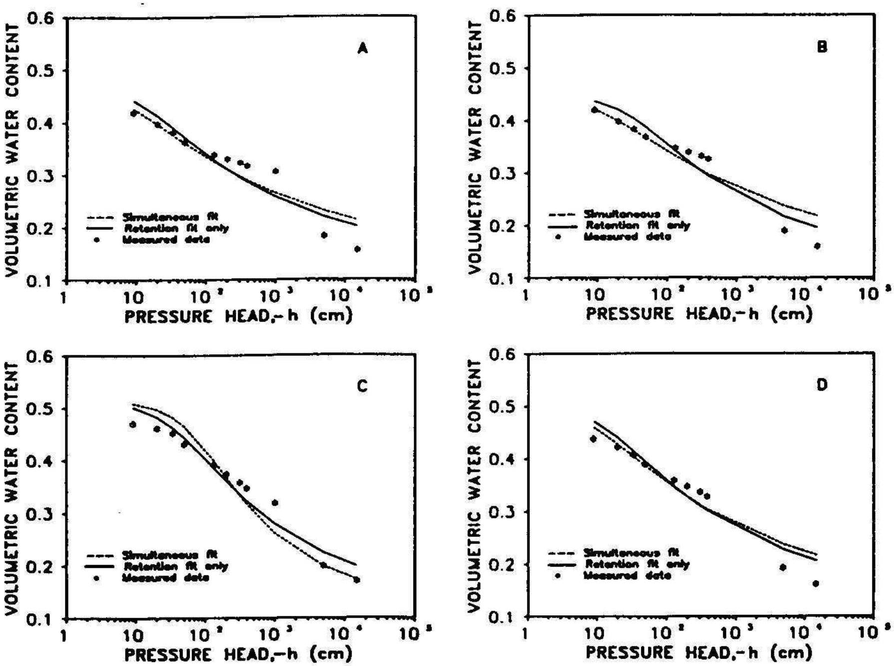

Fig. 1. Soil water retention curves for two untrafficked samples (A,B) and two wheel-trafficked samples (C,D). Stars represent data points. The solid lines represent the fitted curves to the retention data alone. Dashed lines represent fitted curves to both retention and conductivity data.

Figure 1 shows water retention data for four soil cores. For all cores, fitted curves from retention data alone, and from simultaneous retention and conductivity data, are similar. Figure 2 shows soil hydraulic conductivity data for the same soil cores as used in Figure 1.

The unsaturated curves predicted from water retention data do not match the measured conductivity nearly as well as do the curves fitted simultaneously to retention and conductivity data. Thus, saturated conductivity and water retention data could not always be used to satisfactorily describe unsaturated conductivity.

Figure 3 shows the soil hydraulic conductivity data for the same soil cores of Figures 1 and 2. In this instance, unsaturated hydraulic conductivities measured at 3-cm tension were used as matching points instead of using the saturated hydraulic conductivities. The results indicate that the unsaturated hydraulic conductivity curve can be predicted better from retention data when an unsaturated hydraulic conductivity value is used as a matching point, rather than the saturated hydraulic conductivity.

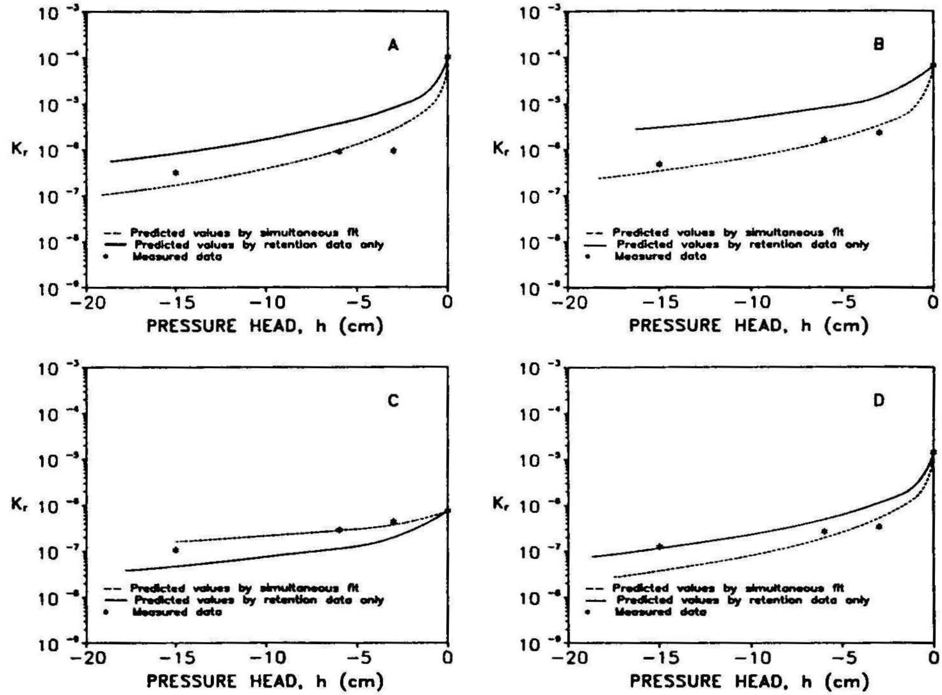

Fig. 2. Observed and calculated values for the $K(h)$ relationship for two untrafficked samples (A,B) and two wheel-trafficked samples (C,D). Stars represent measured hydraulic conductivities. The solid lines represent values estimated from retention data only. The dashed lines represent values estimated from a simultaneous fit to both retention and conductivity data.

Figure 4 shows observed hydraulic conductivity taken from *Brooks and Corey* [1964] and predicted hydraulic conductivity using (4). The parameter n in (4) is based upon air permeability measurements (i.e., Eq. 7). Thus, the hydraulic conductivity is predicted by using air permeability measurements. The predicted relative hydraulic conductivity is fairly close to the observed values. The results would be even better if gas slippage was accounted for. Figure 4 suggests that air permeability might be a useful predictor for hydraulic conductivity. This is of interest because the unsaturated air permeability is much easier to determine than unsaturated hydraulic conductivity. We will continue our research efforts by testing combinations of water retention and unsaturated air permeability data to predict the unsaturated hydraulic conductivity.

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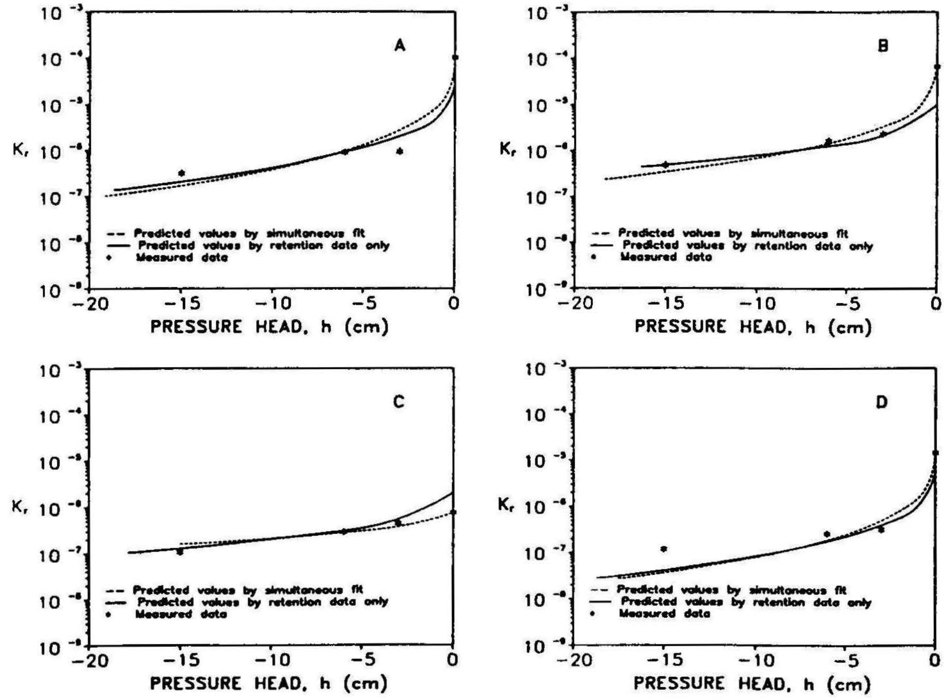

Fig. 3. Observed and calculated values for the $K(h)$ relationship, with the unsaturated hydraulic conductivity data at 3 cm tension being used as matching points.

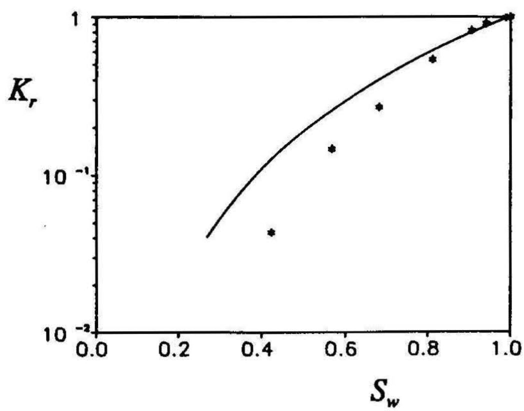

Fig. 4. Observed hydraulic conductivity data taken from *Brooks and Corey* [1964] and hydraulic conductivity calculated from (4) with the parameter m obtained from (7) to predict the unsaturated hydraulic conductivity.

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