Unsaturated hydraulic conductivity of disturbed and undisturbed loam soil

J. M. Abrisqueta1,3*, V. Plana2,3, A. Ruiz-Canales4 and M. C. Ruiz-Sánchez1,3

1 Dpto. Riego. CEBAS-CSIC. P.O. Box 164. 30100 Espinardo. Murcia (Spain)
2 Dpto. Producción Vegetal. ETSIA, UPTC. Cartagena, Murcia (Spain)
3 Unidad Asociada al CSIC de Horticultura Sostenible en Zonas Áridas (UPCT-CEBAS). Murcia. Spain
4 Dpto. Ingeniería Agroforestal. EPSO. UMH. Elche. Alicante (Spain)

Abstract

The soil water content-pressure head curve \([\theta(h)]\), described by van Genuchten, was used to predict some hydraulic characteristics of a Xeric torriorthent soil. Experimental data of volumetric soil water content \(\theta\) and pressure head \(h\) were adjusted to the model, obtaining the three independent parameters used to calculate the unsaturated soil hydraulic conductivity \((K)\) and soil water diffusivity \((D)\). The \(K(\theta)\) functions for disturbed and undisturbed soil samples were statistically different pointing to the effect of soil structure on soil water flow. For soil moisture values close to saturation, \(K\) values were \(0.392\) and \(0.019\) cm h \(^{-1}\) for undisturbed and disturbed soils, respectively. These low values would reflect the loam texture of the soil studied. In absence of roots capable of absorbing water, a supply of more than \(4\) L m \(^{-2}\) h \(^{-1}\) will lead to water-logging and losses through evaporation and runoff.

Additional key words: Mualem model, soil water diffusivity, soil water retention curve, van Genuchten model.

Introduction

The relation between pressure head and volumetric water content in a soil is termed the soil water retention curve or soil moisture characteristic curve because each curve is characteristic of a given soil. The differences between soil water retention curves are attributed primarily to the differences in pore size distribution among soils. These curves are sensitive to changes in bulk densities and the disturbance of soil structures. The curves generally show hysteresis according to the wetting or drying of soils. Therefore it is recommended that these conditions be added to each curve, as required (Miyazaki, 1993).

There is a wide body of literature in which the hydrodynamic characteristics of soils are described based on its water retention curve. Using constant-head Guelph permeameters and a volumetric pressure plate...
extractor, Giakoumakis and Tsarikis (1999) carried out laboratory experiments to determine hydraulic conductivity during infiltration in an unsaturated sandy loam soil. Ahuja et al. (1998) described changes in the soil water retention curve as a consequence of tillage practices and its subsequent natural reconsolidation. Assouline et al. (1998) studied a conceptual model based on the assumption that soil structure evolves from a uniform random fragmentation process to define the water retention function. Nimmo (1997) quantified the influence of soil structure on the water retention curve. Bird et al. (1996), Perfect et al. (1996), Guerrini and Swartzendruber (1997), and Pachepsky and Timlin (1998) applied fractal theory to the study of soil water retention and soil water diffusivity curves. Using the representation of Brooks-Corey for the soil water retention curve, Chu (1995) determined the effect of the initial water content on the parameters of the Green-Ampt equation. Tamari et al. (1993) described a straightforward laboratory procedure for determining the soil hydraulic properties. Both soil water retention curve and unsaturated hydraulic conductivity data are often necessary for solving unsaturated flow problems. Parlange and Hogarth (1997) made a wider ranging commentary on Shao and Horton theory concerning the determination of soil water diffusivity. Parlange et al. (1997) presented a general approximation for the solution to the one-dimensional Richards equation. The results were very accurate when the diffusivity is constant, suggesting that the present general formulation is reliable.

In the present work, the unsaturated hydraulic conductivity and diffusivity of disturbed soil samples were calculated before fitting to the van Genuchten soil water retention curve model (van Genuchten, 1980). It was used the Mualem (1976) model rather than that of Burdine (1953) since it better fitted our experimental data. A comparative study of the hydraulic conductivity as function of volumetric water content \([K(\theta)]\) for disturbed and undisturbed soil samples was carried out.

**Material and Methods**

Experiments were conducted at a commercial mature apricot tree orchard under drip irrigation conditions (Abrisqueta et al., 2001; Plana et al., 2002). The soil was a Xeric torriorthent (Soil Taxonomy) with a loam texture (4% coarse sand, 28% fine sand, 44% silt and 24% clay) according to the USDA (1979).

Four air-dried samples of disturbed soil were taken from the top 25 cm of representative sites of the orchard. The water content of the saturated samples was measured at nineteen potentials (hydraulic heads). Temper pressure cells were used for water potentials between −2 and −30 kPa, and a conventional pressure plate in the range −100 to −1500 kPa (Startsev and McNabb, 2001).

The soil water content \((\theta)\) and pressure head \((h)\) data were fitted to the van Genuchten model [Eq. 1]:

\[
\theta = \theta_s + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^{\gamma}]^n}
\]  

where \(\theta_s\) and \(\theta_r\) are the saturated and residual volumetric water content of the soil, respectively. Values of \(\alpha\), \(m\) and \(n\) were obtained empirically during the fitting procedure. To simplify notation, \(h\) in Eq. [1] was assumed to be positive. Equation [1] with \(m = 1\) has been successfully used in many studies to describe soil-water retention data (Ahuja and Swartzendruber, 1972; Endelman et al., 1974; Haverkamp et al., 1977).

The saturated and residual soil water content, as well as saturated hydraulic conductivity \((K_s)\), were calculated using the methods of Trout et al. (1982) and van Genuchten (1980) (Table 1).

**Table 1. Physical properties of experimental soil**

<table>
<thead>
<tr>
<th>(\theta_r) (cm³ cm⁻³)</th>
<th>(\theta_s) (cm³ cm⁻³)</th>
<th>(K_s) (cm h⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32</td>
<td>0.11</td>
<td>0.132</td>
<td>Trout et al. (1982)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Van Genuchten (1980)</td>
</tr>
</tbody>
</table>
The Mualem model established an equation for predicting the relative hydraulic conductivity ($K_r$) and soil water diffusivity ($D$) from knowledge of the soil water retention curve (Mualem, 1976). The mathematical expressions are the following:

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

$$D = \frac{(1 - m) \cdot K_s}{\alpha m (\theta_s - \theta_f)} \left[ \left( \frac{1}{1 - \frac{1}{m}} \right)^{n-1} + \left( \frac{1}{1 - \frac{1}{m}} \right)^m \right] \quad [3]$$

The relative hydraulic conductivity ($K_r$) is defined as:

$$K_r = \frac{K}{K_s} \quad [4]$$

where $K$ is the unsaturated hydraulic conductivity, and $\theta$ is the dimensionless soil water content, which is defined as:

$$\theta = \frac{\theta - \theta_s}{\theta_s - \theta_r} \quad [5]$$

**Results and Discussion**

**Soil water retention curve**

Fitting the experimental data of volumetric soil water content ($\theta$) and pressure head ($h$) to the model described by van Genuchten (1980) gives the regression curve (water retention curve) which is illustrated in Fig. 1. All the parameters that intervene in the analysis ($\alpha$, $m$ and $n$) were statistically significant (Table 2).

The agreement with the model was very good as indicated the determination coefficient ($R^2 = 0.99$) (Table 2). The limits of this function when $h \rightarrow \infty$ and when $h \rightarrow 0$, corresponds to the residual and saturated moisture, respectively (Fig. 1). This equation has been successfully used in many studies to describe soil water retention data (Tamari et al., 1993; Wu et al., 1993; Zavattaro et al., 1999; Startsev and McNabb, 2001).

**Relative hydraulic conductivity versus pressure head curve**

Substitution of parameters $\alpha$, $n$ and $m (= 1-1/n)$ (Table 2) into Eq. [2] and plotting relative hydraulic

### Table 2. Parameters of the regression analysis: pressure head vs soil water content of experimental soil (Van Genuchten's model)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Significance</th>
<th>$R^2$</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$5.347 \times 10^{-4}$</td>
<td>($P(1) = 0.009$)</td>
<td>0.9964</td>
<td>0.005</td>
</tr>
<tr>
<td>$m$</td>
<td>0.750</td>
<td>($P = 0.003$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>1.294</td>
<td>($P &lt; 0.0001$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$SE$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Determination coefficient. (2) Standard error. (3) Statistic probability level.
conductivity versus pressure head gives the graphic representation of Mualem’s model (1976) (Fig. 2).

It is clear that for pressure head values near zero, the value of \( K_r \) is equal to unity (Fig. 2), i.e., \( K = K_s \) [Eq. 4]. As the pressure head increases, the value of \( K_r \) decreases asymptotically to reach a minimum value corresponding to the residual volumetric water content in the soil. Substituting the values of \( K_r \) into Eq. [4], the hydraulic conductivity of the unsaturated soil can be calculated.

Soil water diffusivity versus water content curve

Substitution of the same parameters \( \alpha, n \) and \( m \) (= \( 1-1/n \)) (Table 2) into Eq. [3] gives a graphical representation of Mualem’s model of the soil water diffusivity versus volumetric water content (Fig. 3).

Note that \( D(\theta) \) becomes infinite when \( \theta \) equals \( \theta_\theta \). Only at intermediate values of \( \theta \) (between 0.18 and 0.30 in Fig. 3) does the diffusivity acquire an exponential dependency on the soil water content. Similar features of the soil water diffusivity were also obtained by Ahuja and Swartzendruber (1972) and by Murali et al. (1979).

The diffusivity, \( D(\theta) \), was used because water content gradients are sometimes easier to measure, and also because some water flow equations are more easily solved with diffusivity than with hydraulic conductivity. The term diffusivity does not indicate moisture transfer by diffusion (Yong and Warkentin, 1975).

Unsaturated hydraulic conductivity versus soil water content curve

Although several \( K(\theta) \) parametric relationships have been proposed and successfully used in the literature (Kutílek and Nielsen, 1994), an exponential model [Eq. 6] was selected for its simplicity and the good fitting obtained:

\[
K = a + b \cdot e^{c \cdot \theta} \quad [6]
\]

The relationship between the volumetric soil water content experimental values and the unsaturated hydraulic conductivity values obtained by Eq. [4] were adjusted to the proposed model [Eq. 6], as can be seen from Fig. 4.

The fitting of the data to the proposed model [Eq. 6] was statistically significant (Table 3). The regression coefficients \( a \) and \( b \) were not significant (Table 3), which denote that the model can be simplified. If data of volumetric soil water content lower than 0.18 and higher than 0.30 were omitted, a simpler and statistically significant (\( P < 0.001 \)) equation was obtained [Eq. 7]:

\[
K = 3.145 \cdot 10^{-7} \cdot e^{0.368 \cdot \theta} \quad R^2 = 0.9814 \quad [7]
\]
Comparison with undisturbed soil samples

Working with undisturbed samples of the same soil under the same edaphoclimatic conditions, Ruiz-Canales (2000) obtained the following statistically significant ($P < 0.001$) equation [Eq. 8] for unsaturated hydraulic conductivity vs. volumetric water content relation:

$$K = 1.62 \cdot 10^{-5} \cdot e^{0.49 \cdot \theta} \quad R^2 = 0.9961 \quad [8]$$

Equations [7] and [8] are shown graphically in Fig. 5. The differences between disturbed [7] and undisturbed [8] soil samples were evaluated by covariance analysis, which indicated that both the ordinate and the slope of the curves were statistically significant different (data not shown). For soil moisture values close to saturation ($\theta \geq 30\%$), hydraulic conductivity was $\geq 0.392 \text{ cm h}^{-1}$ for undisturbed soil, whereas it was lower ($\geq 0.019 \text{ cm h}^{-1}$) in disturbed soil. These low values (according to Trout et al., 1980) would reflect the loam texture of the soil under study.

Under drip irrigation conditions, the soil water content near the emitters is maintained close to saturation, so that the supply of water in excess of 3.92 L m$^{-2}$ h$^{-1}$ will result in water-logging and losses through evaporation, as natural process, and runoff if no plant roots are present to absorb water.

As conclusions, the Van Genuchten (1980) equation provides a useful method of assessing differences in macroscopic soil conditions, and Mualem’s model permits the straightforward calculation of unsaturated hydraulic conductivity and the soil water diffusivity, two parameters which are much used in unsaturated flow studies.

There were clear differences between the $K(\theta)$ functions for disturbed and undisturbed soil samples, pointing to the importance of soil structure in the unsaturated flow of water. For soils close to saturation, significantly different $K$ values were obtained, and for both disturbed and undisturbed soils flows can be considered very low.

In the absence of roots capable of absorbing water, a supply of water in excess of 4 L m$^{-2}$ h$^{-1}$ will lead to water-logging and losses through evaporation and runoff.

---

**Table 3.** Regression analysis: unsaturated hydraulic conductivity vs. soil volumetric water content of experimental soil

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>$R^2$(1)</th>
<th>SE(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---------</td>
<td>---------</td>
<td>-----</td>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>1</td>
<td>-1.04·10^{-4}</td>
<td>4.94·10^{-7}</td>
<td>35.89</td>
<td>0.9648</td>
<td>0.004</td>
</tr>
</tbody>
</table>

(1) Adjusted determination coefficient. (2) Standard error. (3) Statistic probability level.

---

**Figure 4.** Unsaturated hydraulic conductivity vs. volumetric soil water content curve [Eq. 6] of experimental soil. Bars on data points are ± SE of the mean (n = 4).

**Figure 5.** Comparison of $K(\theta)$ functions for disturbed (o, ---) and undisturbed (—) soil samples. Natural logarithmic scaling is in the ordinate axis.
Acknowledgements

This work was supported by a CICYT (HID1999-0951) grant to the authors.

References


