Estimating unsaturated hydraulic conductivity and retention curve from tension disc infiltrometer data in sandy soil

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ABSTRACT

One of the essential requirements in agriculture, environment, engineering and irrigation and drainage system design is to use a functional and effective method to estimate the unsaturated soil hydraulic properties. Tension disc infiltrometers are becoming increasingly popular devices for in situ measurement of the unsaturated hydraulic properties of soil. This study mainly aims to estimate unsaturated hydraulic conductivity and soil moisture characteristic curve from tension disc infiltrometer data in sandy soil. For this purpose, the unsaturated hydraulic conductivity was measured through tension disc infiltrometer in sandy soil on 6 suctions of zero, 3, 6, 9, 12 and 15 cm in three replications. In order to analyze the results, the method proposed by Logsdon and Jaynes (1993), which is a non-linear regression method, was used. In addition, soil moisture curve was estimated by results obtained from the measurement using RETC Software (1991). Results indicated that moisture curve can be estimated indirectly with a good approximation through measuring unsaturated hydraulic conductivity by tension disc infiltrometer using RETC Software.

Key words: unsaturated hydraulic conductivity, tension disc infiltrometer, Soil Moisture Characteristic Curve, RETC Software.

Introduction

One of the essential requirements in agriculture, environment, engineering and irrigation and drainage system design is to use a functional and effective method to estimate the unsaturated soil hydraulic properties. Soil hydraulic properties are physical properties describing water-soil relationship. The main property is the definition of the relationship between the amount of water retention and suction in soil (soil water retention curve) and hydraulic conductivity and suction (hydraulic conductivity curve) [14].

Moisture characteristic curve has many applications in water and soil issues. For instance, this curve is used for predicting hydraulic conductivity in saturated and unsaturated circumstances, available water for plant, and mineral movement in soils. However, designing this curve and also determining unsaturated hydraulic conductivity through laboratory or field approaches is very time-consuming and costly; furthermore, its changes from one point to another point are vast, and numerous measurements are required for gaining accurate results. These limitations made researchers to obtain unsaturated soil hydraulic characteristics using simple physical properties of soil such as texture, organic matter content and bulk density [10].

The most common approach for designing soil moisture curve is laboratory method of using pressure plates. Application of this device requires a lot of time to run experiments; in addition, since the tests are conducted on small soil samples, there is a possibility of lowered accuracy in tests’ results. In this research, an attempt was made to estimate soil moisture curve not only by pressure plates but also by tension disc infiltrometer. Reason for using this equipment is simplicity and swiftness of tests using this device.

Most laboratory methods are steady state procedures based on direct inversion of Darcy’s law [8]. There are four methods to analyze the disc infiltrometer data for in the steady flow state: 1- solving simultaneous equations by Ankeny et al. [1], 2- Exponential phase solving method, Elrick and Reynolds, 3- Logsdon and Jaynes Method [5] and 4- How to use the discs of different diameters by Elrick and Reynolds and Smettem and Clothier [9], each of which have their own advantages and disadvantages [8].

In this study, the analysis method of Logsdon and Jaynes [5] was used for a sustained analysis of
tension disc infiltrometer data due to the use of the multiple tension method with a disc size.

1.1. Analysis of tension disc infiltrometer data in the steady flow state:

Due to the three-dimensional water flow underneath the disc, a special formula is needed to consider the water side infiltration. The data obtained from tension disc infiltrometer data are usually analyzed based on Wooding algebraic equations (1968) to penetrate the soil from a circular source in the three-dimensional condition with an indefinite border and a stable and uniform flow.

\[ Q_\Psi = \pi r^2 k(\Psi) + 4\Phi_\Psi \]  

(1)

Where \( Q_\Psi \) is the volumetric infiltration rate of steady state flow for a given suction like \( \Psi \), \( R \) is the diameter of the circular porous sheet (disc), \( K(\Psi) \) is the hydraulic conductivity in \( \Psi \), \( \Phi_\Psi \) is the matrix flux potential which is defined as follows:

\[ \Phi_\Psi = \int_0^\Psi K(\psi) \, d\psi \]  

(2)

\( \Psi_1 \) is the initial suction in soil. Logsdon and Jaynes applied the algebraic solution of the equation (1) based on the pressure - hydraulic conductivity relationship of Gardner [3].

\[ K(\Psi) = K_s \exp(\alpha\psi) \]  

(3)

If \( \Psi \geq 0 \) we will have:

\[ K(\Psi) = K_s \]

\( \alpha \) is assumed constant for any given soil. The opposite of \( \alpha \) is partly called macroscopic capillarity in \( (\lambda c) \) length scale [2]. For the initial moistures which are too much lower than the \( \Psi_1 \)-related moistures \( (K_\Psi \gg K_s) \), the following equation will be obtained after the placement of equation (3) in equation (1):

\[ \Phi_\Psi = \frac{K(\psi)}{\alpha} \]  

(4)

1.2. Regression method:

Logsdon and Jaynes [5] presented a nonlinear regression equation based on Wooding equation [15] (Eq.1) for sustained analysis of the infiltration values measured by the tension disc infiltrometer data, through the multiple tension method with a disc size – which will provides fast and acceptable results and no negative amount compared to the other methods:

\[ Q_\Psi = \left[ 1 + \frac{4}{\pi r^2} \right] k_s \exp(\alpha\psi) \]  

(5)

That contains two unknowns of \( \alpha \) and \( K_s \) which are obtained from the regression. After solving the simultaneous equations for two or more suctions, the value of \( k(\psi) \) will be obtained by placing these quantities in equation (3). They also showed that in this method, \( k(\psi) \) is approximately equal with the \( k(\psi) \) obtained from the one-dimensional tests on the sampled columns and also concluded that this method is more coordinated than the Ankeny’s method [1], [9].

Materials and Methods

The soil used in this test was located in the Large Karoun River bank located in southwestern Iran. The Karoun River margins have been always used in agriculture due to its fertile soil and the constant availability of fresh water for irrigation of crops. Knowledge of the water flow rate in soil causes the application of the appropriate management for the irrigation planning. Therefore, considering the importance of the Large Karoun River margin in terms of agriculture, the soil of this region was chosen for test. In the laboratory, the percentage of soil texture’s organic matters and bulk density was determined through hydrometer method. Table (1) shows physical properties of the studied region soil.

Table 1: Physical properties of the studied region soil.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>The percentage of soil porosity</th>
<th>The percentage of organic matters</th>
<th>The percentage of bulk density (g/cm³)</th>
<th>The percentage of components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40.22</td>
<td>2.38</td>
<td>1.58</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sandy</td>
</tr>
</tbody>
</table>

1.3. Measurements of Suctions Greater Than One Meter:

Measurement of moisture at high suctions (with a positive sign) is not valid by exerting negative pressure. Since, once pressure reaches 1 bar (1000 cm of water column), water leaks from membrane side with no air bubble leak. Therefore, high suctions were measured by exerting positive pressure. Soil characteristic curve at high suctions is affected by soil texture and is independent from soil structure.
were taken out of the container and then weighed. Next, they were put in oven and then their dry matter was measured after 24 hours. Following the same procedure, other plates were put in their locations in the device based on pressure decline. At higher pressures, duration of pressure execution on samples was increased. Hence, pressure levels of 0.1, 0.3, 0.6, 0.8, 1, 1.5, 3, 5, 10, and 15 bars were executed on soil samples and weight moisture percentages similar to these pressure levels were measured.

1.4. Estimation of Moisture Curve by Tension Disc Infiltrometer:

In this research, a tension disc infiltrometer was implemented to estimate unsaturated hydraulic conductivity. Hydraulic conductivity was measured in 6 suctions of 15, 12, 9, 6, 3, and 0 cm at three replications using this device. The collected data were analyzed using the nonlinear regression method of Logsdon and Jaynes [5] (Eq.5), and finally α and Ks were determined for each test.

Assuming the hydraulic conductivity equation of Gardner [3] (Eq (1)), Logsdon and Jaynes estimated the parameters of α and Ks from all data couples of (Qn, h) concurrent with the establishment of non-linear regression. More than two measurements are needed to establish the accurate regression. For this reason, measurements are performed in the 6 mentioned suctions.

Further, the data collected by the tension disc infiltrometer including the steady state infiltration rate measured in different suctions were multiplied by the reservoir area (A = 29.22 cm²) to achieve the rate of the flow ejected in each suction. Table (2) show the steady state infiltration rate measured by disc infiltrometer.

<table>
<thead>
<tr>
<th>test</th>
<th>Pressure Head (cm)</th>
<th>Initial soil water content (cm³/cm³)</th>
<th>Time period application (min)</th>
<th>Infiltration rate (cm/sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-15</td>
<td>0.24</td>
<td>8</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>-12</td>
<td></td>
<td>5</td>
<td>0.0116</td>
</tr>
<tr>
<td></td>
<td>-9</td>
<td></td>
<td>8</td>
<td>0.0116</td>
</tr>
<tr>
<td></td>
<td>-6</td>
<td></td>
<td>7</td>
<td>0.0166</td>
</tr>
<tr>
<td></td>
<td>-3</td>
<td></td>
<td>7</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>5</td>
<td>0.0283</td>
</tr>
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<td>2</td>
<td>-15</td>
<td>0.21</td>
<td>9</td>
<td>0.0133</td>
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<td></td>
<td>-12</td>
<td></td>
<td>7</td>
<td>0.015</td>
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<td>7</td>
<td>0.02</td>
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<td></td>
<td>5</td>
<td>0.0213</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>6</td>
<td>0.025</td>
</tr>
<tr>
<td>3</td>
<td>-15</td>
<td>0.23</td>
<td>12</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>-12</td>
<td></td>
<td>7</td>
<td>0.0066</td>
</tr>
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<td></td>
<td>-9</td>
<td></td>
<td>7</td>
<td>0.01</td>
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<td></td>
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<td></td>
<td>0</td>
<td></td>
<td>7</td>
<td>0.0216</td>
</tr>
</tbody>
</table>

Results and Discussion

Figure (1) indicates the correctness of non-linear regression in Logsdon and Jaynes method [5] in three replications in order to estimate parameters of Gardner's exponential function (1958, α and Ks). Table (3) shows average values for estimated unsaturated hydraulic conductivity in executed suctions.

![Graph](Q(h)-h)

**Fig. 1:** Correctness of Non-linear regression in Logsdon and Jaynes method (1993) in three replications to estimate parameters of Gardner’s exponential function (α, Ks).
1.5. Estimating soil water retention curve of disc-permeameter measurements:

For determining moisture contents according to applied tensions, the retention curves of sandy soil were estimated via model's RETC (1991) of obtained hydraulic conductivity curve.

The parameters of hydraulic conductivity based on Van Genuchten- Mualem's model [13] were estimated with high regression. Table (5) shows estimated parameters of Van Genuchten- Mualem's model [13] by RETC.

Table 5: The estimated parameters of Van Genuchten- Mualem's model (1980) by RETC.

<table>
<thead>
<tr>
<th></th>
<th>(\alpha)</th>
<th>(\theta_0)</th>
<th>(\theta_s)</th>
<th>(m)</th>
<th>(n)</th>
<th>(l)</th>
<th>(K_s)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial estimation</td>
<td>0.0312</td>
<td>0.045</td>
<td>0.43</td>
<td>0.6904</td>
<td>3.2301</td>
<td>0.5</td>
<td>0.0067</td>
<td>0.99986</td>
</tr>
<tr>
<td>Final estimation</td>
<td>0.02256</td>
<td>0.045</td>
<td>0.43</td>
<td>0.6904</td>
<td>0.87103</td>
<td>0.5</td>
<td>0.00075</td>
<td></td>
</tr>
</tbody>
</table>

Curves estimated using this method were closer to field conditions rather than to the moisture curves, which were obtained by laboratory methods performed on small intact samples or gained by measuring easily determined soil parameters using existing models. Parameters estimated by RETC Model such as \(\alpha\) and \(K_s\) demonstrated greater consistency with soil structure status in field rather than with soil texture.

Conclusion:

The main objective of this research is estimating soil moisture curve using tension disc infiltrometer. Hydraulic conductivity of this soil was measured by tension disc infiltrometer at 6 suctions of 15, 12, 9, 6, 3, and 0 cm in three replications. The information obtained by the equipment was analyzed through Non-linear Regression Method of Logsdon and Jaynes [5]. Results of this test (suction-hydraulic conductivity data pair) were used as input data for RETC Software (1991), and data fitting was carried out via Van Genuchten- Mualem model [13]. Measurement of suctions ranging from 0.1 to 15 bars was performed by pressure plates.

Regarding the significance of simultaneous information of suction, moisture, and hydraulic conductivity in many issues of water and soil and also with respect to costliness and time-consuming of conducting laboratory measurements for estimating soil moisture curve, it is observed that the results of this research properly revealed that it is possible to estimate moisture curve indirectly with a good approximation by measuring unsaturated hydraulic conductivity using tension disc infiltrometer through RETC Software. It is recommended to use moisture curve for conducting estimation in areas, where information pertinent to unsaturated hydraulic conductivity are available through tension disc infiltrometer.

Acknowledgments

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References


