Effects of infiltration time on the calculated sorptivity with White method for a sandy loam soil

Wei Hu¹, Quanjiu Wang², Mingan Shao²* and Zhengshan Ju⁴

¹Key Laboratory of Water Cycle and Related Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.
²State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resource, Northwest A&F University, Yangling 712100, Shaanxi, China.
³Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.
⁴Land Consolidation and Rehabilitation Center, Ministry of Land and Resources, Beijing 10035, China.

Accepted 24 August, 2011

Sorptivity (S) is one of the important soil hydraulic parameters, which can be estimated by disc infiltration data at the early stage with one dimensional infiltration theory. With the purpose of understanding the effects of infiltration time (IT) on the estimated S, two sizes (radius of 5 and 2.5 cm) of disc infiltrometer were used to perform disc infiltration under five pressure heads (0, -3, -6, -9, -15 cm) using a packed sandy loam soil. S values for different IT were estimated with White method. Results showed that the estimated S was in general overestimated and it increased with the increase of IT. The relative measurement error as compared with the Parlange method increased with the increase of IT, a behavior that could be well fitted by a logarithmic function. There was a tendency that the relative measurement error decreased with the decrease of pressure head, and the optimized value of IT (IT_{OP}) in general increased exponentially with decreasing pressure head, ranging from 20 to 75 s for disc radius of 5 cm and 8 to 26 s for disc radius of 2.5 cm. The estimated S values and relative measurement errors for smaller disc were greater than those of larger disc. Atentions should be given to the suitable IT for determining S by White method. Furthermore, the relatively larger disc size should be preferred under the premise of a good hydraulic contact between disc and soil surface.

Key words: Disc infiltrometer, Philip, sorptivity, sandy loam soil.

INTRODUCTION

Sorptivity (S) is a measure of the capacity of the medium to absorb or desorb liquid by capillary. Many other hydraulic properties such as macroscopic capillary length (White and Sully, 1987) and hydraulic conductivity (White and Perroux, 1989) can be derived from S value. Accurate estimation of S is, therefore, very important to model soil water movement for agronomical and hydrological applications.

Many methods are available for determining S with disc infiltration data (Scotter et al., 1982; Smettem and Clothier, 1989; Cook and Broeren, 1994; vandervaere et al., 2000a, b). Among which, the method developed by White et al. (1992) (termed as"White method" hereafter) has been widely used in the recent decades. Under the assumption of no contribution of gravity and horizontal capillary on the water flow for the early-time disc infiltration, S can be easily determined as the slope of cumulative infiltration versus the root of infiltration time with one dimensional infiltration theory (Philip, 1957). This can largely simplify the calculation procedure involved. According to the literature published, however, the infiltration time (IT) believed to be valid for one dimensional infiltration differed much with researchers. Perroux and White (1988) took the valid time for one dimensional flow as 6 to 2450 s depending on soil type; Logsdon and Jaynes (1993) considered it to be 15 s, while Hussen and Warrick (1993) did not consider the...
time valid for one dimensional infiltration. Therefore, the determination of valid time for one dimensional infiltration is to a great extent subjective. The possible effects of IT on the S estimate should be clarified.

In this study, a sandy loam soil was chosen as experimental material. Three dimensional disc infiltration with disc radius of 5 and 2.5 cm was performed following Smettem et al. (1994) with multi-pressure heads, that is, 0, -3, -6, -9, -15 cm. S values with various pressure heads were estimated with White method and their relative measurement errors were also determined in relation to the S values measured by the method of Parlange (1975) (termed as “Parlange method” hereafter). The objective of this study was to explore the effects of IT on the S estimate by White method, furthermore, the effects of disc radius was also discussed.

MATERIALS AND METHODS

Basic theory

White method

In the early time infiltration, vertical capillary dominates flow while the contribution of gravity and horizontal capillary can be neglected. Therefore, cumulative disc infiltration versus infiltration time can be expressed as (Philip, 1957):

\[ I = S t^{0.5} \]  

where \( I \) is the cumulative infiltration depth at a given pressure head (cm), \( t \) is infiltration time (min). Plotting \( I \) of early infiltration stage against \( t^{0.5} \) and identifying portion of the graph with straight-line behavior, then \( S \) in cm min\(^{-0.5}\) is estimated from the slope of the fitted straight line (White et al., 1992).

Parlange method

The approximation given by Parlange (1975) has been proved to result in accurate estimate of \( S \) (Elrick and Robin, 1981). Therefore, it was selected as the referenced method to evaluate the relative accuracy of \( S \) estimate with different IT using White method. Approximate solution given by Parlange (1975) can be written as:

\[ S^2 = 2 \int_{\theta_0}^{\theta_f} \left( \theta_0 + \theta - 2\theta_n \right) D(\theta) d\theta \]  

where \( S \) is sorptivity (cm min\(^{-0.5}\)), \( \theta_0 \) and \( \theta_f \) is initial soil water content and steady soil water content at a given pressure head, respectively (cm\(^3\) cm\(^{-1}\)). In this study, \( \theta_0 \) was set as the mean value of two steady soil water content, measured with disc radius of 5 and 2.5 cm. \( D(\theta) \) is soil diffusivity (cm\(^2\) min\(^{-1}\)), which is obtained by the following equation given by Wang et al. (2004):

\[ D(\theta) = D_s \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^L \]  

where \( D_s \) is diffusivity of saturated soil and \( L \) is a dimensionless parameter, which can be obtained by the following formulas:

\[ D_s = \frac{a}{\theta_s - \theta_n} \left( \frac{\theta - \theta_n}{b} - 1 \right) \]  

\[ L = \left[ \left( \frac{\theta_s - \theta_n}{b} - 1 \right) - 1 \right]^{-1} \]  

In which, \( \theta_r \) is residual soil water content (cm\(^3\) cm\(^{-3}\)). Considering the extremely low initial soil water content, \( \theta_0 = \theta_n \) is assumed. \( \theta_s \) is saturated soil water content (cm\(^3\) cm\(^{-3}\)), which is empirically derived by:

\[ \theta_s = 1 - \frac{\rho_b}{2.65} \]  

where \( \rho_b \) is bulk density (g cm\(^{-3}\)). \( a \) and \( b \) in Equation (4) and (5) can be simply linearly fitted by the following relationship:

\[ i = \frac{a}{x_f} \]  

\[ I = bx_f \]  

where \( i \), \( I \), \( x_f \) is infiltration rate (cm min\(^{-1}\)), cumulative infiltration depth (cm), and wetting front distance (cm), respectively.

Infiltration experiment

Soil samples

A sandy loam soil classified as Ust-Sandiic Entisol was provided as infiltration material. After air dried, soil samples were passed through a 1 mm sieve and packed into the steel box (40 cm in length, 40 cm in width, and 60 cm in height) with dry bulk density of 1.38 g cm\(^{-3}\). The proportion of clay (<0.002 mm), silt (0.002 to 0.02 mm), and sand (>0.02 mm) were 5.3, 20.0, and 74.7%, respectively. Initial soil water content was 0.008 cm\(^3\) cm\(^{-3}\).

Disc infiltration

Two disc infiltrometers with radius of 5 and 2.5 cm were used for disc infiltration. Before infiltration, soil surface was carefully leveled with no contact material to ensure a good hydraulic contact (Smettem et al., 1994). Three dimensional disc infiltration was carried out under the pressure head of 0, -3, -6, -9, and -15 cm. Three repeats were performed for each pressure head. Cumulative infiltration was recorded with time. Disc infiltration stopped as steady infiltration when infiltration depth was the same for a successive equal time. Reading was recorded every 15 s in the first 3 min and every 1 min thereafter. Immediately after the arrival of steady infiltration, soil samples near surface were quickly obtained and the steady soil water content was measured by gravimetric method.

One dimensional horizontal infiltration

The method developed by Wang et al. (2004) was employed to
RESULTS AND DISCUSSION

S estimated by Parlange method

For this sandy loam soil, saturated soil water content was 0.479 cm$^3$ cm$^{-3}$. Parameter $a$, $b$, and $L$ were 2.626, 0.38, and 8.98, respectively. $D_s$ was 23.84 cm$^2$ min$^{-1}$. All these soil parameters were used to calculate $S$ with Parlange method. For pressure heads of 0, -3, -6, -9, and -15 cm, $S$ values were 1.158, 1.083, 1.077, 1.072, 0.990 cm min$^{-0.5}$, respectively, indicating an obvious decreasing trend of $S$ with decreasing pressure head.

Effects of infiltration time on $S$ estimate

The IT for estimating $S$ by White method was selected as 30 to 150 s. After plotting cumulative infiltration against the root of IT (Figure 1 for radius of 5 cm and pressure head of -3 cm), all the coefficients of determination were greater than 0.94; implying that it was statistically reasonable to estimate $S$ using infiltration data within 150 s. $S$ values estimated with radius of 2.5 cm were generally greater than those measured with radius of 5 cm (Figure 2), indicating a great effect of disc size on $S$ estimate. The smaller the disc size, the more differences of one and three dimensional infiltration existed, which means that more contribution of gravity and lateral capillary were neglected for smaller disc. For both disc sizes, $S$ values increased with increasing pressure head as expected. With increasing IT, $S$ estimates increased obviously (Figure 2). This was due to the fact that with time elapse, vertical capillary plays a smaller role in soil water flow, while gravity and lateral capillary contributes relatively more to the infiltration.

Effects of infiltration time on relative error of $S$ estimate

In order to quantify the accuracy of $S$ estimated by White method, relative error analysis was performed using Parlange solution as the referenced method. Relative error can be expressed as:

\[
RE\% = \left( \frac{S_{W,\Psi} - S_{P,\Psi}}{S_{P,\Psi}} \right) \times 100
\]
where RE% is relative error, $S_{W, \psi}$ and $S_{P, \psi}$ is the $S$ estimated by White method and Parlange method at the pressure head of $\psi$. Positive sign of relative error indicates a overestimation of $S$ and vice versa. Greater absolute value of relative error corresponds to the poorer estimate. The mean relative error for different IT and pressure heads with both disc sizes are shown in Figure 3. $S$ values were in general overestimated, except for a few cases such as lower pressure head (e.g., -6, -9, -15 cm) and shorter IT (within 75 s), where $S$ values were likely to be underestimated. The relative errors for small disc were considerably larger than that for big disc. For both disc sizes, as infiltration time increased, the extent of overestimation increased due to the increased importance of gravity and lateral capillary ignored. In order to define the optimized IT ($IT_{OP}$) for accurate estimation of $S$, relationship of RE% with IT was fitted (Figure 3). As Figure 3 shows, their relationships can be well fitted by the natural logarithmic function:

$$RE\% = \alpha \ln(IT) - \beta$$

where $\alpha$ and $\beta$ are fitted parameters. Therefore, the $IT_{OP}$ was the IT value corresponding to zero $RE\%$. As for radius of 5 cm, the $IT_{OP}$ were 22, 20, 37, 55, and 76 s for pressure head of 0, -3, -6, -9, -15 cm, while these values were 9, 8, 13, 16, and 26 s, respectively, for radius of 2.5 cm (Table 1). For both disc radius, the $IT_{OP}$ increased with the decrease of pressure head, and this trend can be well fitted by exponential function (Figure 4). This implies that relatively long IT can be accepted for infiltration under lower pressure head. Obviously, the shorter IT is necessary for the smaller disc infiltrometer to get accurate $S$ estimates with White method. Practically, too small value of $IT_{OP}$, say less than 30 s, should not be expected, since it is difficult to have manual recording of infiltration with such short time, especially for light soils like sandy loam. At this situation, a relatively larger disc size is a good alternative because of its relatively small measurement error and large $IT_{OP}$.

**Conclusions**

A sandy loam soil was used to conduct three dimensional disc infiltration to investigate the effects of infiltration time (IT) on the calculated $S$ with White method. $S$ estimated by smaller disc size were greater than that estimated by larger disc size. For both disc sizes, $S$ increased with IT and was in general overestimated. The relative measurement error was greater for smaller disc size and it increased with IT, which could be well fitted by a natural logarithmic function. The optimized value of IT ($IT_{OP}$) generally increased with decreasing pressure head in an exponential form, ranging from 20 to 75 s for disc radius of 5 cm, and from 8 to 26 s for disc radius of 2.5 cm for pressure head of 0 to -15 cm. There was a tendency that the relative measurement error decreased with decreasing pressure head, hence longer IT can be accepted under the lower pressure head for an accurate estimation of $S$. Therefore, attentions should be given to the suitable IT and disc size. $IT_{OP}$ should decrease with pressure head rise, and relatively large disc was preferred to measure $S$. 

**Figure 2.** Estimated sorptivity ($S$) of various pressure heads for different infiltration time (IT) (broken line and solid line refer to disc radius of 5 and 2.5 cm, respectively).
Figure 3. Calculated and fitted (by natural logarithmic function) relative error (RE%) versus infiltration time (IT).

Table 1. Fitted parameters for the relationship of relative error (RE%) and infiltration time (IT).

<table>
<thead>
<tr>
<th>Pressure head (-cm)</th>
<th>Disc radius of 5 cm</th>
<th>Disc radius of 2.5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>0</td>
<td>25.06</td>
<td>77.49</td>
</tr>
<tr>
<td>3</td>
<td>25.70</td>
<td>77.04</td>
</tr>
<tr>
<td>6</td>
<td>24.33</td>
<td>87.93</td>
</tr>
<tr>
<td>9</td>
<td>24.15</td>
<td>96.97</td>
</tr>
<tr>
<td>15</td>
<td>20.38</td>
<td>88.37</td>
</tr>
</tbody>
</table>

*Fitted IT value when $RE\%=0$, fitting equation is $RE\% = \alpha \ln(\text{IT}) - \beta$. 
This study was carried out with one soil, and the general tendency should be suitable for other soil textures, but still more data should be available for different soils to get more quantitative results. In addition, this study was limited to laboratory experiment, and more work should be done in fields to make practical guidelines for the in-situ measurement of soil hydraulic parameters.

ACKNOWLEDGEMENTS

The study was financially supported by the National Natural Science Foundation of China (41001131), National Science and Technology Support Program (2009BAC55B07), and the Knowledge Innovation Project (KZCX2-YW-359) of the Chinese Academy of Sciences. We thank the two anonymous reviewers for their constructive comments that greatly improved the earlier version of this manuscript.

REFERENCES