Comparison of confined and unconfined infiltration in transparent porous media

G. A. Siemens,¹ S. B. Peters,¹ and W. A. Take²

Received 20 February 2012; revised 4 December 2012; accepted 9 January 2013; published 12 February 2013.

1 Infiltration is often assumed to occur with little or no impedance from the air within the vadose zone. If this assumption is not valid air counterflow may occur, while the infiltration rate and degree of saturation within the transmission zone may be significantly reduced. Accurate predictions of infiltration rates are important for applications such as moisture balance calculations and predictions of pore water pressures in landslide triggering. Existing results for confined infiltration show contradictory evidence for either air pressure remaining at a threshold or continual increase of air pressure. In this paper, the effect of air entrapment is investigated in the laboratory using recently developed techniques of unsaturated transparent porous media and digital photograph interpretation. These techniques enable the full saturation profile to be quantified every 5 s. The experimental data are used to quantify the decrease in infiltration rate and degree of saturation within the transmission zone in the confined infiltration, to accurately locate the wetting front, and to assess the stability of the wetting front. The results confirm previous observations in which infiltration in an open system was observed to occur significantly faster than in a closed system. However, in this study, the air pressure ahead of the wetting front was observed to reach a threshold value, which was a function of the ponding height and suction at the wetting front. A Green-Ampt infiltration model based on this observation of air confinement was observed to provide a better fit to the experimental data than the one based on the continual increase in air pressure assumption.


1. Introduction

Infiltration is often assumed to occur with little or no impedance from the air within the vadose zone. However, this assumption is not strictly correct, as the entrapment of pore air has been shown to impede the rate of infiltration [e.g., McWhorter, 1971; Vachaud et al., 1974; Touma et al., 1984; Wang et al., 1998; Culligan et al., 2000; Hammecker et al., 2003]. In situations such as these, the migration of the infiltrating fluid causes the air phase to be displaced into an increasingly smaller pore volume. This subsequently leads to higher pore air pressures, counterflow of air in the opposite direction as the infiltrating fluid, a reduction in the infiltration rate, and a corresponding reduction in the wetting front advancement rate. This change in infiltration rate is important to understanding problems dominated by infiltration processes in the vadose zone (e.g., moisture balance of fields from an agricultural perspective, prediction of erosion rates, or the conditions leading up to the triggering of rainfall-induced landslides). In order to understand the complex relationship between the air and liquid phases during unsaturated infiltration, measurements are needed of transient pore air and infiltrating fluid pressures, the transient position of the wetting front, and transient measurements of the degree of saturation profile of the system. Unfortunately, whereas transient measurements of the two fluid pressures are relatively easily accomplished experimentally, technology to measure moisture content has typically been restricted to both low sampling rates (i.e., not suited for transient measurements) and at discrete locations only (i.e., not continuous profiles of degree of saturation). Alternatively, light transmission techniques including those developed by Tidwell and Glass [1994], Niemet and Selker [2001], and Darnault et al. [2001] have been successfully used as a noncontact method to measure saturation fields within the thin section apparatuses.

Laboratory investigations of the hydraulic behavior of unsaturated soils often involve placing unsaturated soil in a column apparatus with boundary conditions controlled at the top and bottom of the apparatus and instrumentation placed at discrete points along the length of the column [Buckingham, 1907; Lane et al., 1946; Ligon et al., 1962; Prill et al., 1965; Watson, 1967; McWhorter, 1971;
Vachaud and Thony, 1971; Zachmann et al., 1981; Corey, 1954; Wang et al., 1997, 1998; Culligan et al., 2000; Yang et al., 2004; Bathurst et al., 2007; Ma et al., 2011). Previous experimental work considering infiltration with confinement of air ahead of the wetting front used several types of apparatuses and had some differing findings. McWhorter [1971] reported infiltration with confined air results on Poudre Sand using oil. The apparatus replicated different depths to an impermeable boundary by changing the volume of the air reservoir at the base of the column. Culligan et al. [2000] investigated confinement of air by allowing the entrapped air to vent through different diameter capillary glass tubes, which thus dictated the second stage of air counterflow by controlling the rate of air pressure release and the subsequent changes in infiltration rate. Weeks [2002] researched air compression on a large scale where water levels rose in observation wells due to intense rain sealing the surface soil layer to air counterflow. Wang et al. [1998] noted that the air pressure recorded in their infiltration tests rose to near hydrostatic pressure levels. In each of these cases and others [Powers, 1934; Adrian and Franzini, 1966; Wilson and Luthin, 1963; Peck, 1964; Brustkern and Morel-Seytoux, 1970; Vachaud et al., 1974; Touma et al., 1984], two distinct stages of infiltration have been noted. The first stage consists of the wetting front moving downward and compressing the air below. The second stage begins when air counterflow is initiated upward through the advancing wetting front. The second stage of infiltration continues until an impermeable boundary is reached at depth.

[4] Infiltration at the laboratory and field scale has been modeled extensively using the well-known Green-Ampt equation [Green and Ampt, 1911]. The Green-Ampt equation has also been modified to account for air counterflow by Sonu and Morel-Seytoux [1976], Grismer et al. [1994], Wang et al. [1997, 1998], Hammecker et al. [2003], and others. Discrepancies arise in the air pressure value whether it is a function of just the ponding height and the capillary pressure at the wetting front or to also include the depth of wetting front. Another point of discrepancy lies in the selection of a conductivity of the transmission zone. Often both the conductivity and the head at the wetting front are selected empirically.

[5] In the literature there are contradictory findings from both the experimental results and the numerical simulations in terms of the air pressure buildup and release during counterflow (air pressure either holds at a threshold or continues to rise as the wetting front proceeds through the profile). A new experimental technique is utilized in this paper to investigate the effect of air entrapment on the mobility and degree of saturation of the wetting front using unsaturated, transparent porous media. Shown in Figure 1 is an advancing wetting front in transparent soil approaching a phreatic surface. Near the bottom of the photograph the transparent porous media are at 100% saturation, and the black background is visible. Moving upward past the capillary zone the porous media are at its residual moisture content, and the particles become visible and appear white. Continuing to move upward past the wetting front, within the transmission zone near the top of the photograph, the air phase is visible as well as a distinct wetting front. Using this change in light intensity, Peters et al. [2011] developed a relationship between pixel intensity and degree of saturation within column experiments to allow saturation measurements with a resolution of a pixel. Thus, full-field saturation profiles can be recorded throughout infiltration experiments.

[6] In this paper, the air pressure buildup along with the wetting front mobility and degree of saturation will be quantified through novel experiments using two gradations of transparent porous media and simulations using a modified Green-Ampt relationship. The experimental results, which apply various air venting conditions, show that the degree of saturation within the transmission zone is reduced by entrapment of the air phase ahead of the wetting front. The rate of wetting front advancement is also reduced as air counterflow through the transmission zone occurs simultaneously. For modeling, knowledge of the degree of saturation throughout the profile allows use of the unsaturated conductivity curve for input into the modified Green-Ampt model to significantly improve model results.

2. Materials and Experimental Technique

2.1. Transparent Porous Media

[7] The transparent porous media material selected for use in the infiltration tests is a fused quartz with a refractive index of 1.459. The coarse and fine gradations used are representative of uniformly graded sands with 100% of its particles passing the 4.75 and 2 mm sieves, respectively. Individual particles appear clear when dry, while a cluster of dry particles appears white. The properties are summarized in Table 1 with further details provided by Peters et al. [2011] and Ezzein and Bathurst [2011]. As placed dry
densities from multiple tests ranged initially between 1100 and 1175 kg/m$^3$ corresponding to porosities of 0.48–0.51.

The transparent porous media were placed in the column using wet pluviation or dry tremie techniques. During wet pluviation the column is first filled with pore fluid, and then the grains are rained in. The dry tremie technique involves lowering a pipe filled with dry particles to the bottom of the column, opening the bottom of the pipe, and slowly raising the pipe allowing the grains to fill the space below. The pore fluid was selected to match the refractive index of the porous media. A blended mixture of Petro Canada Krystol40 ($RI = 1.450$) and Life Brand™ unscented baby oil ($RI = 1.463$) was used to achieve the equivalent refractive index ($RI = 1.459$). The fluid mixture was produced by combining the quantities of each mineral oil until the target refractive index was met. Details of the fluid properties are presented by Peters et al. [2011], and properties of the blended oil mixture are listed in Table 2 along with the properties of water for comparison.

2.2. Column Apparatus

Infiltration testing was carried out within the 1450 mm tall column apparatus [Peters et al., 2009; Siemens et al., 2010; Peters et al., 2011] shown in Figure 2. Constructed with 19 mm thick Perspex sheets joined at right angles the column had an interior cross-sectional area of 2075 mm$^2$ (45.6 mm × 45.6 mm). Digital photographs were collected with three CANON EOS Digital Rebel XTi single-lens reflex cameras. Six GE-Druck PDCR-81 pore pressure transducers (PPTs) were used to measure the pore pressure along the length of the column (a PPT is visible in Figure 1). Prior to arrival of the wetting front the PPTs measure the pore air pressure, and after the wetting front passes they measure the pore oil pressure. Manometers are also placed along the side of the apparatus (manometer port visible in Figure 1), which were opened to allow venting of air when required. The different combinations of boundary conditions applied during infiltration tests are shown in Figure 3, which are termed open system (Figure 3a) and closed system (Figure 3b). The open system consists of constant head boundary conditions at the surface and base as well as manometer ports open along the length of the column. The closed system consists of a constant head condition at the surface, no-flow boundary condition at the base, and no air venting allowed along the column length.

3. Unsaturated Properties of Transparent Porous Media

3.1. Retention Curve

The retention curve of the coarse gradation was measured using a hanging column experiment on a 12 mm thick specimen. The retention curve measurements for both the coarse and fine gradations as well as fitted curves are plotted in Figure 4a. The coarse gradation retention curve is typical of uniform sand with an air entry value (AEV) of 0.1 kPa and a steep transition zone. The fine gradation has a higher AEV of 0.58 kPa and a distinct change in the slope of the retention curve at $S = 0.4$ over the suction range tested.

Table 1. Transparent Porous Media Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Coarse Gradation</th>
<th>Fine Gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index</td>
<td>1.459</td>
<td>1.459</td>
<td></td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.24</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td>Particle size distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{10}$ mm</td>
<td>0.75</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>$D_{50}$ mm</td>
<td>1.16</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>$D_{60}$ mm</td>
<td>1.75</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Coefficient of uniformity</td>
<td>2.3</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Coefficient of curvature</td>
<td>1.0</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Minimum dry density kg/m$^3$</td>
<td>1050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated conductivity: mineral oil m/s</td>
<td>$1 \times 10^{-3}$</td>
<td>$4 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Saturated conductivity: water m/s</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$From Ezzein and Bathurst [2011].

Table 2. Oil and Water Properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Water</th>
<th>Oil Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density g/cm$^3$</td>
<td>1.0$^a$</td>
<td>0.845</td>
<td></td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.333$^a$</td>
<td>1.459</td>
<td></td>
</tr>
<tr>
<td>Dynamic viscosity (25°C) cP</td>
<td>0.89$^a$</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>Dynamic viscosity (30°C) cP</td>
<td>0.80$^a$</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>Surface tension (25°C) dyne/cm</td>
<td>72.0$^a$</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Contact angle on fused quartz $^b$</td>
<td>$^b$</td>
<td>0$^b$</td>
<td></td>
</tr>
<tr>
<td>Contact angle on Perspex $^b$</td>
<td>53</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Munson et al. [1998].

$^b$Sears and Zemanski [1955].
curves were fitted to the data. The van Genuchten equation in terms of saturation is

\[ S = S_r + \frac{S_s - S_r}{(1 + (\psi / a_{vG})^{1/n_{vG}})^{m_{vG}}} \]  

(1)

where \( S \) is the degree of saturation; \( S_s \) and \( S_r \) are the saturated and residual saturations, respectively; \( \psi \) is the suction; and \( a_{vG}, n_{vG}, \) and \( m_{vG} \) are the curve fitting parameters. The Fredlund and Xing equation is

\[ S = C_{v \psi} \left( \frac{S_s}{\ln \left( \frac{1 - \psi / \psi_r}{\ln (1 - 1,000,000/\psi_r)} \right)^{m_{FX}}} \right) \]  

(2)

where \( e \) is the natural number; \( a_{FX}, n_{FX}, \) and \( m_{FX} \) are the curve fitting parameters; \( C_{v \psi} \) is further defined as

\[ C_{v \psi} = 1 - \frac{\ln (1 - \psi / \psi_r)}{\ln (1 - 1,000,000/\psi_r)} \]  

(3)

where \( \psi_r \) is the suction corresponding to the residual moisture content. The fitting parameters are listed in Table 3. In both cases, the curves provide a reasonable fit to the measured data.

### 3.2. Unsaturated Conductivity

[10] In addition to the retention curve the other unsaturated material property of interest for infiltration modeling is the unsaturated conductivity curve. The saturated conductivity was measured using numerous constant head tests that generally followed ASTM D 2434 [Siemens et al., 2010]. Results are plotted in Figure 4b at \( S = 1 \). For unsaturated conductivity tests, constant flow conditions were applied at the surface and a constant head boundary condition at the base. The average degree of saturation along the column length was interpreted from the digital photographs [Peters et al., 2011]. Unsaturated and saturated conductivity values were interpreted by applying the Darcy [1856] equation with the results plotted versus degree of saturation in Figure 4b. The test database consists of data collected from multiple column configurations and placement techniques. As expected, conductivity decreased with decreasing degree of saturation.
saturation. The coarse gradation data have measured conductivity decreasing approximately 2 orders of magnitude at $S = 0.37$ from its saturated value. The fine gradation data also show conductivity decreasing significantly from its saturated value over a small range of saturation.

[11] In addition to the measuring unsaturated conductivity the relationship was estimated from the van Genuchten [1980] and Fredlund and Xing [1994] input parameters. The fitted unsaturated conductivity curves are also plotted in Figure 4b in terms of degree of saturation. The van Genuchten equation based on the Burdine [1953] model used is

$$k_u = k_s \frac{1 - (\alpha_{vs} \psi)^{(\theta_o - 2)}}{(1 + (\alpha_{vs} \psi)\theta_o)^{-2\theta_o \psi_V}}$$

(4)

where $k_u$ is the unsaturated conductivity, and $k_s$ is the saturated conductivity. The Leong and Rahardjo [1997] equation for unsaturated conductivity is

$$k_u = k_s \frac{1}{[\ln(\psi / \psi_{\text{sat}})]^{\psi_{\text{sat}}}}$$

(5)

The experimental data are well represented by both estimations.

4. Infiltration Results: Coarse Gradation

[13] To investigate the influence of entrapped air on wetting front mobility and degree of saturation, two constant head infiltration tests are presented for each gradation. The difference between the tests was the boundary condition at the base and whether air venting was allowed along the length of the column (Figure 3).

4.1. Test 1: Infiltration in an Open-Coarse Sand System

[14] The boundary conditions applied in Test 1 were constant elevation head boundary condition to the top and bottom of the column as illustrated schematically in Figure 5. Test results are plotted in Figures 5 and 6 and include degree of saturation profiles at selected time intervals (Figures 5a–5f), location of the wetting front with time (Figure 6a), corresponding pore pressure profiles (Figure 6b), and pore pressure versus time (Figure 6c). As the constant head pond is applied the oil flows through the profile, and a sharp wetting front is noted on the profiles. After the wetting front passes, the degree of saturation increases to an average saturation of $S = 0.92$. Plotted in Figure 6a, the wetting front advanced relatively rapidly and at a near linear rate with time. Before the wetting front passes, the PPTs measure 0 kPa air pressure, indicating the air ventilation provided by the manometers was effective. As the wetting front passes, the PPT elevation pore pressure increased from 0 kPa to a value corresponding to the PPT depth below the surface. Once the wetting front passed, the lowest manometer pressure rose along the length of the column to its equilibrium pressure profile. Test 1 was complete when the wetting front reached the base of the column at $t = 380$ s.

4.2. Test 2: Infiltration in a Closed-Coarse Sand System

[15] Test 2 results for infiltration in a closed system include five saturation profiles (Figure 7) as well as the wetting front location, pore pressure profiles, and pore pressure versus time (Figure 8). Similar to Test 1, the initial degree of saturation profile for Test 2 is at residual moisture content. As the test is initiated, the two stages of infiltration are noted in the results. First, the wetting front traveled downward relatively quickly (Figure 8a), and the air pressure rises uniformly along the length of the column (Figure 8c) from time $t = 0–25$ s. Then, the air counterflow started and the wetting front proceeded at a constant rate for the remainder of the test. The pressure along the length of the column remained consistent between 1.2 and 1.6 kPa for all the PPTs during the air counterflow stage. From the
saturation profiles, the wetting front proceeds downward during the test with the transmission zone average saturation measured at $S = 0.78$. Initially, a sharp wetting front is observed (Figures 7a and 7b); however, as the test continued the wetting front becomes less distinct and more sloped (Figures 7c–7f). Test 2 was complete when the wetting front reaches the fluid surface at elevation 200 mm at $t = 875$ s.

4.3. Infiltration Results Comparison: Coarse Gradation

[16] The degree of saturation and the mobility of the wetting front are functions of the boundary conditions during infiltration. A visual comparison of Test 1 and Test 2 is illustrated in Figure 9, and a close-up examination of the wetting front advancement is plotted in Figure 10. In Figure 9 cropped photos of the open and closed tests were taken from between elevation 800 and 1350 mm, which is the upper portion of the column. Comparing the location of the wetting fronts between the two tests shows clearly how allowing dissipation of the air allows significantly quicker advancement of the wetting front. Comparing consecutive photos allowed visual observation of the air bubbles as they meandered through the transparent medium following a variable path on their journey to the surface. Some air bubbles reached the surface and dissipated into the atmosphere, whereas others remained trapped within the transmission zone. The continual retention of air bubbles within the transmission zone influenced the lower degree of saturation observed in the results.

[17] A close-up of selected wetting front profiles are shown in Figure 9 to demonstrate quantitatively the affect of whether the infiltration system is open or closed. Comparision of Figures 9a and 9b shows the distance between the wetting fronts is greater when air dissipation is allowed (Figure 9a) compared with the entrapped case (Figure 9b). In fact, for every one profile shown from Test 1 there are approximately three profiles plotted for Test 2. Also, as a
result of the upward movement and retention of escaping air within the transmission zone, the final degree of saturation in the transmission zone is lower for the confined air test as shown by the vertical lines on the right side of each plot. The added air resistance from the confined air has altered the shape of the wetting front and has made the leading edge less sharp than the flatter wetting front of the unconfined air test.

Finally, a summary of the recorded wetting front location with time and the final saturation profiles for the two tests are plotted in Figure 11. During the first few seconds of the test, the wetting front advancement for both tests is essentially the same. Then, the wetting front advancement rate in Test 2 slows down, and both remain constant for the remainder of the tests. The difference in wetting front mobility is obvious with the venting of air in advance of the wetting front allowed it to advance approximately 3 times faster than when air pressure was built up ahead of the wetting front. In addition, the final degree of saturation is significantly greater in the open system compared with the closed system (Figure 11b). In the open system, the final degree of saturation is approximately $S = 92\%$; however, when air is entrapped the average degree of saturation is only $S = 78\%$.

As noted in section 1, one of the discrepancies in the literature is the air pressure observed ahead of the wetting front. In Test 2 all the PPTs measured between 1.2 and 1.6 kPa air pressure which is approximately equal to the corresponding height at the surface. Consistent with the constant pressure noted ahead of the wetting front in Test 2 (Figure 8c), constant pressure during ponded infiltration was noted by Brustkern and Morel-Seytoux [1970], Vachaud et al. [1974], Touma et al. [1984], and Grismer et al. [1994]. In contrast, confined air infiltration tests conducted by Wang et al. [1997, 1998] showed continued increases in air pressure to near hydrostatic pressure early in their tests. The continued increase of air pressure was not noticed in Test 2 since it was released through the transmission zone.

Modified Green-Ampt Infiltration Modeling

In order to gain further insight into infiltration behavior the test results were modeled. The Green and Ampt [1911] infiltration model is often used to determine the rate of infiltration and is illustrated in Figure 12. Traditionally, one assumption of this equation is that the air pressure ahead of the wetting front is atmospheric. Since entrapped air has been seen to significantly reduce the infiltration rate, the use of the traditional equation will therefore overpredict the actual rate of infiltration. Wang et al. [1997] derived a model that is valid for 1-D infiltration in closed systems for cases where air pressure is released when air pressure exceeds the air-bubbling pressure and air pressure continually increases during infiltration. In the tests reported here, air pressure reached a maximum when air counterflow initiated and then held that value for the remainder of the test. Therefore, the Wang et al. [1997] model is not appropriate for modeling these tests. Similar to both Grismer et al. [1994] and Hammecker et al. [2003], the final equation will include a term for the air pressure $(h_{af})$ below the wetting front as follows:

$$f = k(S) \left( \frac{z + h_{wb} + h_o - h_{af}(z)}{z} \right)$$

where $f$ is the infiltration rate, $k(S)$ is the unsaturated conductivity, $z$ is the depth of wetting front, $h_{wb}$ is the oil entry value, $h_o$ is the height of ponding, and $h_{af}(z)$ is the gauge pressure of the air phase ahead of the wetting front as a function of $z$.

5.1. Input Parameters

This section will describe the process for selecting the input parameters for modified Green-Ampt modeling, which are listed in Table 4. In previous cases [Vachaud et al., 1974; Touma et al., 1984; Wang et al., 1998; Hammecker et al., 2003], the conductivity for the transmission
The final parameter to determine is air pressure $h_{af}(z)$, which will be a function of the wetting front depth as air compresses and then counterflow is induced. Prior to infiltration, the air pressure is atmospheric, $h_b$. The air is modeled as compressing ahead of the wetting front according to Boyle’s law. From the majority of the literature, air pressure will rise to a maximum value before the initiation of air counterflow. Since after air counterflow is initiated in Test 2, air bubbles exited the surface on a continuous basis, and the recorded air pressure remained relatively constant with time it is assumed that air counterflow for the gradation is steadily exiting from the surface.

We now have two air pressure equations dependent on the stage of infiltration:

$$h_{af} = h_b \left( \frac{z}{B-z} \right), \text{ air compression (Stage 1)}$$
$$h_{af} = h_o + h_{wb}, \text{ air counterflow (Stage 2)}$$

where $B$ is the depth below the surface to an airflow barrier, such as the phreatic surface (Figure 3).

The remaining values of the modified Green-Ampt equation are the infiltration rate and wetting depth. When the air pressure ($h_{af}(z)$) is substituted into the modified

---

**Figure 8.** Test 2 infiltration in a closed-coarse sand system: (a) wetting front elevation versus time, (b) pore pressure profiles, and (c) pore pressure versus time. Note selected profiles correspond to degree of saturation plots in Figure 7.
Green-Ampt equation defined in equation (6), the equation has two cases as follows:

\[ f = k\{S\} \left( \frac{z + h_o + h_{sb} - h_o(z/(B - z))}{z} \right), \text{ air compression} \tag{8} \]

\[ f = k\{S\}, \text{ air counterflow} \]

The above equation is complete for the \((f, z)\) relationship, and one can substitute in the values of \(z\) and determine the infiltration rate with wetting depth for entrapped air infiltration. Since \(f\) is a measurement of a rate, the time can be calculated using the following relationship between cumulative infiltration \(F\) and time \(t\).

**Figure 9.** Visual comparison of the wetting front mobility and degree of saturation (between 800 and 1350 mm above base of coarse sand column). Column on left-hand side of each time interval corresponds to Test 1 (infiltration into an open system), while right-hand side corresponds to Test 2 (infiltration into a closed system). (a) \(t = 0\) s, (b) \(t = 25\) s, (c) \(t = 50\) s, (d) \(t = 75\) s, and (e) \(t = 100\) s.

**Figure 10.** Comparison of degree of saturation plots at constant 5 s time intervals during infiltration tests in coarse sand: (a) Test 1: infiltration in an open system and (b) Test 2: infiltration into a closed system.
\[
\frac{df}{dt} = \frac{\Delta \theta \Delta z}{C1}
\]

where \(\Delta \theta\) is the change in volumetric water content. Setting the above equation for infiltration rate equal to the modified Green-Ampt equation (equation (6)) and knowing \(F = 0\) at \(t = 0\), for the infiltration during air compression, we get

\[
t = \frac{\Delta \theta}{k[S]} \left( z - (h_o + h_{wb} - h_{af}(z)) \ln \left( 1 + \frac{z}{h_o + h_{wb} - h_{af}(z)} \right) \right)
\]

and during air counterflow, equation (10) simplifies to

\[
t = \frac{\Delta \theta}{k[S]}
\]

Equations (10) and (11) provide a relationship for infiltration in terms of time \((t)\) and wetting front depth \((z)\). This can now be viewed with the infiltration rate found earlier for an infiltration rate \((f)\) and time \((t)\) relationship.

5.2. Infiltration Modeling: Coarse Gradation

Figure 13a compares the infiltration in an open system with the traditional Green-Ampt model. Initially, the infiltration rate is high, and then it approaches a constant value asymptotically. As anticipated, the model results compare well with the experimental results throughout the test. Noted on the plot is the saturated conductivity \((k = k[S = 1.0])\) and the unsaturated conductivity corresponding to \(S = 0.92\) which was determined using transparent porous media. The conductivity value for \(S = 0.92\) correlates much better to the experimental results showing the benefit of the ability to measure the degree of saturation within the transmission zone using transparent porous media. Using the conductivity value corresponding to \(S = 1.0\) would overestimate the infiltration rate and therefore underestimate the runoff.

Test 2 was modeled using equation (9) and plotted in Figure 13b. In Test 2 the experimental results show the infiltration rate drops significantly to a minimum and then stays constant at the conductivity corresponding to the degree of saturation measured in the transmission zone. Also shown on the plot is the saturated conductivity of the coarse gradation. Use of the saturated conductivity value shown would greatly overestimate the infiltration rate, and the conductivity corresponding to the measured degree of saturation \((S = 0.78)\) is exactly that measured during the test. For comparison, the model that allows the air pressure to increase to a hydrostatic level is plotted which underpredicts the infiltration rate throughout the test. The experimental results for the closed system showed the air pressure ahead of the wetting front reaching an equilibrium value that is similar to the ponded height.

5.3. Impact of Pore Fluid on Infiltration Results

To assess the impact of the selected pore fluid on the infiltration results the relative pore fluid properties of the oil mixture and water must be considered (Table 2) as.
well as their interaction with the fused quartz. The density of the oil mixture is 84.5% of water, while the viscosity is approximately 10 times that of water. As expected, the surface tension of the oil is less (approximately one third), while the contact angle on fused quartz is equivalent (0°/C14).

To convert the measured retention curves to their water equivalent, a scaling factor of 2.3 was calculated [Leverett, 1941]. The remaining material parameter is the conductivity.

EZzein and Bathurst [2011] measured the saturated conductivity of water and mineral oil in fused quartz and found that the saturated conductivity for water was 3.5 that for oil (Table 1).

The impact of using oil instead of water on the infiltration results can be assessed both qualitatively for the wetting front behavior and quantitatively for the infiltration results. Since water has a lower viscosity and higher surface tension the wetting front would be expected to have more fingering and therefore be more variable than the oil wetting front (Figure 10). Instead of advancing through the profile consistently, there would be expected to be some aspects of the wetting front that would move faster than the rest. The speed of the wetting front would also be affected by a change in pore fluid. From equation (6) the infiltration rate is calculated using the porous media properties as inputs as well as the test configuration. For the same test configuration the only change in input parameters would be the conductivity value that would be approximately 3.5 times greater and the suction at the wetting front ($h_{wb}$) term that would be 2.3 times greater for water than for oil. Overall, the wetting front would advance 3.5 times faster with slightly more variation near the surface until the impact of the higher $h_{wb}$ term is negated by the depth of the wetting front ($z$). Therefore, the impact of using mineral oil as the pore fluid only caused minor changes to the expected behavior using water.

5.4. Infiltration Results and Modeling: Fine Gradation

In order to assess the impact of the saturated hydraulic conductivity a second set of infiltration tests in an open and closed system was performed using the fine gradation. The results appear similar to the coarse gradation tests including the relative slopes of the wetting front location versus time as well as the pore pressure measurements. Quantitatively, the difference is a 30-fold increase in the time scale for both tests owing to the reduction in the conductivity of the fine gradation relative to the coarse. Once again, the air pressure in the closed system increases immediately following ponding at the surface and stays at the same pressure for the remainder of the test. Even with an order of magnitude reduction in the conductivity the pore air and pore oil pressure response remains similar. Hydrostatic pressures were not approached in either case. Air pressure ahead of the wetting front in these tests is a function of the ponding height and the suction at the wetting front. In both tests the ponding heights are similar and significantly greater than the suction at the wetting front for either gradation (see Table 4 for Green-Ampt parameters), which results in similar air pressure ahead of the wetting front.

Green-Ampt models were also completed on the fine gradation tests, and the results are plotted in Figure 14. Infiltration in an open system shows an initially high infiltration rate and then decreases as the wetting front advances, while in a closed system the infiltration rate is lower but remains relatively constant. The Green-Ampt model parameters for each test are tabulated in Table 4.

![Figure 13](image-url)
rate asymptotically approaching the conductivity associated with the degree of saturation of the transmission zone ($S = 0.88$) in Figure 14a. Once again use of the unsaturated conductivity curve provided a significantly improved estimation over the saturated conductivity value. The closed system infiltration experiment had infiltration rate decreasing very early in the test until a constant value was reached. Some variation is noted for the remainder of the test which oscillated above and below an average value. The modified Green-Ampt model of the closed system test followed the experimental results very closely. This model required use of a lower conductivity than predicted using the fitted conductivity curves (Figure 4b); however, the value selected is still well within the range measured during the constant flow tests. For comparison the Green-Ampt model, which allows air pressure to continually increase ahead of the wetting front, was also applied to the experimental results. As in the coarse gradation tests this model significantly underpredicts the infiltration rate for the fine gradation test as well as overpredicts the air pressure ahead of the wetting front (data not shown). From the pore pressure results, which showed increasing pressure to a limiting value and then remaining constant for the remainder of the test, allowing increase in pressure to the hydrostatic value does not apply to the test results observed in this paper which is consistent with the majority of previous experimental results in closed systems.

6. Conclusion

The effect of air entrapment on the mobility and the degree of saturation of the wetting front during infiltration was investigated in the laboratory using transparent porous media. The unsaturated flow properties of the transparent porous media were characterized which highlighted the benefits of transparent porous media including measurement of the complete degree of saturation profile. Four infiltration tests under varying boundary conditions were reported that displayed the impact of air entrapment on the wetting front advancement rate as well as degree of saturation on two gradations. Air entrapment had the effect of significantly reducing the wetting front advancement rate as well as the degree of saturation within the transmission zone. The reduction in degree of saturation resulted in a corresponding reduction in the unsaturated conductivity within the transmission zone. Complete degree of saturation profiles were measured at intervals as low as 5 s throughout infiltration tests; the location of the wetting front is also known throughout; the unsaturated conductivity function was measured directly for the two gradations; quantitative measurement of the stability of the wetting front during infiltration in open and closed systems was made, and qualitative measurement of air counterflow through the transmission zone was made. Finally the open and closed system tests were modeled using traditional and modified Green-Ampt estimations to account for buildup of air pressure in advance of the wetting front.

The notable conclusions that can be drawn from this research lie within the use of transparent porous media as well as within the results of the infiltration modeling. The digital photo analysis technique is capable of effectively capturing the wetting front location with time as well as the measurement of the degree of saturation within the transmission zone which is a major contribution to laboratory testing of infiltration. Knowledge of the degree of saturation allowed direct measurement of the unsaturated conductivity curve as well as determination of the unsaturated conductivity of the transmission zone. During the infiltration tests the digital photo analysis technique provided thousands of measurements of degree of saturation at every time interval. The infiltration results show that the air pressure ahead of the wetting front in the closed tests was a function of the ponding height and the wetting front suction. Finally, the Green-Ampt modeling included the buildup of the air pressure in advance of the wetting front as well as the infiltration rate throughout the test.
[35] Acknowledgments. We acknowledge the support of the Natural Sciences and Engineering Research Council to this research. We also appreciated the efforts of the Editor, Associate Editor, and reviewers whose reviews and suggestions substantially improved this manuscript.

References