Filter Paper Column for Measuring Transient Suction Profiles in Expansive Clay

William J. Likos and Ning Lu

An inexpensive experimental system for measuring suction profiles during transient moisture movement processes in unsaturated expansive clays was developed. The system relies on measurements of total suction using the noncontact filter paper technique at several stations along a one-dimensional soil column. Performance of the system was demonstrated for a column of compacted Ca\textsuperscript{2+}-smectite undergoing evaporation at the top boundary under ambient laboratory conditions for 91 days. The system was most applicable during latter stages of drying when the rate of moisture movement was slow enough to be adequately captured by the required 7-day measurement interval and the suction values are large enough to offset scatter. Final water content and suction profiles were determined gravimetrically and compared with values obtained from the filter paper measurements. Desiccation cracking did not significantly affect the accuracy of the filter paper system. The research forms an experimental basis to develop or verify theoretical models aimed at predicting moisture flux for in situ expansive soil subject to infiltration or evaporation processes.

Prediction of moisture movement in the unsaturated soil zone located near the ground surface is essential for numerous problems in geotechnical, geoenvironmental, and transportation engineering. Typical examples include modeling of saturated-unsaturated groundwater flow for surface contaminant spills; design of soil-based cover systems for landfills and hazardous waste isolation; water balance modeling under infiltration, runoff, and evaporative processes; and heave prediction for shallow foundations or pavements constructed on expansive soils.

The movement of moisture in soil is fundamentally governed by flow in response to a gradient in hydraulic head. In the case of unsaturated soils, this gradient is described in terms of soil suction, which is in turn dependent on the moisture content of the soil through the soil–water characteristic curve (SWCC). To accurately predict moisture movement in unsaturated soil, methods for modeling, estimating, or directly measuring subsurface suction profiles under changing moisture conditions are required.

Moisture conditions in the field can be changed under two principal mechanisms: infiltration or evaporation. As cycles of infiltration and evaporation occur over time, the subsurface suction and water content profiles experience transient changes in response to the varying boundary conditions. Infiltration into soil, which is relatively well understood, results primarily from natural precipitation, irrigation, or the pooling of surface runoff. Numerous analytical and numerical solutions to Richard's equation for predicting subsurface infiltration profiles in unsaturated soils have been developed and, for the most part, have been experimentally verified (1, 2). Evaporation from soil, however, is a significantly more complex mechanism, which occurs in the form of combined liquid and vapor transport both at depth and at the ground surface. Evaporative flux is dependent not only on the relevant soil properties—which include hydraulic conductivity, vapor diffusivity, and the SWCC—but also on the predominant climatic conditions, which include temperature, relative humidity, and wind speed parameters (3). Evaporation models, which account for these combined soil–atmospheric factors, have been successfully demonstrated (4–6) but are generally limited to nondeformable soils such as sands under well-defined or simplified atmospheric and soil conditions.

Infiltration and evaporation processes in unsaturated soils are further complicated when deformable soils such as clays are considered. Here, the often significant changes in fabric that occur during the wetting or drying process must be accounted for. This condition is particularly true for expansive clays, in which extensive volume change, adsorption, and fracturing are quite common. Despite continuous modeling efforts that attempt to account for these factors (7, 8), the prediction of fluid flow in expansive soils remains an extremely challenging task. Consequently, practical engineering problems that require knowledge of moisture movement in unsaturated expansive soils, such as heave prediction, are typically approached from a largely empirical standpoint. Significant limitations in the capability of instrumentation for measuring the wide range of suction sustainable by expansive soils have resulted in a paucity of experimental data related to the subject.

An inexpensive experimental approach for direct measurement of suction and moisture content profiles during transient fluid flow processes in unsaturated expansive clays is presented. The work forms an experimental basis for the future development or verification of more rigorous theoretical models aimed at predicting suction and moisture flux in natural expansive soil deposits subject to infiltration or evaporation.

A one-dimensional laboratory soil column was constructed such that suction measurements could be obtained using the non-contact filter paper technique at several measurement stations located with increasing depth from the soil surface. A similar testing concept was initially proposed by Fredlund for in situ measurements of total suction profiles in road or airfield subgrade materials (9). Performance of the laboratory system was demonstrated for a 42-cm-high column of compacted Ca\textsuperscript{2+}-smectite undergoing transient evaporation over a period of 91 days. Total suction and moisture content profiles were plotted with depth as the soil column was allowed to dry from near its
optimum water content under exposure to ambient atmospheric conditions. To assess the accuracy of the system, gravimetric measurements of the final water content profile were obtained for comparison with the filter paper–based measurements.

**MATERIALS AND METHODS**

**Filter Paper Column**

Experimental studies of fluid flow in unsaturated soils require measurement of either water content or suction profiles under changing moisture or suction boundary conditions. If suction is measured, the measurement system must be applicable for the chosen soil type and for the suction range of interest. For unsaturated expansive clays, which are capable of sustaining suction well into the range of megapascals (MPa) over a large range of water content, traditional instrumentation such as tensiometers (range = 0 to 100 kPa) or thermocouple psychrometers (range = 100 to 8000 kPa) is usually inappropriate. In many cases, the cost of suction measurements alone precludes their use in routine engineering practice.

Filter paper methods, however, which include the contact technique for matric suction measurements and the non-contact technique for total suction measurements (10), are a low-cost alternative. Filter paper methods are applicable over suction for a range of approximately 100 kPa to 100 MPa, which covers the practical range of interest for expansive soils. If rigorous testing procedures are followed, the accuracy and precision of filter paper measurements for expansive soils have been shown to be more than adequate for most engineering purposes (11).

A cylindrical testing column was outfitted with eight measurement stations for measuring total suction using the non-contact filter paper technique. Figure 1 shows a schematic drawing of the testing system. The laboratory column, which was constructed from 0.635-cm (0.250-in.) wall transparent acrylic, is 42 cm in total length and 8.8 cm in diameter. Soil was compacted into the column in several lifts using a standard Proctor compaction rammer. Transient suction and moisture content profiles were monitored using the filter paper stations as water was allowed to either infiltrate into the surface of relatively dry soil or evaporate from the surface of relatively wet soil.

Eight suction measurement stations consisting of a cylindrical glass jar, 6 cm long and 2 cm in diameter, were located on the column wall at increasing depths from the soil surface. Figure 2 shows the detail of a typical measurement station. Holes were drilled through the outside wall of the soil column such that the plastic caps of the measurement jars could be press-fitted into the column. The plastic caps also had centered holes (1 cm in diameter) drilled into them to allow communication between the soil and the inside of the measurement jar. Teflon tape was wrapped around the outside of the plastic caps to ensure a sealed environment between the vapor phase of the soil pore water and the inside of the jar. Relative humidity in the jar was assumed to be in equilibrium with the soil's pore water vapor.

A curled piece of filter paper (initially oven-dried) was placed inside the jar for total suction measurements. The paper was curled by temporarily by wrapping it around a short piece of 0.318-cm (0.125-in.) outside diameter steel tubing, which was done with powder-free latex gloves. During column testing, total suction measurements were obtained as a function of depth every 7 to 14 days by unscrewing the measurement jars from the plastic caps and determining the water content of the filter papers gravimetrically (±0.0001 g). The filter paper water content was related to total soil suction using a predetermined calibration curve. Each suction measurement represented the effective total suction over the entire equilibration increment. After each measurement, the filter paper was replaced with a new piece from the same batch.

**Filter Paper Calibration**

All filter papers used in the current testing series were Whatman No. 42, 5.5-cm-diameter papers from manufacturer Batch 920880. This batch was independently calibrated before testing to account for possible batch-to-batch variation in the calibration characteristics of Whatman No. 42 papers (11). Calibrations were carried out following the general procedures outlined in ASTM D5298 using solutions of NaCl and KCl and corresponding to total suction ranging from approximately 4.5 to 2.75 log kPa (35,000 kPa to 560 kPa). A second series of calibrations was conducted to examine any possible effects of handling and curling the papers into the measurement station jars. This involved placing an entire measurement station into the headspace of a larger jar filled with various calibrated salt solutions.
Figure 3 shows calibration curves for curled and uncurled filter papers. Linear trend lines based on least-squared regression analysis are shown through the data points. There is no significant difference between the calibration curves for the curled and uncurled papers. For subsequent total suction calculations, the following calibration curve, based on the combined data, was used:

\[
\psi_t = -0.138 \psi_{wp} + 5.48
\]

where \( \psi_t \) is total suction (log kPa) and \( \psi_{wp} \) is the filter paper water content (%).

Soil Properties and Preparation

Expansive soil for testing was sampled from an outcrop of the Benton shale formation near Denver, Colorado. The material is typical of that within the Upper Cretaceous shale formations, including the Benton and Pierre, that are well-known sources of swelling-related structural damage along the Colorado Front Range (12). The material, referred to herein as "Soda Lakes smectite" is a marbled, waxy, bentonite consisting primarily of discrete Ca\(^{2+}\)-smectite with trace amounts of kaolinite, quartz, and feldspar. Table 1 summarizes the other basic engineering and index properties.

The SWCC, shown as Figure 4, was determined using the traditional non-contact filter paper technique for 100 continuously disturbed subsamples (11). The SWCC is bilinear with an inflection point occurring at approximately 4 log kPa (10,000 kPa), and it may be described by a two-part series of equations:

\[
\psi_t = -0.108 \psi_{wp} + 6.74 \quad \psi_t > 4.0 \text{ log kPa}
\]

\[
\psi_t = -0.076 \psi_{wp} + 5.89 \quad \psi_t \leq 4.0 \text{ log kPa}
\]

where \( \psi_t \) is total suction in log kPa and \( \psi_{wp} \) is the soil water content (%).

Before column testing, the material was crushed to pass a No. 4 sieve, mixed with distilled water, and allowed to cure in a sealed plastic container for 48 h. A molding water content of 38.05% was chosen, which is approximately 2% dry of optimum and 3% wet of the plastic limit. After curing, the soil was compacted into the column in 10 lifts with a standard Proctor rammer, which resulted in a dry-density of 1.24 g/cm\(^3\). Filter papers were then inserted into the individual measurement stations, which are listed in terms of their depth relative to the soil surface \( z \) in Tables 2 and 3. The assembled column was exposed to ambient laboratory conditions and allowed to dry by evaporation from the soil surface for a period of 91 days. Suction measurements were obtained using the filter paper stations at time increments ranging from 7 to 13 days.

Evaporation testing was conducted in the Colorado School of Mines (CSM) and U.S. Geological Survey Geotechnical Measurements Laboratory located on the CSM campus. The atmospheric conditions in this laboratory (temperature and relative humidity) are independently controlled using a dedicated conditioning system.

### Table 1 Engineering and Index Properties of Soda Lakes Smectite

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mineralogy</td>
<td>discrete smectite, trace kaolinite, quartz, feldspar</td>
</tr>
<tr>
<td>Percent Clay</td>
<td>90%</td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>111%</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>35%</td>
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<tr>
<td>Plasticity Index</td>
<td>76%</td>
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<tr>
<td>Activity</td>
<td>85%</td>
</tr>
<tr>
<td>USCS(^a) Classification</td>
<td>CH</td>
</tr>
<tr>
<td>Max. Dry Density, ( p_{max} )</td>
<td>1.22 g/cm(^3)</td>
</tr>
<tr>
<td>Optimum Moisture Content</td>
<td>40%</td>
</tr>
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</table>

\(^a\)USCS = Universal Soil Classification System.
isolated from the surrounding building through an air lock. The exact conditions during testing were measured by a relative humidity/temperature probe located near the soil column (Vaisala HMI-38). Figure 5 shows the ambient total suction and temperature traces recorded over the first 34 days of testing. Total suction values were calculated from the relative humidity and temperature measured by the probe using Kelvin’s equation (13). Both suction and temperature were relatively constant over the first 34 days, with suction averaging 5.43 log kPa (268,000 kPa) and temperature averaging 22.5°C. Although it was not possible to continue the trace over the entire 91 days of testing, it is assumed that the atmospheric conditions did not vary significantly beyond the recorded trace.

RESULTS

Figure 6 shows total suction profiles in the soil column determined over the 91-day testing period. The vertical dashed line showing the initial suction profile was calculated from the initial average water content of the soil (38.05%) using the SWCC (Equation 2). The suction data are summarized in Table 2. Measurements obtained at Station 7 (z = 20.5 cm) were found to be unreliable, most likely because of a poor seal between the plastic cap of the measurement jar and the column wall.

Figure 7 and Table 3 show water content profiles recorded over the 91-day testing period. These values correspond to the measured suction profiles.

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**Table 2** Total Suction (kPa) Measured During Transient Evaporation at Each Filter Paper Station

<table>
<thead>
<tr>
<th>Station</th>
<th>z (cm)</th>
<th>7 days</th>
<th>14 days</th>
<th>21 days</th>
<th>28 days</th>
<th>36 days</th>
<th>43 days</th>
<th>52 days</th>
<th>65 days</th>
<th>73 days</th>
<th>84 days</th>
<th>91 days</th>
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<td>1</td>
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<td>4,477</td>
<td>13,137</td>
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<td>33,577</td>
<td>39,954</td>
<td>45,255</td>
<td>39,206</td>
<td>31,767</td>
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<td>2</td>
<td>5.5</td>
<td>3,090</td>
<td>3,648</td>
<td>4,964</td>
<td>7,605</td>
<td>11,407</td>
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<td>18,994</td>
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<td>3</td>
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<td>3,240</td>
<td>2,797</td>
<td>3,864</td>
<td>3,790</td>
<td>4,676</td>
<td>6,866</td>
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<td>11,929</td>
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<td>4</td>
<td>10.5</td>
<td>1,096</td>
<td>1,183</td>
<td>1,222</td>
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<td>1,556</td>
<td>1,788</td>
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<td>1,664</td>
<td>1,777</td>
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<td>8</td>
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<td>2,464</td>
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**Table 3** Water Content (%) Calculated During Transient Evaporation at Each Filter Paper Station

<table>
<thead>
<tr>
<th>Station</th>
<th>z (cm)</th>
<th>7 days</th>
<th>14 days</th>
<th>21 days</th>
<th>28 days</th>
<th>36 days</th>
<th>43 days</th>
<th>52 days</th>
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<th>73 days</th>
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<tr>
<td>4</td>
<td>10.5</td>
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<tr>
<td>8</td>
<td>24.5</td>
<td>36.95</td>
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<td>35.25</td>
<td>33.92</td>
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<td>33.69</td>
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<td>32.87</td>
<td>32.16</td>
<td>32.59</td>
<td>31.82</td>
</tr>
</tbody>
</table>
sured suctions at each station and were calculated using the SWCC (Equation 2).

**DISCUSSION OF RESULTS**

**Transient Profile Behavior**

Both the suction (Figure 6) and water content (Figure 7) profiles indicate the gradual drying process as the soil column evaporated from its surface. The 91-day testing period was not sufficient for the column to reach complete equilibration with the average ambient atmospheric conditions ($\psi = 5.43$ log kPa, Figure 5). The final suction and water content near the surface ($z = 3$ cm) at the 91-day measurement increment were 4.66 log kPa and 19.26%, respectively.

A relatively large amount of water was lost from shallow depth ($z < 10$ cm) within the time required for the first suction measurement (7 days). As the depth from the soil–atmosphere interface and the length of testing increased, the rate of evaporation decreased. Others (14, 15) have described similar behavior for one-dimensional evaporation from sand and clay surfaces. The general trend is
interpreted to indicate a gradual desaturation of the soil, governed in the early stages by relatively fast evaporative loss through a more conductive (i.e., nearly saturated) water phase and in the later stages by relatively slow loss through a less conductive, more discontinuous, water phase. Use of the filter paper column may be more appropriate during this latter stage of drying, in which the rate of evaporation is slow enough to be adequately captured by the required 7-day measurement interval.

The degree of scatter in the suction measurements is significantly larger for relatively low values of suction ($\psi < 3.5 \log kPa$). This is indicated in the transient suction profile (Figure 6) by the more frequent occurrence of the profiles' crossing each other within the relatively deep ($z > 15 \text{ cm}$) zone. The increased scatter at low suctions also is shown in the SWCC (Figure 4) as described and analyzed in a previous publication (11). In applications in which greater precision within this range of suction is required, the filter paper column may not be an appropriate measurement system.

Measurement Verification and Observation of Cracking Depth

Following the final suction measurement increment at 91 days, the soil column was disassembled by splitting it with a table saw along its long axis. Qualitative observations of the depth of cracking were made, and 11 samples along the column length were removed for gravimetric determination of the final water content profile.

Figure 8a compares the 91-day water content profiles calculated from the filter paper suction measurements and the final water content profiles determined gravimetrically after disassembly. Similarly, Figure 8b compares the final suction profiles. In general, the final water content and suction profiles agree reasonably well, which lends verification to the filter paper measurement system and procedure. The significant deviation about the relatively wet point located at $z = 24.5 \text{ cm}$ cannot be conclusively explained, although it is likely related to the general loss of precision in filter paper measurements at relatively low values of total suction.

Observation of the disassembled soil column at 91 days indicated that fracturing of the bulk soil matrix occurred during the evaporation process, reaching a final depth of approximately $z = 13 \text{ cm}$. Cracks occurred both within the soil mass and along the interface between the soil and the acrylic column. The size and connectivity of the cracks decreased with increasing depth, ranging from approximately 1 to 2 mm in width at the surface and 0.5 mm at depth. No cracks were apparent at depths greater than approximately 15 cm.

The effect of cracking is to increase the surface area of soil exposed to the vapor or air phase. Consequently, the rate of evaporation is expected to increase. Evidence of this effect is shown in the total suction (Figure 6) and water content (Figure 7) profiles by the increased rate of drying for $z$ less than approximately 10 to 15 cm. It does not appear that the cracking process had a significant effect on the filter paper measurements in this range, as evidenced by the profile comparisons shown on Figure 8.

**SUMMARY AND CONCLUSIONS**

A new type of laboratory experimental system for direct measurement of suction and moisture content profiles during transient fluid flow processes in unsaturated expansive clays was developed. The system relies on measurements of total suction as a function of depth in a one-dimensional soil column using the non-contact filter paper technique.

The performance of the experimental system was demonstrated for a column of compacted Ca++-smectite undergoing evaporation for 91 days under ambient laboratory atmospheric conditions. During the initial stages of drying, in which the rate of evaporation near the soil surface was relatively fast, the 7-day increment required for filter paper equilibration places some limitation on the applicability of the measurement system. The system is more appropriate during latter
stages of drying in which the rate of evaporation is slow enough to be adequately captured by the required measurement interval. Scatter on the order of 1,500 kPa was noted in suction measurements for values less than approximately 3,100 kPa. The system may not be suitable in applications in which higher precision within this range is required. At higher suctions, however, the measurement scatter significantly decreased. To assess the accuracy of the system, water content and suction profiles after the 91-day testing period were obtained gravimetrically and compared with the values obtained from filter paper measurements. The profiles compared well, which indicates that the accuracy of the system is sufficient for most practical engineering or modeling applications. Desiccation cracking observed in the relatively shallow portion of the soil column did not appear to have an effect on the accuracy of the filter paper measurements.

This work forms an experimental basis for the future development or verification of theoretical models aimed at predicting moisture flux in natural expansive soil deposits subject to infiltration or evaporation processes. Excluding the electronic balance used for determining filter paper water content, the total cost of developing transient suction and water content profiles was less than US$100. Given the system’s low cost, simplicity, and accuracy, it is an attractive candidate for further research.

ACKNOWLEDGMENT

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REFERENCES