Effect of Air- and Water-Filled Voids on Neutron Moisture Meter Measurements of Clay Soil

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Air- and water-filled voids around neutron moisture meter (NMM) access tubes have been cited as sources of volumetric water content ($\theta_v$) measurement error in cracking clay soils. The objectives of this study were to experimentally quantify this potential error stemming from (i) uncertainty in bulk density ($p_b$) sampling and (ii) the impact of air- and water-filled voids. Air- and water-filled voids were simulated using ~0.6-cm (small) and ~1.9-cm (large) annuli around access tubes. After NMM measurements were taken in a tightly installed access tube, either a small or large annulus was installed in the same borehole. Additional NMM measurements were taken with the annulus filled with air, and then water and $p_b$ and $\theta_v$ were measured. The RMSE of the NMM calibration using all 11 installations was 0.02 m$^3$ m$^{-3}$. However, if two cores were used for calibration, the ratio of NMM-measured $\theta_v$ to in situ $\theta_v$ was significantly different ($p < 0.05$) from measured $\theta_v$ half the time (RMSE, 0.012–0.05 m$^3$ m$^{-3}$). Small air-filled voids created drier estimates of $\theta_v$ (bias, $-0.039$ m$^3$ m$^{-3}$; $p < 0.001$), whereas small water-filled voids were not significantly different from the calibration. Air- and water-filled voids from larger annuli were significantly lower and higher ($p < 0.001$) than core-measured $\theta_v$ with biases of $-0.068$ and $0.080$ m$^3$ m$^{-3}$, respectively. Although this work does not correct NMM-predicted $\theta_v$ to matrix $\theta_v$, it does bound NMM error under field conditions in a cracking clay soil.


Abbreviations: NMM, neutron moisture meter.

Accurate measurements of soil volumetric water content ($\theta_v$) have applications in agriculture, engineering, land surface models, and many other areas of scientific research. Common techniques used to nondestructively measure $\theta_v$ include time-domain reflectometry (Topp et al., 1981), capacitance (Paltineanu and Starr, 1997), and neutron scattering (Gardner and Kitham, 1952). The advantage of time-domain reflectometry and capacitance sensors is that they can be left in place for unsupervised temporal measurements; however, these sensors require direct contact with the soil. Shrink-swell soils add additional complexity to $\theta_v$ measurements because these soils change in volume and bulk density ($p_b$) with changes in $\theta_v$. Form large vertical desiccation cracks, and tend to pull away from objects inserted in the soil as the soil dries. Although the neutron moisture meter (NMM) cannot be automated for unsupervised measurements and requires maintenance of an access tube to take readings, the NMM does not require direct soil contact and responds to a relatively large volume of soil, making it a particularly suitable sensor for shrink-swell soils (Fares et al., 2004). However, air- and water-filled voids can influence measurements taken with any soil moisture sensor, including the NMM. Voids such as desiccation cracks or voids due to loose-fitting access tubes may fill with water in dry shrink-swell soils after a rainfall or rainfall simulations. Free water flows preferentially through such voids and may remain for 24 h or more, increasing NMM-measured $\theta_v$ (Bagnall, 2014). Very little is known about the degree of influence voids have on NMM measurement. However, when experiments on soil–plant–water relationships in Vertisols are conducted, problems and questions associated with these voids arise (Crespo, 2014; Jarvis and Leeds-Harrison 1990; Li et al., 2003; Tokumoto et al., 2011).
Pores that occur in the soil matrix of shrink-swell soils, often classified as Vertic intergrades and Vertisols, can be separated into three main classes: (i) inter-pedal pore space, (ii) shrinkage cracks, and (iii) subsidence (Fityus and Buzzi, 2009; Kishné et al., 2009; Kutílek, 1996; Stewart et al., 2016). Water can be found in all pore space classes, but it is the inter-pedal pore space, or the soil matrix, that controls water availability to vegetation and latent heat flux from the soil surface. Hydrology and land surface models often use Richard’s equation (Richards, 1931) or other hydrology models to estimate soil water content in the matrix. However, the shrinkage cracks can in some cases occupy between 5 and 7% of the total soil volume (Ackerson et al., 2017) and are a potential source of error in measuring and modeling soil water content in shrink-swell soils (Topp and Davis, 1981). We refer to volumes of air or water that are not soil matrix and are within the measurement volume of the NMM as voids regardless of how they were formed.

During measurements with the NMM, the source and detector of the instrument are lowered into the soil through an access tube. The NMM uses fast neutron (4.5 MeV) scattering, emitted from a $^{241}$Am-Be source in the probe, to infer soil water content. The fast neutrons are scattered into the surrounding soil and collide with hydrogen nuclei, losing energy and slowing down. A detector in the probe counts the returning slow neutrons (<2.0 MeV), which are proportional to the soil water content (Hignett and Evett, 2008). The response of the NMM is for the region of influence, the resulting neutron count represents the response of the sensor may be an estimate of soil matrix water content. Whether the response of the sensor is from collisions with primarily hydrogen atoms in a roughly spherical region of influence. Li et al. (2003) estimated the radius of the region of influence for 95% of measured thermalized neutrons as

$$A = 9\left(\theta_v\right)^{-0.33}$$  \hspace{1cm} [1]$$

where $A$ (cm) is the axial distance of influence, and $\theta_v$ is the volumetric water content (m$^3$ m$^-3$). If an air-filled void is present in the region of influence, the resulting neutron count represents the hydrogen content of both the void and the soil.

Li et al. (2003) used a numerical model to simulate the effect of air- and water-filled annular voids of various sizes on NMM-measured $\theta_v$ in a clay soil. Results indicated that air-filled and water-filled voids decreased and increased NMM-measured $\theta_v$, respectively. For example, the simulated effects of a 1.0 cm air-filled void caused NMM count ratios to estimate $\theta_v$ at 0.18 m$^3$ m$^-3$ when matrix water content was 0.35 m$^3$ m$^-3$, a 49% reduction in apparent water content. Again, for a soil with true $\theta_v$ of 0.35 m$^3$ m$^-3$, the numerical model calculated a $\theta_v$ of 0.46 m$^3$ m$^-3$ in the presence of a 1.0-cm water-filled annular void, which represents a 31% increase in water content. High contrast between void water content and soil water content increased errors; therefore, water-filled voids had the greatest effect for dry soil, and air-filled voids had the greatest effect for wet soils.

Increasing void size (from 0.25 to 1.0 cm for air-filled voids and from 0.5 to 2.0 cm water-filled voids) increased the absolute effect of both air- and water-filled voids. Water-filled voids had smaller influences relative to air-filled voids at small void sizes, but at large void sizes, water-filled voids had a greater influence on NMM-measured $\theta_v$ than did air-filled voids. Li et al. (2003) found that numerical simulations compared well with field measurements of one tightly fitting NMM access tube and two access tubes surrounded by a 2.75-cm void filled with air and then water. Although this study is informative, it did not model water contents (0.25 and 0.35 m$^3$ m$^-3$) as high as those observed for Vertisols in the field (e.g., 0.48 m$^3$ m$^-3$) and made no measurements at low water contents when Vertisols are expected to crack. Also, the numerical simulations overestimated changes in NMM-measured $\theta_v$ resulting from water-filled voids compared with experimental data collected by Bagnall (2014).

The objective of this study was to experimentally quantify potential discrepancies between NMM measurements of soil $\theta_v$ based on in situ calibration and the measured $\theta_v$ of the inter-pedal pore space in a shrink-swell clay soil. This goal was motivated by the need for accurate measurements of inter-pedal water content with an NMM for use in hydrology modeling as well as for determination of mass balance of water in a soil profile on shrink-swell soils. In an experiment when the soil is dry but irrigation or a heavy rainfall results in preferential flow through cracks, we want to understand how to interpret NMM measurements. Conversely, we want to understand how extensive soil cracking may be changing NMM measurements. To address this goal, some understanding of the error in an NMM calibration is needed. Our objectives were to quantify (i) uncertainty in NMM calibration from soil $\rho_b$ sampling and (ii) errors due to air- and water-filled voids around the access tube. To quantify the effect of shrinkage cracks, we created two sizes of artificial voids between an NMM access tube and the soil. The artificial void, or annulus, was a uniform cylindrical void around the NMM access tube. The NMM readings were made without the annulus, with the annulus filled with air, and with the annulus filled with water. These NMM readings were compared with direct measurements of $\theta_v$ from soil cores.

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**Materials and Methods**

**Site Description**

The study was conducted at the Texas A&M University REllis Campus, Bryan, TX (30.634° N, 96.483° E). The soil at the site is a Burleson clay soil (a fine, smectitic, thermic Udic Haplustert), which formed in very deep clay alluvium that is moderately well drained. All B horizons have the same clay content (~60%). The slope at the site is <1%. Burleson clay is dominated by smectitic clay minerals and is characterized by a high shrink-swell potential with a coefficient of linear
extensibility of 0.17 mm$^{-1}$ (Neely et al., 2018). During dry periods, desiccation of Burleson clay results in the formation of large shrinkage cracks. Shrinkage cracks can extend to a depth of 1.5 m and occupy 5% of the total soil volume (Ackerson et al., 2017). The vegetation at the study site is dominated by native annuals and native perennial grasses.

**Installation and Measurements**

A hydraulic soil auger was used to auger a hole with a slightly smaller diameter than the access tube or annulus to be installed. The access tube or annulus was pushed into the soil with hydraulics (Giddings Machine Company) to ensure a tight fit. Care was taken not to compress or compact the soil surrounding the access tubes and annuli.

All NMM (CPN 503 HydroProbe, InstroTek Inc.) readings were taken using 32-s counts from 20 to 100 cm depth at 10-cm depth increments. The NMM uses a $^{241}$Am-Be neutron source and $^3$He detector. Standard count readings were taken at the beginning and end of each measurement. Count ratios were calculated by dividing each NMM reading (count) by the average standard counts from the corresponding borehole.

Data were taken from 11 annuli in all. Six of these annuli were the large size; of those, three were measured in the spring during wet soil moisture condition (February–April) and three were measured in the summer during dry soil moisture condition (August). Five small annuli were also measured (two in the spring and three in the summer). For each of the 11 annuli in this study, an NMM access tube was installed with no voids surrounding it, resulting in 11 tight-fitting NMM access tube measurements. A set of 10-cm depth increment NMM readings were taken in this access tube to represent a no-void, ideal NMM measurement. Next, the access tube was removed, the original borehole was widened using a core, and either a large or a small annulus was installed, centered on the same hole as the access tube. Cores extracted from the annulused hole were checked to confirm that the widened borehole was centered on the initial NMM access tube borehole. The small and large annuli were installed a few meters apart, and NMM readings from every annulus were compared with a no-void NMM reading taken in that same location. The NMM readings were taken with the annulus void empty to simulate air-filled soil cracks. Then the top cap was removed, and the annulus void was filled with water. This third set of NMM readings represented water-filled soil cracks.

When the NMM readings with no void, an air-filled void, and a water-filled void were completed, four intact soil cores were collected ~5 cm away and surrounding each annulus (Fig. 1) using a coring tube of 6.2 cm diameter to a depth of 135 cm.

Core samples were visually monitored for compaction using a core with a window. No compaction occurred. Each core was cut into 10-cm increments starting 15 cm below the soil surface for determination of soil water content by oven drying. Depth increments for the cores were selected to ensure that cores would overlap NMM measurement positions. The soil core increments were weighed and oven-dried at 105°C for 72 h for determination of gravimetric water content ($\theta_g$) and $\rho_b$. Volumetric water content was calculated by multiplying $\theta_g$ by $\rho_b$ and assuming a water density of 1000 kg m$^{-3}$.

**Construction of Annulus**

Air-filled and water-filled soil cracks surrounding NMM access tubes were simulated using aluminum (Al) annuli, and the NMM readings were compared with NMM readings taken in tightly installed (i.e., no void between soil and access tube) NMM access tubes. The annuli were constructed by attaching an outer Al tube to the Al access tube (Fig. 2A), thereby creating a void outside the access tube. Aluminum bottom and top caps were used.
Therefore, the thickness of the Al outer tube of the annuli was 
(Neely et al., 2018). The water content of the soil was measured 
(void + wall thickness of annulus) and 0.6 and 1.9 cm for the water-
2 wk for redistribution. During the 2 wk, sites were covered by 
which affects the distance a fast neutron will travel from the source 
with the NMM just prior to the cracks being filled with cement. 
was brought to field capacity by thoroughly wetting and allowing 
observations in studies by Neely et al. (2018) and Kishné et al. (2009). For 
NMM access tubes in Neely et al. (2018). In Neely’s study, NMM 
photographs were taken such that each pixel represented a 0.04-
form soil water content conditions in the vertical soil profile as 
occupying a 1-m radius around the access tubes was then calculated 
and allowed to dry. The soil was excavated at 5-, 15-, 30-, 50-, 70-, 
and 90-cm layers from the soil surface, and high-resolution digital 
photographs were taken such that each pixel represented a 0.04-
mm² area. The percentage of the area with cement-filled cracks 
occupying a 1-m radius around the access tubes was then calculated 
(Neely et al., 2018). The water content of the soil was measured 
with the NMM just prior to the cracks being filled with cement. 
The annuli voids created in this study model soil void spaces 
that occupy ~2 to 4% of the cross-sectional area of the NMM mea-
urement area for the small and large annuli, respectively. Although 
the cross-sectional area will change based on soil water content, 
which affects the distance a fast neutron will travel from the source 
and detector, these estimates assume a relatively dry soil. We assume 
cracks can start to open at ~0.35 m³ m⁻³ and drier, based on observa-
tions in studies by Neely et al. (2018) and Kishné et al. (2009). For 
comparison, we adapted the areal crack volumes from Neely et al. 
(2018) (Fig. 3). These values represent the mean void space around 
four independent access tubes and ranged from <1 to 7%. Hence, 
the range of annuli voids created in this experiment are well within 
the range of open cracks that are expected to occur in a Vertisol in 
field conditions. However, the geometry of the annulus tube are a ”worst-case scenario” because they surround the NMM access tube, unlike natural desiccation void spaces (crack 
networks) that are likely to occur under field conditions. The clas-
sification of ”worst-case scenario” is particularly appropriate when 
considering our measurements under dry conditions with water-
filled annuli. It is unlikely that these circumstances would occur 
under field conditions because these cracks are likely draining and 
not completely filled with water. However, the purpose of the experi-
ment was to create a high and low bound of the NMM experimental 
error, and the annuli represent a reasonable estimation of the effect 
of air- and water-filled voids in shrink-swell soils.

Comparison with Soil Cracking

The cross-sectional areas of the constructed annuli were com-
pared with field measurements of in situ soil cracking around three 
NMM access tubes in Neely et al. (2018). In Neely’s study, NMM 
access tubes were installed 2 m apart at this same site, and the soil 
was brought to field capacity by thoroughly wetting and allowing 
2 wk for redistribution. During the 2 wk, sites were covered by 
black plastic to reduce evapotranspiration and to achieve as uni-
form soil water content conditions in the vertical soil profile as 
possible. At the conclusion of the study and at dry soil water con-
tion, soil cracks were filled with a white Portland cement slurry 
and allowed to dry. The soil was excavated at 5-, 15-, 30-, 50-, 70-, 
and 90-cm layers from the soil surface, and high-resolution digital 
photographs were taken such that each pixel represented a 0.04-
mm² area. The percentage of the area with cement-filled cracks 
occupying a 1-m radius around the access tubes was then calculated 
(Neely et al., 2018). The water content of the soil was measured 
with the NMM just prior to the cracks being filled with cement. 
The annuli voids created in this study model soil void spaces 
that occupy ~2 to 4% of the cross-sectional area of the NMM mea-
surement area for the small and large annuli, respectively. Although 
the cross-sectional area will change based on soil water content, 
which affects the distance a fast neutron will travel from the source 
and detector, these estimates assume a relatively dry soil. We assume 

Table 1. Dimensions of tubes used as neutron moisture meter access tubes and to create outer annuli.

<table>
<thead>
<tr>
<th>Type of Al tube</th>
<th>Inner diameter cm</th>
<th>Outer diameter cm</th>
<th>Wall thickness cm</th>
<th>Length cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access tube</td>
<td>4.9</td>
<td>5.1</td>
<td>0.1</td>
<td>150</td>
</tr>
<tr>
<td>Small outer tube</td>
<td>5.7</td>
<td>6.3</td>
<td>0.3</td>
<td>142</td>
</tr>
<tr>
<td>Large outer tube</td>
<td>7.0</td>
<td>7.6</td>
<td>0.3</td>
<td>142</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of the percentage of area occupied by cracks measured at the site by Neely et al. (2018) to the percentage of area of the neutron moisture meter (NMM) measurement volume that was occupied by large- and small-annulus voids used in this experiment. The NMM measurement volume was dependent on soil water content and was calculated using Eq. [1]. Error bars for measured crack area are standard deviations of areal crack volume around four access tubes (Neely et al. 2018). Error bars for annuli are the standard deviations from five small and six large annulus measurements.
corresponded to the NMM reading at that depth. Soil data were analyzed with histograms and ANOVA statistics.

Our first objective focused on assessing the potential error from soil $\rho_b$ sampling at the time of NMM calibration. The motivation was to quantify the impact of calibration on the resulting predictions of water content. First, we calibrated the NMM using all 11 installations by regressing the mean $\theta_v$ of the four soil cores taken at each installation on the corresponding count ratios obtained from the NMM access tubes installed with no void. Then, we ran Monte Carlo simulations of potential NMM calibration realizations using two, four, or six installations (NMM readings with the corresponding mean $\theta_v$ of the four soil cores). Our parameters for running the Monte Carlo simulations included using whole soil profiles (complete installation datasets), using an equal number of installations for calibration taken in each season, sampling installations with replacement, and running the simulations for 10,000 iterations. We validated the resulting calibrations with two installation measurement sets (one from each season) on the resulting RMSE and bias of the simulated calibration. Validation measurement sets were held out of the calibration. Slope and intercept of the simulated calibration lines were compared with the calibration line using all the data (11 installations). Although the Monte Carlo simulations using two installations do not require 10,000 iterations, the simulation using six installations yielded over 9500 unique RMSE and bias values. To maintain consistency, we used 10,000 iterations for all simulations.

The motivation for our second objective was to quantify the impact of air- and water-filled voids around NMM access tubes during the time of measurement. We applied the calibration equation calculated from all 11 installations to predict $\theta_v$ for (i) access tubes (no void), (ii) small annulus sizes with water in the void (small water-filled void), (iii) small annulus sizes with air in the void (small air-filled void), (iv) large annulus sizes with water in the void (large water-filled void), and (v) large annulus sizes with air in the void (large air-filled void). The access tube (no void) condition was included for comparison. Bias and RMSE were calculated for each of the count ratio sets using the mean $\theta_v$ of the four soil cores at the corresponding depth. The calculated $\theta_v$ for each set of annulus-based count ratios was subtracted from the measured $\theta_v$ to assess the effect of the four annulus types. Because we are applying a calibration equation that was developed using tightly installed access tubes, this dataset allows us to compare how air- or water-filled void space affects predictions of $\theta_v$, compared with the actual soil $\theta_v$ (mean $\theta_v$ of the four soil cores).

Results and Discussion

A histogram of $\rho_b$ for all soil moisture conditions and depths showed a normal distribution of $\rho_b$ measurements (data not shown). An ANOVA for $\rho_b$ was run with depth, moisture condition (wet or dry), and the interaction of depth and moisture as factors (Table 2). The residuals of this model were plotted to confirm that they had an acceptably constant variance (not shown). The interaction between moisture condition and depth was not significant ($p = 0.51$). Moisture condition was moderately significant ($p = 0.016$), with mean $\rho_b$ values of 1.43 and 1.40 Mg m$^{-3}$ for dry soil conditions (summer) and wet soil conditions (spring), respectively. Depth was slightly significant ($p = 0.027$).

A post hoc Tukey’s honestly significant difference test showed that $\rho_b$ measurements at only two depths (110 and 20 cm) were statistically different from one another ($p = 0.041$). Boxplots of $\rho_b$ values for wet and dry moisture conditions (Fig. 3A) show that dry cores taken in the summer exhibited wider distributions with higher medians and ranges.

The coefficient of variation for $\rho_b$ collected in dry moisture condition was twice that of $\rho_b$ in wet moisture condition and $\theta_g$ in both moisture conditions (Table 2). This shows that the effects of large voids from soil shrinkage during the dry summer likely contributed to measurement variability. We expect this variability is real and may lead to large variability in $\theta_v$, measurements under dry, cracking soil conditions.

The $\theta_v$ was much higher for wet moisture condition measurements than for dry condition measurements (Fig. 4B). Overall mean $\theta_v$ was 0.34 kg kg$^{-1}$ in wet moisture condition and 0.19 kg kg$^{-1}$ in dry condition. Results of an ANOVA showed moisture condition, depth, and the interaction term to be significant ($p < 0.001$). Because of the significant interaction, no post hoc test was run. However, there was a trend of increasing $\theta_v$ with depth in dry moisture condition and an increase in water content in wet moisture condition to 70 cm, with a slight decrease after (Fig. 4B). Changes of water content with depth are small compared with changes with moisture condition. Most of the variability in core-measured $\theta_v$ is from the $\rho_b$ measurement. The $\rho_b$ of shrink-swell soils changes with water content, and collecting core samples of high-clay soil, especially when soil cracks are present during dry conditions, creates variability in measurements.

Uncertainty in Soil Bulk Density Sampling for Calibration

Calibration of the NMM relates count ratios to $\theta_v$, which was determined by multiplication of soil $\rho_b$ (Mg m$^{-3}$) and $\theta_g$ (kg kg$^{-1}$), both obtained from the mean of four soil cores taken at each access tube installation. The NMM linear calibration equation obtained using NMM count ratios from access tubes without voids and measured $\theta_v$ from the 11 cores was

<table>
<thead>
<tr>
<th>Moisture status</th>
<th>$n$</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>217</td>
<td>1.40</td>
<td>0.08</td>
<td>1.23–1.68</td>
<td>0.06</td>
</tr>
<tr>
<td>Dry</td>
<td>241</td>
<td>1.43</td>
<td>0.20</td>
<td>0.97–1.86</td>
<td>0.14</td>
</tr>
<tr>
<td>Wet</td>
<td>217</td>
<td>0.34</td>
<td>0.02</td>
<td>0.27–0.39</td>
<td>0.06</td>
</tr>
<tr>
<td>Dry</td>
<td>241</td>
<td>0.19</td>
<td>0.01</td>
<td>0.16–0.21</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 2. Summary statistics for bulk density ($\rho_b$) and gravimetric water content ($\theta_g$) by moisture condition across depths. Number of samples, mean, standard deviation (SD), range, and coefficient of variation (CV) are shown.
The RMSE of calibration was 0.02 m$^3$ m$^{-3}$, and the $r^2$ was 0.96.

Figure 5 shows the simulated NMM calibrations using two and six installation sets for the simulated calibration, along with the individual data points from the installations (points). The graphs of $\theta_v$ and count ratio when using two and six installations show much more variability for dry soil measurements than for wet soil measurements. For example, the count ratios range from slightly $>1.1$ to $>1.5$ for a measured $\theta_v$ of $\sim0.23$ m$^3$ m$^{-3}$ (Fig. 5). Calculated $\theta_v$ values using the calibrations were compared with core-measured $\theta_v$ to calculate RMSE and bias of each calibration. Increasing the number of installation datasets used for calibration did not significantly affect the mean RMSE or bias, but it did reduce the frequency of calculating $\theta_v$ with a bias significantly different from zero or an RMSE $>0.035$ m$^3$ m$^{-3}$ (Fig. 5).

A paired $t$ test between $\theta_v$ values based on simulated calibration equations using two installations and the mean $\theta_v$ of the four soil cores showed that calibration-predicted $\theta_v$ was significantly different from core-measured $\theta_v$ for 51% of the simulations ($p < 0.05$). When the simulated calibrations used four and six installations, calibration-predicted $\theta_v$ was significantly different from core-measured $\theta_v$ for 44 and 41% of the simulations, respectively ($p < 0.05$). Before we determined how voids affect the predicted water content with an NMM, we wanted to know if our calibration contributes to error between the instrument measurements and the water content of the soil. In this context, the Monte Carlo simulations provide some evidence that, even when using tightly installed access tubes, there may be error resulting from the calibration process itself. The potential error is higher under dry soil conditions, with up to 0.02 m$^3$ m$^{-3}$ difference between calibration lines calculated using two to six installations compared with using all 11 installations. Increasing the number of installations from two to six does not significantly improve the accuracy of the NMM; this finding is in agreement with the recommended field methodology of using two installations (one in dry and one in wet soil conditions) when calibrating an NMM (Hignett and Evett, 2008).

Errors from Air- and Water-Filled Voids around the Access Tube

Count ratios were collected from the NMM access tubes without voids and with annuli surrounding the access tubes (two sizes, both water- and air-filled). Core-measured $\theta_v$ (mean of four soil cores) values were subtracted from the five calculated $\theta_v$ sets (converting count ratios to $\theta_v$ using our calibration equation). Boxplots of differences for the five sets are plotted in Fig. 6. Because the count ratios used to create the calibration are also used to calculate the no-void $\theta_v$, the mean difference for access tubes without an annulus was zero, but it is plotted for reference, and the normal distribution about the mean is observable as well. Air-filled annuli had negative differences (undercalculated $\theta_v$), whereas water-filled voids overestimated $\theta_v$. A paired $t$-test showed calculated $\theta_v$ to be significantly larger than core-measured $\theta_v$ for the large water-filled annuli ($p < 0.001$; mean, $0.080$ m$^3$ m$^{-3}$) and smaller for the large air-filled annuli ($p < 0.001$; mean, $-0.068$ m$^3$ m$^{-3}$).
m$^{-3}$) and small air-filled annuli ($p < 0.001; \text{mean, } -0.040 \text{ m}^3 \text{ m}^{-3}$). Small water-filled annuli had a mean difference of 0.003 ($p = 0.31$); this value was not significantly different from measurements of tubes with no voids. Results indicate that small water-filled cracks have no significant effect on $q_v$ calculations made with the NMM. Larger voids had larger effects on NMM-measured $q_v$ calculations than smaller voids, regardless of being filled with air or water. For the small annulus size, air-filled voids had a greater absolute mean difference from core-measured $q_v$ than did water-filled voids. The reverse was true for the large annuli: water-filled voids had greater absolute errors than air-filled voids.

The NMM-measured $q_v$ values were calculated using Eq. [2] and the NMM count ratios from the annuli. Regression lines were then fit between NMM-measured $q_v$ and core-measured $q_v$ (Fig. 7). The regression line from count ratios taken with small annuli had slightly smaller intercepts and slightly larger slopes compared with the access tube calibration line (Table 3; Fig. 7).

Small annuli slopes and intercepts were not significantly different from a one-to-one line, indicating the NMM count ratios obtained from those annuli-calculated $q_v$ were not different from core-measured $q_v$ ($p < 0.001$). Conversely, regression lines using count ratios from large annuli had larger intercepts and smaller slopes than the regression with the access tube calibration line. Both large annuli slopes and intercepts were significantly different from a one-to-one line ($p < 0.001$). However, a $t$ test ($\alpha = 0.05$) showed that the slopes of the air- and water-filled annuli were not significantly different. Hence, the NMM had the same response to changes in $q_v$, regardless of the void was water filled or air filled, but water- and air-filled voids changed the $y$-intercept. Slopes of the regression lines from large annuli are small, which indicates a loss of sensitivity of the NMM to measure soil $q_v$ in the presence of large voids because a larger change in soil $q_v$ is required before a change in NMM-measured $q_v$ is observed. For example, a 0.10 m$^3$ m$^{-3}$ change in $q_v$ would only be measured as a 0.07 m$^3$ m$^{-3}$ change in $q_v$ in the presence of the large air-filled void.

The large water-filled annuli overestimated $q_v$ more when the soil was dry. Given that measured ranges in $q_v$ a for a

![Fig. 6. Boxplots of differences between neutron moisture meter (NMM)-measured $q_v$ and core-measured $q_v$ (mean of four soil cores taken at each installation) for large and small annuli filled with either air or water along with NMM access tubes with no void. All NMM-measured $q_v$ values were calculated using the calibration equation from all 11 tight-fit access tube installations. Significantly different means ($p < 0.001$) are marked with asterisks.](image)

![Fig. 7. Calculated soil water content ($q_v$) from five count ratio sets plotted against core-measured $q_v$ (mean of four soil cores taken at each installation). All neutron moisture meter (NMM)-measured $q_v$ values were calculated using the calibration equation from all 11 tight-fit access tube installations. Each line is surrounded by a shaded polygon that captures 95% of the calculated points.](image)
The absolute error of NMM measurements caused by voids is Burleson clay ranged from 0.15 to 0.5 m³ m⁻³ in field conditions, qv for the selected water-filled voids did not change the NMM water. This comparison shows that the response of the NMM qv at the dry end, but our experiment had a smaller range in qv, respectively. Across the same range in qv, the smaller and larger air-filled annuli count ratios underestimated water content by 13 to 20% and 6 to 34%, respectively. The absolute error of NMM measurements caused by voids is dependent on the water content of the soil matrix; specifically, the error is larger when void water content is in high contrast to soil matrix water content.

Table 4 compares our experimental results with the simulated results from Li et al. (2003) for two soil thv values (0.25 and 0.35 m³ m⁻³) and for similarly sized voids filled with air and water. This comparison shows that the response of the NMM to air- and water-filled voids was always overcalculated by the numerical model. The simulated percent change in thv is double or more than observed in our field study in all cases; in fact, small water-filled voids did not change the NMM thv for the selected thv in Table 4. Furthermore, the size of the air void did not influence the percent change in thv for our experimental data in this case. Our experiment had a smaller range in thv at the dry end, but our experiment covered wetter conditions up to field capacity. The simulation by Li et al. (2003) stopped at 0.35 m³ m⁻³, thereby limiting the range of water contents we are able to compare. At the higher thv observed in our study, the size of air voids does change the percent thv underestimated (Fig. 7).

### Conclusions

In an NMM calibration, the main source of error is in the ρh measurement. When performing a calibration of an NMM in a shrink-swell soil with one wet and one dry set of calibration readings in the field, about half of the NMM-measured thv values will be significantly different from what exists in the field. Four calibration observations can reduce this number, but six calibration observations do not statistically improve the measurement. All NMM users should take great care in measuring ρh for calibration to avoid more error than is inherent from variability in ρh.

Errors due to air- and water-filled voids around the NMM access tube increased with increasing void size. Small water-filled voids of ~0.6 cm diameter (or 2% areal void space of the NMM measurement) do not significantly affect NMM thv measurements. The presence of larger voids around the access tubes resulted in a loss of sensitivity in NMM thv to measured soil thv. A water-filled annulus of 1.9 cm diameter or ~4% areal void space can increase the NMM thv measurement by 26 and 48% with dry and wet soil conditions, respectively. When the soil is cracking and creating areal void space that includes 2 to 4% of the areal space of the NMM measurement, the NMM-measured thv could be underestimated by as much as 11 to 16%, respectively. Our field study showed that the effects on NMM-measured thv due to air- or water-filled voids around NMM access tubes are much less than has been estimated by numerical simulation (Li et al., 2003). Water-filled cracks <0.6 cm in diameter do not practically affect NMM-calculated thv, and errors from larger cracks can be bounded by the experimental measurements presented.

This work presents bounds for NMM error in response to voids that are likely to occur in shrink-swell soils provided that users know whether they are filled with air or water. This work does not allow exact correction of NMM-measured thv to matrix thv. A more thorough empirical correction would require a wider

### Table 3. Summary of regression lines between water content measured by neutron moisture meter and cores as well as root mean squared error and bias.

<table>
<thead>
<tr>
<th>Count ratio source</th>
<th>Intercept</th>
<th>Slope</th>
<th>RMSE</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>No void</td>
<td>0.015±1†</td>
<td>0.958a</td>
<td>0.005</td>
<td>0.000</td>
</tr>
<tr>
<td>Small air void</td>
<td>−0.050a</td>
<td>1.028a</td>
<td>0.040</td>
<td>−0.039</td>
</tr>
<tr>
<td>Small water void</td>
<td>−0.031a</td>
<td>1.043a</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>Large air void</td>
<td>0.028b</td>
<td>0.739b</td>
<td>0.074</td>
<td>−0.068</td>
</tr>
<tr>
<td>Large water void</td>
<td>0.200b</td>
<td>0.671b</td>
<td>0.088</td>
<td>0.080</td>
</tr>
</tbody>
</table>

† Data followed by a lowercase a are not significantly different (p < 0.001) from a 1:1 line that has a slope of 1 and an intercept of 0; a lowercase b indicates that the slope is not significantly different from another slope with the same letter (p < 0.001).

### Table 4. Comparison of experimental volumetric water content (thv) data determined by neutron moisture meter (NMM) and measured in cores from this study to simulated data from Li et al. (2003).

<table>
<thead>
<tr>
<th>Simulated void</th>
<th>Experimental void</th>
<th>Void fill</th>
<th>Core-measured thv</th>
<th>Simulated thv †</th>
<th>Simulated change in thv †</th>
<th>NMM thv</th>
<th>NMM change in thv</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.2</td>
<td>air</td>
<td>0.25</td>
<td>0.14</td>
<td>−44</td>
<td>0.21</td>
<td>−16</td>
</tr>
<tr>
<td>1.0</td>
<td>1.2</td>
<td>air</td>
<td>0.35</td>
<td>0.18</td>
<td>−49</td>
<td>0.31</td>
<td>−11</td>
</tr>
<tr>
<td>1.0</td>
<td>0.9</td>
<td>water</td>
<td>0.25</td>
<td>0.33</td>
<td>32</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.9</td>
<td>water</td>
<td>0.35</td>
<td>0.46</td>
<td>31</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>−</td>
<td>2.5</td>
<td>air</td>
<td>0.25</td>
<td>−</td>
<td>−</td>
<td>0.21</td>
<td>−16</td>
</tr>
<tr>
<td>−</td>
<td>2.5</td>
<td>air</td>
<td>0.35</td>
<td>−</td>
<td>−</td>
<td>0.29</td>
<td>−17</td>
</tr>
<tr>
<td>2.0</td>
<td>2.2</td>
<td>water</td>
<td>0.25</td>
<td>0.45</td>
<td>80</td>
<td>0.37</td>
<td>48</td>
</tr>
<tr>
<td>2.0</td>
<td>2.2</td>
<td>water</td>
<td>0.35</td>
<td>0.58</td>
<td>66</td>
<td>0.44</td>
<td>26</td>
</tr>
</tbody>
</table>

† Data from Li et al. (2003).
range of annulus sizes to be measured and would only be useful if the volume of cracks around an access tube was truly known and restricted to being around the access tube, as are annuli.

Acknowledgments
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References