Measuring soil water content through volume/mass replacement using a constant volume container

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ABSTRACT

Accurate and rapid measurement of soil water content is important in research and applications, such as hydrological processes, farmland water management, and ecological issues. Soil particle density (SPD) and water content were measured using a proposed constant volume container (CVC) through volume/mass replacement (VMR). The CVC consisted of a vessel body and a lid to limit the water surface to a constant level, with 3-mm-diameter inlet to fill up the container with water to the full level as well as an outlet orifice to drain excess water. The mathematical algorithms for partitioning water and soil particles of the soil sample were detailed. Measurements and computational procedures were performed on two soils with varied water contents. The unique structure of the CVC effectively eliminated volume measurement errors caused by liquid surface tension, resulting in 50% lower measurement standard deviation of SPD compared with those obtained using a pycnometer or a volumetric flask. The SPD values of loam and clay loam soil were 2.64 and 2.66 Mg m⁻³, respectively. The soil water contents of the tested soils determined with the measured SPDs by using the CVC exhibited equivalent accuracies to those measured through oven-drying, with R² = 0.98. Moreover, soil water content (5–35%) measured with an assumed SPD of 2.65 through VMR using the CVC showed an equivalent accuracy to that determined through oven-drying. This finding indicated the feasibility of measuring soil water content through VMR using the SPD of 2.65 Mg m⁻³ in these two experimental soils. Theoretical analysis and computation showed that soil organic matter content (SOM) affected SPD, thereby indirectly influenced the accuracy of soil water content measurements through VMR. The VMR method with the CVC could achieve acceptable accuracy with SOM values lower than 2% and soil water content higher than 5%. This approach can be used as an alternative to oven-drying with appropriate accuracy and efficiency, and it is potentially useful for measuring soil water content or bulk density in the field.

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1. Introduction

Determination of soil water content is important in studies of heat, water and chemical transport and retention in soil. The physical properties of soil should be characterized to understand agricultural and environmental processes in modern soil physics research and applications. Soil water content is an essential part of the air, liquid, and solid and environmental processes in modern soil physics research and applications. The physical properties of soil should be characterized to understand agricultural and environmental processes in modern soil physics research and applications. Soil water content is an essential part of the air, liquid, and solid and environmental processes in modern soil physics research and applications. Soil water content also plays an important role in plant growth (Robinson et al., 2008), and it is related to irrigation management and exchange of mass and energy in the soil–plant–atmosphere continuum (Yin et al., 2013). The amount of water available to plants from the soil determines when and how much irrigation water should be applied (Evans et al., 1996). Application of excessive water may decrease crop quality as a result of the adverse effects of waterlogged plant roots; by contrast, treatment with insufficient water may lead to irreversible damage to crops because of drought stress (Huisman et al., 2003). Therefore, accurate and rapid measurement of soil water content is important in water and fertilizer management (Gao et al., 2012), as well as in the management of various geostuctures, such as pavements, foundations, and earthen dams (Vereecken et al., 2008). Overall, determination of soil water content is of paramount importance in engineering, agronomy (Haines, 1923), geology, ecology, and biology (Campbell, 1974).
Thermal drying, particularly oven-drying, is the only available method that directly measures soil water content, and can be used to calibrate other indirect approaches (Schmugge et al., 1980; Terhoeven-Urselmans et al., 2008), such as neutron scattering (Amoozegar et al., 1989; Chanasyk and Naeth, 1996; Elder and Rasmussen, 1994; Fityus et al., 2011; Jayawardane et al., 1984; Li et al., 2003), and dielectric techniques, including time domain reflectometry, frequency domain reflectometry, and capacitance analysis (Eller and Denoth, 1996; Gardner et al., 1997; Jacobsen and Schjonning, 1993; Kelleners et al., 2004; Rao and Singh, 2011; Robinson and Dean, 1993; Selig and Manusukhani, 1975; Topp et al., 1982; Topp and Reynolds, 1998; Topp et al., 2000; Whalley et al., 1992). These indirect measurement techniques are widely used, but their accuracy depends on the users’ experience, careful calibration and soil properties. Oven-drying shows high accuracy and reliability but requires a long time to deliver results. Furthermore, the measuring accuracy of this technique is influenced by drying period, which varies from one soil to another as required by different standards, thereby produces systematic measurement errors. This technique also requires the use of an oven and is therefore not feasible for field work. In some cases, the alcohol burning method may be used to rapidly measure soil water content. However, this method is unsuitable for soil with a high proportion of organic matter.

Volume replacement can be used to measure soil water as long as the replacing substance is easy to handle or measure. The volume of water or air is easier to measure than that of air; hence, water can be used to replace air in the soil in volume replacement method. Papadakis (1941) described a rapid replacement method for soil water measurement using a flask; however, this method has not been widely accepted because of the difficulty in transferring the wet soil sample into the flask. Moreover, the errors induced by variation in water density and exact volume of the flask should be determined when using this approach. Prihar and Sandhu (1967) resolved the limitation of time lag between soil sampling and availability of measurements by using the replacement method. In their approach, accurate meniscus readings remain difficult because of liquid surface tension; foam floating on the liquid surface is also difficult to remove, and may affect the accuracy of the readout. Furthermore, the accuracy of this approach is influenced by the uncertainty of whether trapped air is completely expelled by shaking such a long-necked flask. During the measurement, a pipette was used, which is tedious to operate. They took the soil particle density (SPD) as 2.67 Mg m$^{-3}$ and for soil with different SPD values, soil water content could be obtained by adding or subtracting 0.5 for every 0.02 Mg m$^{-3}$ change in SPD; however, the basis for such adjustments has not been explained. The proposed two-piece flask method also requires longer processing time per sample than oven-drying. Aggarwal and Tripathi (1975) also reported a replacement method using a wide-mouthed pycnometer for determination of soil water content; this technique requires less processing time per sample but should be carefully conducted to ensure its accuracy. In this method, soil water content should be measured under a constant temperature and the measurement requires a shaker; thus, this pycnometer method is unsuitable for field measurement. In addition, the procedure for determining SPD remains unclear, despite the fact that this parameter must be included in their proposed equations.

Rapid and accurate determination of the volume of water and soil particle mixture is a key factor that affects the feasibility of soil water measurement through volume/mass replacement (VMR). To the best of our knowledge, a direct and accurate method for measuring solid volume with irregular shape has not been established, provided that this material presents shape of scattered granules and uncertain constituents. Researchers have experimented with filling a graduated glass or a measuring cylinder with a certain amount of water; in this method, the solid matter to be measured is placed in the water, and the increase in water volume is read to determine the volume of the solid. Although this method seems reasonable, potential measurement errors cannot be neglected, considering that the measurer cannot accurately determine the increase in height of the water surface because of liquid surface tension. The same limitation exists when measuring the volume of pure liquid. Thus far, a measuring cylinder, or a graduated glass is commonly used for liquid volume measurements, but this technique yields a relatively low accuracy. In most cases, soil samples exist in the form of a mixture of water and soil particles or a mixture of water, soil particles, and air; and the volume of this multi-phase mixture is usually difficult to be accurately measured using a traditional graduated cylinder or glass.

Particulate organic matter (POM) and light fraction (LF) organic matter are potentially labile (active) fractions of soil organic matter (SOM) and are used as indicators of short-term changes in soil management practices. These two fractions mainly consist of partially decomposed plant residues, microbial residues, seeds, and spores forming organo-mineral complexes with soil mineral particles (Sequeira et al., 2011). Gregorich and Janzen (1996) defined LF as the fraction recovered by density fractionation and POM as the fraction recovered by size fractionation alone or by the combination of size and density fractionation procedures. The density of SOM ranges from 1.1 Mg m$^{-3}$ to 1.5 Mg m$^{-3}$ (Ruhlmann et al., 2006), which is much lower than SPD. When the proportion of organic matter in soil is high, the accuracy of soil water measurement may be influenced; thus, the appropriate application scope of the VMR method for determining soil water content needs to be defined.

In this study, a constant volume container (CVC) was proposed and designed to rapidly and accurately measure the volume of soil mixture for determining soil water content through VMR. The procedures for

![Fig. 1. Structure of the constant volume container.](Image)
measuring soil water content and SPD were illustrated in this study. Correlation analysis was also conducted to compare the VMR and oven-drying methods. Furthermore, the possible effect of SOM on measurement accuracy was theoretically analyzed.

2. Materials and methods

2.1. Structure of the CVC

In this study, accurate volume measurement of water and soil particle mixture is the basis of VMR. The proposed CVC is a key apparatus for volume measurement.

Fig. 1 illustrates the structure of the CVC both photographically and schematically. The lid (2) accurately fits the vessel body (1) to ensure that air is not trapped between the lid and the vessel body. The lower brim of the inlet (3) and any parts of the lid bottom are positioned lower than the upper brim of the overflow outlet (4). The upper brim of the inlet is higher than that of the outlet. The lid is positioned over the vessel, and the inlet and outlet are situated on opposite sides of the closed apparatus. As the water rises to a level higher than the lower edge of the overflow outlet, excessive water drains out of the container. Therefore, a constant volume of water or a mixture of soil particles and water can be attained inside the CVC.

The accuracy of measuring the volume of water or the mixture of water and soil particles by using the CVC is determined by its unique structure. The volume of the CVC is pre-determined during manufacture, and this structure can be fabricated into various sizes to satisfy measurement requirements. In this study, the CVC was made of aluminum alloy (Alloy grade 5083) and designed with a diameter of 74.9 mm, a height of 65.78 mm, and an inlet diameter of 3 mm. The alloy has a thermal expansion coefficient of 23.4 μm m\(^{-1}\) K\(^{-1}\), and does not tend to deform when exposed to temperature variation. Changes in CVC volume with temperature (Table 1) indicate that the maximum volume change is less than 1 cm\(^3\) when the measurement is conducted within a range from 5 to 40 °C, which is around the ambient temperature (20–25 °C).

2.2. Calibration of the CVC

The volume of the CVC is pre-determined during manufacturing and calibrated by weighing the container filled with distilled water at ambient temperature (20–25 °C). The volume of the CVC is calculated with Eq. (1):

\[
V_c = \frac{M_w(T)}{1000 \rho_w(T)}
\]

where \(V_c\) is the constant volume of the CVC, m\(^3\); \(M_w(T)\) is the mass of distilled water in the CVC at temperature \(T\) (°C), kg; \(\rho_w(T)\) is the density of water at temperature \(T\) (°C), Mg m\(^{-3}\).

The vessel body of CVC is filled with distilled water to nearly full, and then covered with the lid. Additional water is added by using an injector. The pinhead of the injector is inserted below the water surface inside the vessel body through the inlet. Water is injected drop by drop until a drop of water runs out through the overflow outlet. Finally, the constant volume of water inside the vessel can be accurately determined by the CVC.

### Changes in constant volume container (CVC) volume with temperature.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume change (%)</td>
<td>0.0351</td>
<td>0.0702</td>
<td>0.1053</td>
<td>0.1405</td>
<td>0.1756</td>
<td>0.2107</td>
<td>0.2459</td>
<td>0.2811</td>
</tr>
</tbody>
</table>

2.3. Determination of soil particle density

Soil particle density can be determined by using the CVC. The dried soil of known mass is placed into the CVC before the container is filled up with distilled water. The volume of the soil particles and their density are calculated as:

\[
V_{sp} = V_c - \frac{M_t - M_{sp}}{1000 \rho_w(T)}
\]

\[
\rho_{sp} = \frac{M_{sp}}{1000 V_{sp}}
\]

where \(V_{sp}\) is the volume of soil particles, m\(^3\); \(M_t\) is the mass of the water and soil particle mixture filling up the CVC, kg; \(M_{sp}\) is the mass of the soil particles, kg; and \(\rho_{sp}\) is the SPD, Mg m\(^{-3}\).

2.4. Measurement of soil water content

The partitioning principle is based on the model of soil three-phase composition, which consists of soil particles, water, and air. The initial soil mass is determined by the mass of soil particles and water when the mass of air is neglected. The partitioning procedure is as follows.

A specific amount of wet soil of known mass is placed into the CVC. The relationship among each volume fraction of mixture in the CVC is illustrated in Fig. 2. An appropriate amount of distilled water at ambient temperature is poured into the CVC to immerse the soil sample. The mixture is stirred carefully at a constant speed for 2–3 min to expel the trapped air before adding more distilled water to fill the CVC nearly full. The mixture is continuously stirred for another 2 min. The foam is carefully removed from the surface of the mixture, and the lid is fitted to the vessel body. Additional distilled water is added drop by drop into the closed vessel through the inlet by inserting the pinhead of the injector below the surface of the mixture. Water is added until a drop of water runs out through the overflow outlet. Eventually, the air is replaced by the supplied water, and a constant volume of water and soil particle mixture inside the CVC is accurately determined.

The volume of the CVC is partitioned into the following components:

\[
V_c = V_{sp} + V_w + V_f
\]
where $V_{sp}$ is the volume of soil particles, m$^3$; $V_w$ is the volume of water originally held by the soil sample, m$^3$; and $V_r$ is the air-filled volume replaced by supplementary water, m$^3$.

The corresponding components of mass are given as:

$$M = M_{sp} + M_w + M_r$$  \hspace{1cm} (5)

where $M$ is the total net mass of the mixture inside the CVC, kg; $M_{sp}$ is the mass of soil particles, kg; $M_w$ is the mass of water originally residing in the soil sample, kg; and $M_r$ is the mass of water replacing the air-filled volume, kg.

The mass ($M_0$) of the wet soil sample is the mass of the soil particles and the original water in the soil and can be written as:

$$M_0 = M_{sp} + M_w.$$  \hspace{1cm} (6)

After rewriting Eq. (5), the mass of the distilled water that fills up the rest of the CVC is:

$$M_r = M - (M_{sp} + M_w).$$  \hspace{1cm} (7)

The corresponding volume is determined as:

$$V_r = \frac{M_r}{1000\rho_w T}.$$  \hspace{1cm} (8)

The volume of soil particles and initial soil water is derived as:

$$V_{sp} + V_w = V_c - V_r.$$  \hspace{1cm} (9)\hspace{1cm}Eq. (6) can be rewritten as:

$$V_{sp}\rho_{sp} + V_w\rho_w(T) = \frac{M_0}{1000}.$$  \hspace{1cm} (10)

where $\rho_{sp}$ is assumed as 2.65 Mg m$^{-3}$ in this study.

When Eqs. (9) and (10) are simultaneously solved, $V_{sp}$ and $V_w$ can then be derived as:

$$V_w = \frac{1000\rho_{sp}(V_c-V_r)-M_0}{1000(\rho_{sp}-\rho_w(T))}$$  \hspace{1cm} (11)

$$V_{sp} = \frac{M_0-1000\rho_w(T)(V_c-V_r)}{1000(\rho_{sp}-\rho_w(T))}.$$  \hspace{1cm} (12)

Gravimetric soil water content ($\theta$) is calculated as:

$$\theta = \frac{V_w\rho_w(T)}{V_{sp}\rho_{sp}} \times 100\%.$$  \hspace{1cm} (13)

For measuring soil bulk density, the undisturbed soil sample is obtained by a standard soil corer. Soil bulk density can be determined using the measured mass of soil particles ($M_{sp}$) from Eq. (14) and the known volume of the standard soil corer:

$$M_{sp} = 1000V_{sp}\rho_{sp}.$$  \hspace{1cm} (14)

$$\rho_b = \frac{M_{sp}}{1000V_{cr}}.$$  \hspace{1cm} (15)

where $V_{sp}$ is the volume of soil particles determined by the CVC, m$^3$; $\rho_b$ is the soil bulk density, Mg m$^{-3}$; and $V_{cr}$ is the volume of the standard corer, m$^3$.

The volumetric soil water content $\theta_v$ can be determined as:

$$\theta_v = \theta\rho_b.$$  \hspace{1cm} (16)

2.5. Soil samples

Soil samples were collected from two regions in China. The properties of the two soils are listed in Table 2. Soil 1 (loam) was obtained from Jilin City, Jilin province in northeastern China, and Soil 2 (clay loam) was collected from Yangling, Shaanxi province in northwestern China.

Thirty-five soil samples with varied soil water contents were sampled from the field by using standard soil corer with a volume of 100 cm$^3$. These samples were weighed immediately after sampling and sealed

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>CaCO$_3$ (%)</th>
<th>Organic matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>15</td>
<td>40</td>
<td>45</td>
<td>0.64</td>
<td>1.72</td>
</tr>
<tr>
<td>Clay loam</td>
<td>29</td>
<td>48</td>
<td>23</td>
<td>7.68</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Table 2
Properties of the two tested soils.

![Graph](image.png)

Fig. 3. Correlation between gravimetric soil water contents measured by volume/mass replacement (VMR) method and oven-drying method.

Note: $R^2$ is the coefficient of determination; RE is the relative error; RMSE is the root-mean-square error.
with plastic bags for further soil water and bulk density measurements through VMR and oven-drying. Samples directly obtained from the field may not satisfy varied soil water contents, which are evenly distributed in a range of 0 to 30%. Experimental soil was therefore oven dried and passed through a 2 mm sieve before processing to obtain designed soil water contents of 10%, 15%, 20%, 25%, and 30%. In order to ensure the soil was fairly dry, the soil was re-dried after sieving and stored in a sealed container before it was used for preparing the designed soil water content samples or for SPD measurement.

Soil samples with designed water content were prepared according to Eq. (17). Dry soil was spread evenly on a tray, and water was sprayed uniformly on the soil. Another layer of dry soil was spread on the wet soil, and water was sprayed again. This procedure was repeated until the weighed water and soil were used up. The soil samples were stored in the sealed container for 2 days prior to the measurements.

\[ w_0 = \frac{m_w}{m_s} \times 100\% \quad (17) \]

where \( w_0 \) is the gravimetric soil water content, %; \( m_s \) is the mass of the dry soil particles, kg; and \( m_w \) is the mass of the water, kg.

Experiments were conducted with loam and clay loam to verify the conceptions and computational procedures of the VMR method for measurement of soil water and SPD. Soil samples of 80–90 g with varied soil water contents were tested, and the measurements of each soil sample were repeated at least three times through VMR and oven-drying.

### 2.6. Measurements

Soil samples and the mixture of soil particles and water were weighed by an electronic balance, with an accuracy of 0.01 g. Water temperature was determined by a thermometer, with an accuracy of 1 °C.

For determining soil water content and bulk density by the oven-drying method, soil samples were oven dried at 105 °C for 72 h. SPD was also measured through the pycnometer method by using the procedure of ISO/TS 17892-3 (2004), and by the flask method following the procedure on the website of the Globe Program (2014).

### 3. Results

Soil water content measured through VMR and oven-drying showed a linear correlation, with \( R^2 = 0.98 \) both in clay loam and loam. Moreover, the measured water contents of clay loam and loam obtained through VMR were 2.13% and 2.88% higher on average than those obtained through oven-drying, respectively (Fig. 3).

Soil bulk density of the field samples measured through VMR and oven-drying also exhibited a linear correlation, with \( R^2 = 0.99 \) in clay loam and \( R^2 = 0.98 \) in loam, respectively. Furthermore, pairs of measurements were all very close to the 1:1 reference line (Fig. 4).

Wet and dried soil samples were used for measuring SPD through VMR. The results indicated that the measurements were not significantly influenced by soil water content (Table 3). Dried soil samples were also used to determine SPD through pycnometer and flask methods. These methods significantly affected the SPD measurements. However, no remarkable differences were found between the pycnometer and VMR methods in loam, as well as the pycnometer and flask methods in clay loam. The standard deviations of loam and clay loam measured through VMR were about 0.01 Mg m\(^{-3}\), which was about 50% lower than those obtained through the pycnometer and flask methods (Table 4).

### 4. Discussion

#### 4.1. Measurement of SPD

Measurements of SPD through VMR using the proposed CVC show higher precision than those through the pycnometer and flask methods (Table 4). The larger measuring errors of the pycnometer and flask methods may be due to splash and loss of soil particles during heating or boiling to expel the trapped air; this phenomenon is particularly
evident when using the pycnometer, which has a small bottle mouth (Ma et al., 2014). Furthermore, accurate meniscus readings are still difficult when measuring the volume of soil particle and water mixture by using a volumetric flask because of liquid surface tension. Moreover, foam floating on the surface of the mixture in the elongated bottleneck of the flask is difficult to remove, thereby influencing the accuracy of volume measurement. However, the unique structure of the CVC can effectively eliminate volume measurement error caused by liquid surface tension at the inlet. Assuming the increase in height induced by liquid surface tension is constant, the volume measurement error is linearly related to the square of the inlet radius of the vessel. In this study, the vessel body of the CVC had a diameter of 74.9 mm. The CVC with an inlet diameter of 3 mm can reduce the volume measurement error to 0.16% of that of 74.9 mm theoretically estimated by Eq. (18):

\[
\frac{\Delta V_1}{\Delta V_2} = \frac{R_1^2}{R_2^2}
\]

(18)

where \(\Delta V_1\) is the volume measurement error produced by liquid surface tension with radius of \(R_1\), m²; \(\Delta V_2\) is the volume measurement error produced by liquid surface tension with radius of \(R_2\), m²; \(R_1\) and \(R_2\) are the radii of the vessel, m.

4.2. Soil water measurement

The average SPD values of loam and clay loam were 2.64 and 2.66 Mg m\(^{-3}\), respectively (Table 3). Soil water measurements through VMR using these measured SPD values are shown in Fig. 5. A strong relationship was found between VMR and oven-drying, with the \(R^2\) = 0.98 in loam and clay loam. Measurements of the two soils through VMR were about 2% higher on average than those determined through oven-drying. This measuring error is probably due to the trapped air in the micro-pores of soil aggregates, resulting in larger measurements by the VMR method. Moreover, even though the soil samples are dried for a long period of time during oven-drying, a small portion of water still remain in the soil, thereby causing lowered measurements of soil water content (Ma et al., 2013a, 2013b).

For soils with high clay content, the mixture of water and soil particles may need to be heated to further expel the trapped air. Due to the larger open mouth of the CVC with the lid removed, it is more convenient and easy to stir the mixture during heating process.

As shown in Table 3, the measured SPD of the two experimental soils was close to 2.65 Mg m\(^{-3}\). The linear correlation analysis between soil water measurements using the measured SPD of loam and clay loam and those using 2.65 Mg m\(^{-3}\) is illustrated in Fig. 6. It indicates that the SPD of 2.65 Mg m\(^{-3}\) is feasible to use in VMR to determine the soil water content of the two experimental soils (Table 5).

4.3. Effect of SOM on soil water measurement

Organic matter is one of the major solid components in agricultural soil (Johnston et al., 2009; Loveland and Webb, 2003); organic matter content affects SPD, thereby indirectly influencing the soil water measurement accuracy in the VMR calculation process. Measurement errors induced by SOM were theoretically analyzed through simulation, assuming soil samples of \(M_{ts}\) (kg) with gravimetric water contents of 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40%.

\[
M_{ts} + M_w = M_{ds} + pM_{ds} = M_{ts}
\]

(19)

where \(p\) is the gravimetric water content, %; \(M_{ds}\) is the mass of the dry soil particle component, kg; \(M_w\) is the mass of the water originally held by the soil sample, kg.

The density values of soil particles and SOM were assumed to be 2.65 and 1.3 Mg m\(^{-3}\), respectively. The density of water is 0.9978 Mg m\(^{-3}\).
at 22 °C. The total volume of soil particles and soil water \( (V_{ts}) \) was partitioned as follows:

\[
pM_{ds} \frac{M_{ds}}{997.8} + qM_{ds} \frac{(1-q)M_{ds}}{2650} = V_{ts}
\]

where \( q \) is the mass proportion of organic matter, %.

When the densities of these soil particles were assumed to be 2.65 Mg m\(^{-3}\), soil water content was calculated as:

\[
V_w = \frac{2650 \ (V_{ts} - M_{ds})}{2650 - 997.8} \tag{21}
\]

\[
V_{ds} = \frac{M_{ds} - 997.8 \ V_w}{2650 - 997.8} \tag{22}
\]

\[
\theta' = \frac{997.8 \ V_w}{2650V_{ds}} \times 100\% \tag{23}
\]

where \( V_w \) is the volume of soil water, m\(^3\); \( V_{ds} \) is the volume of soil particles, m\(^3\); and \( \theta' \) is the gravimetric water content, %. Subsequently, errors \((\Delta \theta')\) in soil water measurements induced by soil organic content in VMR can be determined as:

\[
\Delta \theta = \theta' - p. \tag{24}
\]

For example, in dry soil particles \((M_{ds})\) of 0.1 kg, the absolute errors in soil water measurements increase with increasing soil water content and organic matter content, whereas the relative errors decrease with increasing soil water content (Table 6).

4.4. Potential application of the VMR method

Time domain reflectometry (TDR) is widely used for measurement of soil water content in agriculture (Ledieu et al., 1986; Roth et al., 1990; Topp and Davis, 1984; Zegelin et al., 1989). The precision of TDR measurements is lower compared with that of oven-drying when the soil water content ranges from 0 to 5% and above 22%. The absolute errors are higher than 2%, and the relative errors are higher than 10% (Sun et al., 2014) because of air gaps created when inserting the probe into the soil (Reeves and Smith, 1992). It indicates that for wet soil with water content higher than 5% and organic matter content lower than 2%, soil water content could be measured using the assumed SPD of 2.65 Mg m\(^{-3}\) through VMR with reasonable measurement accuracy (Table 6). However, for soils with higher organic matter content or lower water content, measurement of the organic matter content or SPD is necessary in order to obtain acceptable measurement accuracy when using the VMR method.

Using the CVC, a portable scale, and an injector, and following the same measurement procedures as in the laboratory, measurement of soil water content or soil bulk density can also be conducted in the field.

5. Conclusions

VMR is a rapid method for partitioning water and soil particle fractions of soil mixture, and it can be used to measure SPD or soil water content as long as the volume of the mixture is accurately determined. A CVC with a unique structure was designed in this study to accurately and rapidly determine the constant volume of water and soil particle mixture. The use of this CVC can reduce the measuring error induced by liquid surface tension remarkably.

As analyzed during the establishment of partitioning model in VMR method, SPD is another key factor that affects the accuracy of soil water measurement. Measured soil water contents by VMR with an assumed SPD value of 2.65 were correlated with those obtained through oven-drying, yielding \( R^2 = 0.98 \) in two experimental soils.

The theoretical analysis showed that SOM affected SPD significantly, thereby influencing the accuracy of partitioning of water and soil particles in VMR. The VMR method with the CVC can achieve acceptable accuracy of soil water measurement when soil water content is larger than 5% and SOM content is less than 2%. The VMR method with the CVC can be used as an alternative approach to the oven-drying method with appropriate accuracy and efficiency. This CVC can also be used for measurement of soil water content through VMR in the field.

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