Study on influence and compensation for soil compactness on volumetric water content measurement

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Abstract. Volumetric water content measurements based on soil dielectric properties are affected by soil compaction. Today’s commercial products produce substantial measurement error as they do not account for the influence of soil compaction. This paper presents a portable soil volumetric moisture content sensor based on the principle of standing wave rate and simultaneous soil compactness measurement. The coupling relationship between soil compactness and soil volumetric moisture content can be easily observed by converting them into polar coordinates. A modified soil volumetric moisture content model based on the soil compactness is also established to support the operation of the proposed sensor.

1. Introduction

Soil moisture content is an important physical factor affecting plant growth and crop yield, and is thus of crucial significance to agricultural and forestry production professionals [1,2]. The changes in soil water content form an important basis for evaluating plant health and guiding irrigation. Soil volumetric water content is typically measured by drying methods, dielectric methods, or neutron meter methods [3-7]; drying methods are most common among them as they are convenient, accurate, and simply operated [8-10]. Dielectric methods, however, have become increasingly popular as they facilitate rapid, efficient, and continuous measurement of soil volume moisture on either portable or fixed equipment [11-13]. The effects of soil compaction on the measured data are rarely considered in plant health assessment or irrigation guidance applications [14-18]. Soil compaction, an important factor affecting soil volumetric water content, is meaningful only when comparing soil volumetric water content measurements under a unified compactness level.

The cone index is widely used to characterize soil compactness. Ayers [19], Vaz [20,21], and Busscher [22] have studied the relationship between soil moisture content, bulk density, and cone index in the laboratory environment and established semi-empirical models accordingly. Lin et al [23] designed a device for the simultaneous measurement of soil cone index and volume water content and to assess the performance of the semi-empirical model. Soil volume water content is closely related to soil cone index; that is to say, soil volume water content is closely coupled with soil compactness. Previously proposed models may not properly account for soil bulk density, however, and come with oversize census monitoring workload in real-world production scenarios. The bulk density needs to be
calculated by test sampling, so rapid measurement is not possible.

In this study, we designed a synchronous measuring device for soil compaction and volumetric water content. We defined the coupling relationship between soil water content and compactness and built a semi-empirical model based on compaction compensation soil moisture content accordingly, then tested the accuracy and stability of the corrected measurement results. Converting the measured soil volumetric water content to the soil volumetric moisture content at the same compactness level gives the soil volumetric water content data measured in an actual agroforestry production environment strong comparability, and provides a highly accurate basis for agroforestry production and ecological monitoring.

2. Materials and methods

2.1. Soil volumetric water content measurement method

There is a monotonous relationship between the soil volumetric content and the soil dielectric constant, so the former can be measured indirectly by measuring the latter. In this study, we recorded the dielectric constant according to the standing wave principle to measure the soil volumetric water content (figure 1). We used a 100 MHz sinusoidal signal as the oscillating signal source to generate the excitation with a transmission line characteristic impedance of 50 Ω. When the electromagnetic wave propagates along the transmission line, the impedance around the ring probe does not match the impedance of the transmission line and a standing wave forms on the transmission line [24-26]. The standing wave can be detected at both ends of the transmission line and the small signal can be amplified via differential signal amplifier to determine the output signal as follows:

\[
\Delta U = 2A\sigma = 2A \frac{Z_p - Z_L}{Z_p + Z_L}
\]

where \(\Delta U\) is output signal voltage difference (V), \(A\) is electromagnetic wave amplitude (V), \(\sigma\) is the transmission line reflection index, \(Z_p\) is the probe impedance (Ω), and \(Z_L\) is the transmission line impedance (Ω). \(Z_L\) is dependent on the physical dimensions and dielectric constant of the insulating...
material, which is 50 Ω here. The transmission line reflection index is a fixed value. Formula (1) indicates that the changes in impedance around the ring probe cause the output signal voltage disparity to change. The impedance around the ring probe is determined by the soil dielectric around the constant, probe size, and oscillating signal source frequency. The soil volumetric water content can be obtained by measuring the output signal voltage difference once the probe size and frequency are determined.

2.2. *Soil compactness measurement based on cone index*

Cone index (CI) is often used to describe soil compactness as an indicator of the soil’s resistance to conical penetration at uniform velocity. When a standard cone penetrates the soil at a uniform speed, the average pressure per unit floor area is the CI. ASAE specifies respectively the specification of two kinds of cones with diameters of 12.83 mm and 20 mm and a conical head cone angle is 30°. CI is expressed as follows:

\[
CI = \frac{N}{S}
\]

where \(N\) is the cone resistance to uniform penetration into soil and \(S\) is the conical head bottom area. In the process of uniform penetration, the resistance of cone penetration into the soil is equal to the pressure applied on the cone meter, so CI can be calculated by measuring the pressure applied on the cone meter and the area of the cone bottom.

2.3. *Compactness synchronization measuring device*

![Figure 2](image_url)

*Figure 2.* Schematic diagram of measuring device. (a) Schematic diagram of device structure, (b) physical image of device.
A diagram of the proposed device is shown in figure 2. A measuring probe is connected to a moisture measuring circuit to collect soil volumetric water content data. The measuring probe is comprised of two stainless steel rings with outer diameter of 20 mm and inner diameter of 18 mm. The rings are installed on a PVC support column (diameter 18 mm) and a conical head (conical angle is 30°, diameter is 20 mm) is installed at the lower end of the support column. The measuring probe is installed at the lower end of the supporting steel pipe (outer diameter is 10 mm, inner diameter is 5 mm). The output signal of the volumetric water content measuring circuit board is transmitted to the acquisition motherboard through a connecting cable inside the steel pipe. The upper part of the supporting steel pipe is equipped with a pressure detection module (JLBT-M2, Bengbu Sensor System Engineering Company, China; range 0-7000 N, output voltage 0-2500 mV, accuracy 2.8 N/mV) and the base. The penetration pressure is measured by the pressure module and CI is calculated according to the data it provides.

2.4. Experimental sample
Soil samples were collected from the Gongqing Forest Farm (116.73°E, 40.11°N) in Shunyi District, Beijing, from Zhenyuan Country in Qingyang City (107.03°E, 35.54°N), Gansu Province, and from the Beijing Forestry University Sanqingyuan Experimental Base (116.34°E, 40.00°N). Samples were collected randomly from three areas each with a depth of 0-40 cm. A total of 30 kg of soil was taken back to the laboratory. The soil samples were dried in a drying oven (105°C, 48h) and passed through a 40 mesh screen to remove stones, roots, and impurities. The samples include clay loam soil (11% sand, 71% silt, 18% clay), loess soil (15% sand, 65% silt, 20% clay), and sand soil (85% sand, 10% silt, 5% clay).

2.5. Experimental procedure

2.5.1. Soil volumetric moisture sensor calibration. Each soil sample was weighed 5 kg with precision electrons. They were recorded as clay loam soil, loess soil and sand soil. A certain amount of water was added to each sample soil and stirred for 10 min until the water and soil were thoroughly mixed and the soil moisture content was uniform. Each type of soil was then equally divided into eight samples; the first sample was placed into a polyvinyl chloride (PVC) calibration barrel (40 cm diameter, 25 cm height) and compacted with nylon rods (50 mm diameter, 50 cm length) freely falling from the surface of the sample about 3 cm to compact it after adding different amount of water, with slight rotation from the periphery to the middle to ensure that the soil in calibration barrel was completely integrated. These steps were performed on the remaining seven samples, and an experimental sample was configured in the barrel. Then the calibration barrel was sealed for 48 hours to ensure the balanced movement of water in the barrel. The sensor was then inserted into the barrel for measurement at an insertion depth of 20 cm.

Each soil sample was measured in 10 replications. The maximum and minimum voltage values were removed, then the remaining eight values were averaged to obtain the current soil sample measurement result. The volumetric moisture content of the soil sample in the calibration barrel was measured simultaneously via drying method. Soil samples of varying volumetric moisture content can be configured by adding different masses of water to the soil samples. Each soil sample in the experiment was configured with eight different volumetric moisture content characteristics. We recorded the volumetric moisture content and voltage value measured by the sensor, then tested the linear fit of the values.

2.5.2. Soil volumetric moisture content measurement under different compactness. Each soil sample was weighed to 10 kg with precision electrons and recorded as clay loam soil, loess soil, and sand soil. According to the soil moisture degree in table 1, 338.0 g, 829.0 g, 1356.0 g, 1800.0 g, and 2212.0 g of water were added to the soil samples to ensure various levels of dryness (or “moisture content”). As described in Section 2.5.1, samples of varying compactness were configured by controlling the
number of nylon rod compaction cycles (1, 2, 4, 6, 8, 10, 12, 14, 16, and 20). Ten samples were configured for each soil moisture degree and 150 samples were configured for each of the three different soil types. The sensor was uniformly penetrated into the sample to 20 cm and the corresponding soil compactness and soil volumetric moisture content were recorded.

| Soil moisture classes | Gravimetric water content /% |
|-----------------------|------------------------------|
| Higher soil water     | >20                          |
| Suitable soil water   | 15-20                        |
| Mild dry              | 12-15                        |
| Moderate dry          | 5-12                         |
| Severe dry            | <5                           |

3. Results and discussion

3.1. Soil volumetric moisture content sensor calibration

The output voltage of sensor and soil volumetric moisture content were linearly fitted as shown in figure 3. The determination coefficients of the linear fitting curves of three soil samples are 0.97, 0.99, and 0.96, which indicates that the output voltage of the sensor has a good linear relationship with the soil volumetric moisture content of the tested sample under the same degree of compactness. In other words, the soil volumetric moisture content can be calculated by the sensor output voltage.

![Figure 3. Fitting curve between output voltage values and soil moisture content. (a) Clay loam soil, (b) loess soil, (c) sand soil.](image)

3.2. Changes in soil volumetric moisture content for different compactness

The changes in soil volumetric moisture content corresponding to different compactness (CI) for the three types of soil samples are shown in figure 4. We found that the change rate of soil volumetric moisture content caused by soil compaction differs under different soil moisture degrees. Soil volumetric moisture content does not change with soil compaction for “severe dry” soil, but increases slowly with soil compactness when the soil is characterized by “moderate drought” and increases rapidly with soil compactness for “mild drought” and “suitable” soil. When soil moisture is very high,
the soil volumetric moisture content and soil compactness remain stable [27,28]. These change trends also appeared to differ for different soil types. The soil volumetric moisture content of Sample 1 increases with soil compactness, while both qualities remain basically constant in Samples 2 and 3 as soil moisture increases.

Figure 4. Changes in volumetric water content with changes in compactness. (a) Clay loam soil, (b) loess soil (c) sand soil.

3.3. Relationship between volumetric moisture content and compactness in polar coordinates

Figure 4 shows that the slope of the curve increases as soil moisture increases, but it is difficult to observe the specific coupling relationship between with soil volumetric moisture content and soil compactness in the planar coordinate system. We converted the soil volumetric moisture content and soil compactness from the planar coordinate system data to the polar coordinate system as follows:
Figure 5. Changes in polar radius with polar angle and $\rho$ is polar radius, $\omega$ is polar angle. (a) Clay loam soil, (b) loess soil, (c) sand soil.

$$\rho = \sqrt{\theta^2 + CI^2}$$  \hspace{1cm} (3)

$$\omega = \arctan\left(\frac{\theta}{CI}\right)$$  \hspace{1cm} (4)

Where $\rho$ is polar radius, $\omega$ is polar angle, $\theta$ is the soil volumetric moisture content and $CI$ is soil compactness. As shown in figure 5, the fitting determination coefficients are all greater than 0.98; the polar angle has a good linear relationship with the polar radius in the polar coordinate system.

3.4. Soil volumetric moisture content modified model based on soil compactness

The polar radius and polar angle satisfy a power function relationship as per the fitting results shown in figure 5. The relationship can be expressed as follows:
\[ \rho = a \cdot \omega^b \]  

where \( \omega \) and \( b \) are constants. The difference in soil types and moisture degrees makes the power function curve coefficients obtained by fitting the power exponential function are also different, so \( \omega \) and \( b \) need to be calibrated for different soil types and moisture degrees. Plugging equations (3) and (4) into equation (5) yields the following:

\[ \theta^2 + CI^2 = a^2 \cdot (\arctan\left(\frac{\theta}{CI}\right))^{2b} \]  

and further simplification produces equation (7):

\[ \left(\frac{\theta}{CI}\right)^2 + 1 = \left(\frac{a}{CI}\right)^2 \cdot (\arctan\left(\frac{\theta}{CI}\right))^{2b} \]  

We propose the following modified soil volumetric moisture content model based on soil compactness:

\[ \left(\frac{\theta}{CI}\right)^2 + 1 - \left(\frac{a}{CI}\right)^2 \cdot (\arctan\left(\frac{\theta}{CI}\right))^{2b} = 0 \]  

According to different soil compactness, substituting into equation (8) and solving the soil volumetric moisture content produces the corresponding volumetric moisture content under the given compaction condition. Converting the measured soil volumetric water content to the soil volumetric moisture content at the same compactness level gives soil volumetric water content data measured in an actual agroforestry production environment high comparability.

4. Conclusions

In this study, we designed a bimetallic ring probe and pressure sensor for simultaneous soil moisture and compactness measurement. The linear fitting determination coefficient determined in our calibration experiment exceeds 0.96, which indicates that the proposed device – which works based on the standing wave principle – accurately measures soil volumetric moisture content. We observed changes in soil volumetric moisture content with changes in soil compactness and built a coordinate transformation to make the coupling relationship between them easier to observe, and established a modified soil volumetric moisture content model accordingly based on soil compactness.

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