Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 7548996, 9 pages
https://doi.org/10.1155/2021/7548996

Research Article

Multifactor Analysis of Calibration and Service Quality of the Soil Moisture Sensor Applied in Subgrade Engineering

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Received 25 July 2021; Accepted 9 August 2021; Published 12 August 2021

Academic Editor: Yongsheng Yao

The soil is an important natural resource, and its moisture status plays a key role in the strength and stability of the soil structure. In civil industries including the agriculture engineering and the forestry engineering, moisture sensors are widely used to test and monitor the engineering properties and long-term service performance of soil. The influence of multiple factors on the quality and the accuracy of the soil moisture sensor should be taken into account. Both laboratory and field tests were performed by the time-domain reflectometry (TDR) method. The soil dielectric constant and magnetic permeability under different moisture contents, different temperatures, and different dry densities were comprehensively evaluated. At the same time, the sensitive factors in the service performance of the TDR sensor have been revealed by the real state of tested soil samples. Based on the testing principle of TDR, a calibration calculation model has been developed to evaluate accurately the moisture content of the subgrade slope. The results show that both the moisture content and the dry density had a significant influence on the dielectric constant and the magnetic permeability of soil. The developed calculation model has a good fitting effect and stability. Through the model, the influence of moisture content and temperature on the soil dielectric constant has been analyzed, and the fitting goodness is above 90%. After half a year of settlement, the soil was gradually drained and consolidated, and the moisture content of the subgrade section gradually decreased. It verified that the monitoring method determined by the laboratory calibration test was effective and accurate.

1. Introduction

In general, soil structure is a three-phase body consisting of solid, liquid, and gas phases [1]. The water in soil exists in many forms, including bound, unbound, and vaporous water. The moisture status of soil is usually tested and monitored to determine the engineering nature of the soil, control the quality of pressure implementation, verify the early warning of geological hazards, and analyze the fine management of agricultural production [2–4]. Water in soil is usually quantified by water content, which is defined as the ratio of water to soil particles in soil except for structural water. In the nature, soil moisture content changes dynamically over time and environmental factors [5]. Environmental factors such as dry evaporation and precipitation alternately change, causing several wet and dry cycles in slope soil [6]. The soil structure is not fully compacted because of the considerable change of water content, leading to harmful accidents, such as subgrade slip, water damage, and uneven settlement of engineering structures [7]. Therefore, testing and evolution of moisture content have been the focus of research in subgrade engineering for a long time.

The progress of sensor technology and the Internet constantly improves and develops the test methods of moisture content [8]. At present, some interesting topics are given increasing attention, such as in situ nondestructive detection [9], automatic real-time monitoring [10], remote wireless transmission [11], and intelligent health management [12]. Among them, the real-time monitoring of moisture content is widely used in agricultural production, geological forecasting, and road-based engineering [13]. In geological engineering, Yang et al. [14] studied the influence of environmental factors on slope stability by monitoring the change of slope moisture content to prevent geological disasters, such as landslides and mudslides. In the area of relic protection, Ruiz Valero et al. [15] monitored the existing environment of a building and evaluated its reinforced stability and water damage. In the subgrade project, Ahmed et al. [16] used the change of moisture content to analyze the influence of freezing, rain, soil, and other factors on subgrade performance. Moisture distribution can be monitored through several methods. The time-domain reflectometry (TDR) method, ground detection radar method, soil resistance method, and capacitance method have been used for a single point or small ranges [17]. The distribution and change of soil moisture in large areas of time and space are usually determined using remote sensing technology [18]. However, many problems with the real-time monitoring of soil moisture content still exist. For example, the suitability and accuracy of test methods are susceptible to soil influences and constraints. In addition, measuring instruments, sensors, and other hardware have common disadvantages, including large size, high energy consumption, high cost, and other issues.

As the basis of road surface, the quality (strength and stability) of a subgrade directly affects the service life of pavement structures [19]. Given the lack of carrying capacity, the subgrade is permanently deformed, resulting in various problems on the road surface, such as subsidence and ruts [20]. This kind of engineering problem is closely related to the moisture content and migration law in soil [21]. The researchers aim to solve this engineering problem by performing in situ monitoring and a water migration model test to calibrate the moisture content of subgrade soil and its evolution mechanism evaluation. The relationship between the soil characteristic parameters (i.e., dielectric constant, conductivity, and resistivity) measured by the sensor and the soil moisture content (i.e., the sensor calibration model) must be determined by obtaining the moisture content of the soil through the sensor [22]. The classical Topp model characterizes the relationship between the volume moisture content of the soil body and the dielectric constant with three polynomials [23]. Ledieu et al. [24] used the square root formula to characterize the relationship between volume moisture content and dielectric constants. Cui et al. [25] validated and compared the feasibility of the Topp and Ledieu models through laboratory and in situ tests. The existing calibration model is relatively complex, and the accuracy of the test results is influenced by other components in the soil [26]. Moreover, the moisture of the subgrade soil evaporates violently because of the perennial high temperature and heavy rainfall in southern China [27]. The moisture content of the subgrade changes extensively; thus, the effect of the moisture content on the modulus of the subgrade must be fully considered. Therefore, monitoring the moisture changes of highway foundations during operation is vital to improve the drainage design and maintenance measures of highways in the area.

Careful consideration of the relationship between soil moisture content and dry density can improve the accuracy of the sensor to determine the moisture content. In addition, the simultaneous detection of the compaction and moisture content changes of the subgrade soil has important engineering significance in subgrade engineering. In the present research, a calculation model for moisture content, dielectric constant, and permeability has been established based on the TDR principle. Laboratory calibration tests were performed using PVC pipes to determine the engineering properties of silt. The influencing factors and changing law of the moisture content were compared and analyzed, and the measurement quality of the sensor was verified. The TDR sensor was applied to the southern subgrade slope to verify the monitoring method by observing the moisture content of the slope for half a year.

2. Testing Principle and Factor Analysis

2.1. Time-Domain Reflectometry and Its Principle. The basic principle of TDR involves the propagation of electromagnetic waves at different rates in material medium with different dielectric constants. The dielectric constant in the soil depends mainly on moisture content because the dielectric constant of water is much larger than that of other substances in the soil.

The dielectric constant of the solid-liquid-gas three-phase mixture evidently changes when the proportion of water in a certain volume of soil varies. Therefore, soil moisture content can be calculated by measuring the dielectric constant of soil. Topp et al. [23] first measured the apparent dielectric constant of soil. They then established the empirical relationship between the volume moisture content and the dielectric constant in different types of soil based on a large number of experiments, as shown in equation (1). In each TDR test unit, the relationship similar to equation. (1) must be calibrated separately and built into the chip to convert the field measurement of ε to the volumetric moisture content of the soil w.

$$w = -0.53 \times 10^{-2} + 2.92 \times 10^{-2}\varepsilon - 5.5 \times 10^{-4}\varepsilon^2 + 4.3 \times 10^{-6}\varepsilon^3, \tag{1}$$

where w is the volumetric moisture content; ε is the dielectric constant of the soil.

Reflection and refraction occur when the electromagnetic wave meets the boundary between two kinds of media in the process of propagation. The propagation velocity of the electromagnetic wave in different media is related to the dielectric constant, as shown in equation (2) [28]. In general, the permeability of a nonmagnetic material (μ) is nearly the same as that of a vacuum (μ_0). Therefore, equation (2) shows that the propagation velocity of the electromagnetic wave is mainly affected by the dielectric constant ε.

$$v_p = \frac{1}{\sqrt{\mu\varepsilon}}, \tag{2}$$

where v_p is the propagation rate of electromagnetic wave; μ is the magnetic permeability of the soil.

The TDR sensor has been widely used in measuring soil moisture content, and its measurement results are fast and accurate. However, TDR sensor application also has some drawbacks [29]. The time (t) between two reflections is very short because of the high velocity (v_p) of the electromagnetic wave and the limited length of the probe. The total time spent on the forward and back propagation of the signal on the probe is greater than the rising edge time of the excitation signal. Realizing ultra-high-speed delay measurement technology is difficult because of the influence of probe length and geometry length.

2.2. Effect Factor Analysis. Based on the abovementioned discussion, TDR calculates the dielectric constant of the propagation medium through the propagation rate of the electromagnetic wave. The dielectric properties of soil are significantly affected by frequency, temperature, and soil dry density.

The existing laboratory experiments showed that the dielectric properties of soil change with frequency potentially because of dielectric polarization. An induced charge generates and weakens the electric field when a dielectric is placed in an applied electric field. The dielectric constant is the ratio of the original applied electric field to the electric field in the final medium. At the micro level, generating an induced charge refers to dielectric polarization, which can be divided into two categories, elastic displacement polarization and relaxation polarization. Elastic displacement polarization is considered an instantaneous polarization; therefore, it is not affected by frequency. For relaxation polarization, the orientation polarization time of the inherent electric distance is between 10^{-2} and 10^{-8}. Thus, if the measurement frequency is within this range or higher than its maximum value, then the dielectric properties inevitably change under the influence of relaxation polarization.

Soil dielectric properties are affected by temperature because temperature plays an essential role in determining relaxation time, as shown in equation (3) [30]. In general, a body is most stable when it has the lowest energy. As the temperature increases, the relaxation time of the medium decreases, as shown in equation (3). Therefore, the dielectric constant increases with the increase of temperature.

$$\tau(T) = \tau_0 e^{(E_a/KT)}, \tag{3}$$

where T is the temperature; K is the Boltzmann constant; and E_a is the effective electric field on the dipole.

The physical explanation is that the energy of the dipole inside the dielectric increases with the increase of temperature, and the dipole changes from relatively stable to active. Macroscopically, the value of dielectric constant increases with the increase of dielectric susceptibility.

The volume of air in soil mainly comes from the contribution of the pores between soil particles. Soil dry density refers to the ratio of the dried soil mass to the original soil volume, as shown in equation (4). Under the same moisture content, the higher the soil dry density, the higher is the mass of soil particles and water in the unit volume. This condition makes the unit volume of soil particles and water increase and the unit volume of natural air decrease. Soil dry density reflects the compactness of the soil and can indirectly reflect air content. Therefore, the higher the soil dry density, the higher is the dielectric constant of the soil. On the contrary, the lower the soil dry density, the lower is the dielectric constant of the soil.

$$\rho_d = \frac{m_d}{V}, \tag{4}$$

where ρ_d is the dry density of soil; m_d is the quality of the dried soil; and V is the volume of soil before drying.

According to domestic and foreign literature, soil moisture content measurement by the TDR method is inevitably restricted by the factors that influence the dielectric properties of soil. In general, the dielectric constant is affected by signal frequency, soil temperature, and soil dry density. However, most TDR sensors on the market do not consider the influence of soil dry density on the results of soil moisture content measurement. This scenario increases the measurement errors of the TDR sensor.

3. Materials and Sensor Calibration

The moisture content of subgrade monitoring is an important means of long-term evaluation of southern humid area subgrade stability. In order to use the TDR sensor to accurately measure the moisture content of subgrade soil change, a laboratory calibration test is one of the essential preparations before on-site monitoring.

3.1. Materials. The soil sample for the test came from the salt soil of a highway subgrade in Guangdong Province. The size gradation is an important parameter to evaluate engineering properties and optimize material properties for soils or mixtures [31]. The particle grading curve is shown in Figure 1. The density of natural soil is 1.21 g/cm^3, and the initial mass moisture content is 4.35%. The liquid limit is 34%, and the plastic limit is 13%. The compaction test determines that the maximum dry density of the soil sample is 1.34 g/cm^3, and the optimum moisture content is 14.6% [32].

3.2. Calibration Method. In this study, a PVC pipe with one end closed was used as a fixed volume container for the moisture content comparison test, and the same soil sample was used for two parallel tests. Under the condition that the initial moisture content and the quality of the soil sample are known, the deionized water that needs to be added is calculated to prepare soil samples with different moisture content. The test soil sample prepared by the wet method is about 8000 g, and the designed moisture content is 7%, 10%, 13%, 16%, and 19%, respectively. The soil samples were sampled to determine the initial mass moisture content after the material was uniformed for 24 hours. In order to simulate the actual compaction state of the subgrade as much as possible, the TDR sensor was placed in the middle of the PVC pipe, and the test soil samples were backfilled and compacted in 10 layers according to the dry density of the construction site, and necessary sealing measures were taken. The schematic diagram of the calibration test device is shown in Figure 2.

The specific evaluation steps are as follows: (a) A thermometer was inserted into the center hole of the probe positioning mold, and the temperature was checked using the thermometer. (b) The thermometer was unplugged. (c)

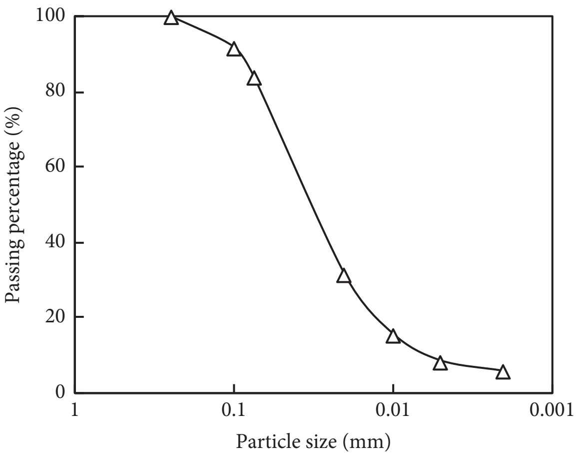


Figure 1: Soil particle sieving result.

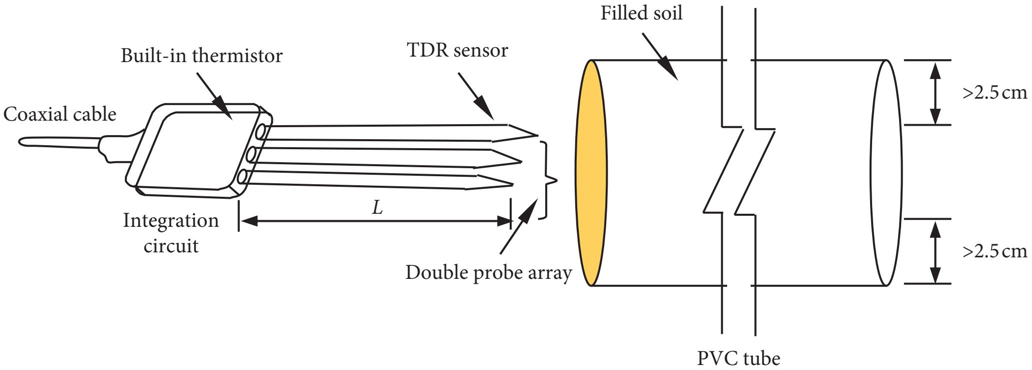


Figure 2: Schematic diagram of the TDR sensor and the calibration test device.

The probe was driven into the soil, the probe positioning mold was removed, and the soil powder at the edge of the PVC pipe was cleaned. (d) The test instruments were connected to determine the dielectric constant and permeability of soil samples through waveform analysis. (e) The soil samples were selected from the upper, middle, and lower parts of PVC pipes, and the average moisture content of soil samples was accurately obtained through the drying method.

The dielectric constant of soil is related to the magnetic conductivity of soil, the proportion of its components, and soil type. Siddiqui et al. established the relationship between the mass moisture content and dry density of soil and the apparent dielectric constant of soil, as shown in equation (5), to consider the influence of dry density. As calibration coefficients, a is related to the dielectric constant of soil particles and the dry density of soil, and b is related to the properties of pure liquid. The calibration of parameters a and b can be obtained using soil samples with different moisture contents and dry densities obtained by the standard compaction test (ASTM D698-2000).

$$\sqrt{\varepsilon} = a\frac{\rho_d}{\rho_w} + bw, \tag{5}$$

where ρ_w represents the density of water; a and b are the calibration coefficients of the dielectric constant.

In general, the soil dielectric constant and magnetic permeability are regarded as two independent parameters. Dielectric constants are used to obtain the soil moisture content, and permeability is used for evaluation. However, these two parameters have an inherent relationship. The soil moisture content can be determined through the test on dielectric constants and magnetic permeability by applying the inner link between them without the density equation. Therefore, considering the soil dielectric constant and magnetic permeability of the influence of soil moisture content, Yu and others proposed the tests of soil moisture content and dry density of the one-step method. First, they set up the dielectric constant of the soil electrical conductivity calibration equation, as shown in equation (6). Then, according to equations (5) and (6), the soil dry density and moisture content can be determined by equations (7) and (8).

$$\sqrt{\mu} = c\frac{\rho_d}{\rho_w} + dw, \tag{6}$$

$$\rho_d = \frac{d\sqrt{\varepsilon} - b\sqrt{\mu}}{ad - cd}\rho_w, \tag{7}$$

$$w = \frac{a\sqrt{\mu} - c\sqrt{\varepsilon}}{ad - cd}, \tag{8}$$

where c and d are the calibration coefficients of the magnetic permittivity.

Moreover, the dielectric constant and conductivity tests are affected by the ambient temperature. The temperature of the field test may not be the same as the temperature of the laboratory calibration. Therefore, temperature compensation is required during field testing. The influence of temperature on the dielectric constant of soil is related to soil type, as shown in equation (9). The test temperature T is generally between 4°C and 40°C.

$$\varepsilon_{20^{\circ}\mathrm{C}} = \varepsilon_T \times f(T), \tag{9}$$

where $f(T)$ represents the temperature compensation function. For noncohesive soil, $f(T) = 0.97 + 0.0015T$, and for cohesive soil, $f(T) = 1.10 - 0.004T$.

Therefore, according to the test results and calibration equation, the least square method was used to fit the test curve, and the corresponding calibration coefficients a, b, c, and d can be obtained.

4. Quality Evaluation and Subgrade Application

4.1. Laboratory Results of Sensor Calibration. Figure 3 shows the regression curve of the calibrated parameter results. Figure 3(a) illustrates the relationship between the dielectric constant and the mass moisture content of the soil, thereby obtaining the calibration coefficients a and b of the dielectric constant. Figure 3(b) illustrates the relationship between the magnetic permeability and the mass moisture content of the soil, thereby obtaining the magnetic permeability calibration coefficients c and d. According to the calibration curve in Figure 3, calibration results are in good agreement. The moisture content and dry density can be obtained by a test in the field through calibration coefficients and prediction formulas. In addition, the parameters of different soil samples can be measured through laboratory tests to establish TDR sensors database. According to the established database, the moisture content and dry density of the field soil samples can be easily and quickly obtained. If the subgrade engineering requires high accuracy, then the sensor test should strictly follow the steps in Section 3.2, and the test soil sample must be calibrated before the test.

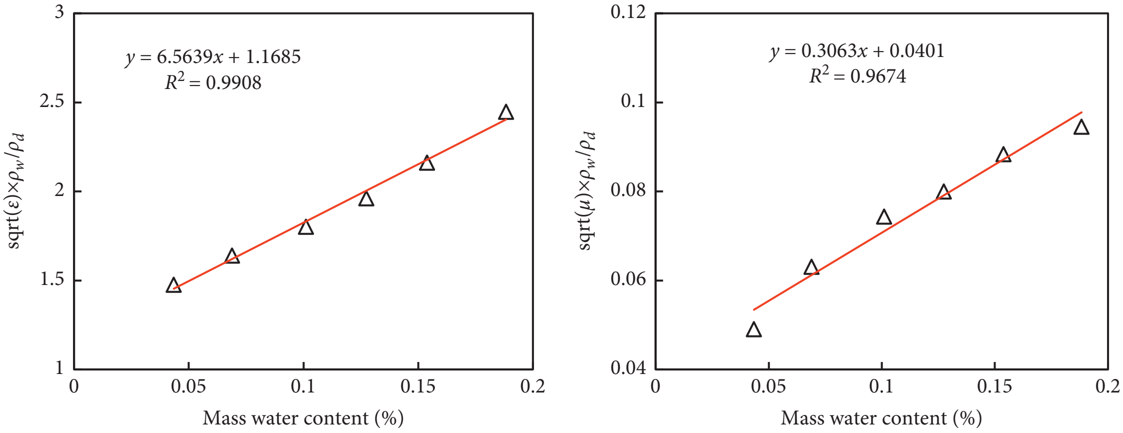
4.2. Comparison between the Calculated and Actual Moisture Content. Figure 4(a) shows the results of moisture content measurement obtained using the TDR sensor at 25°C. The actual soil mass moisture content ranges from 4.35% to 18.83%. The sensor tests six groups of soil samples under different dry density conditions and outputs the dielectric parameters and permeability. The moisture content calculated according to equation (8) is compared with the actual moisture content obtained through the drying method. Ideally, the calculated moisture content and actual moisture content should fall on the straight line with a slope of 1 in Figure 4. However, in most cases, the experimental results show that the calculated moisture content is greater than the actual moisture content, and the absolute error is between −3.35% and 0.68%. Therefore, this finding shows that the measurement accuracy of the sensor in this experiment is not high, and the consistency check R^2 is 84.64%. The reason is that the TDR sensor is calibrated by the general relationship between volumetric moisture content and dielectric constant. According to domestic and foreign literature, the content of bound water in the soil has a considerable effect on the determination of dielectric constant because the apparent dielectric constant of the soil is affected by factors such as soil quality, dry density, and temperature. In a certain frequency range, the dielectric constant of free water is constant, and the dielectric constant of bound water increases as the content of bound water increases.

The digital temperature sensor is used to verify the temperature of the TDR soil temperature-moisture sensor. Figure 4(b) shows the temperature results of the six soil samples with different bulk densities and moisture contents measured by digital temperature sensors and TDR sensors. Figure 4(b) shows that the calculated temperature and the measured temperature fall on both sides of the 45°C line closely, and the absolute error between them is from −1.7°C to 0.9°C. The temperature measurement result of the TDR sensor is relatively reliable, and the consistency test R^2 is 98.85%.

4.3. Effect of Temperature and Dry Density on Sensor Evaluation. Figure 5 shows the effect of temperature on the output current of the TDR sensor's moisture content port under different compaction conditions when the moisture content is 10.11% and 18.83%. The degree of compaction used in this experiment is 90%, 93%, and 96%, and the corresponding dry densities are 1.21, 1.25, and 1.29 g/cm^3. The test results indicate that the output current of the TDR sensor gradually increases as the temperature increases. When the temperature is less than 10°C, the output current rises slowly; however, it rises rapidly when it is greater than 10°C. This phenomenon is also found in soil samples with other moisture content.

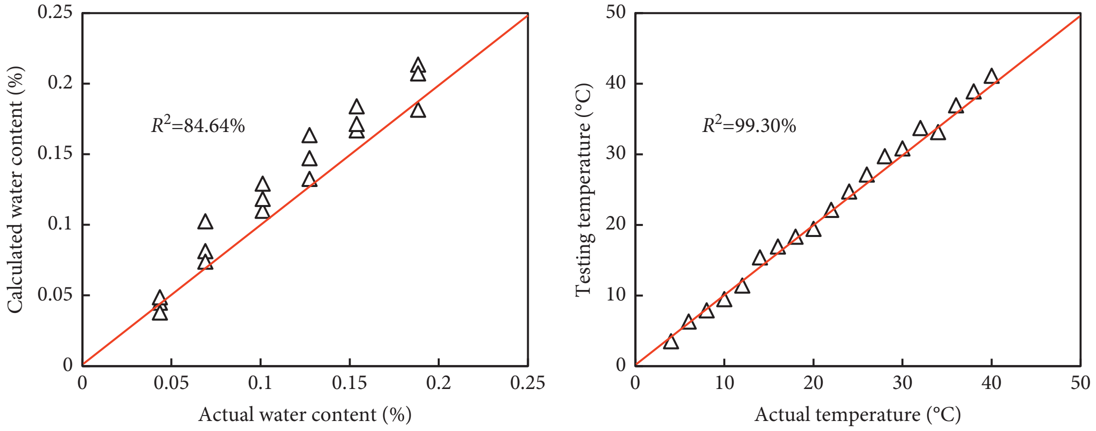
The dielectric properties in matter represent the dynamic balance between molecular polarization and Brownian motion in the electrostatic field. The increase in temperature can accelerate the orientation movement of polar molecules and the Brownian movement of particles in the soil. This situation leads to an increase in the dielectric constant of the soil, which is reflected in the increase in the output current. Figure 5 shows that temperature is one of the main factors affecting the output current of the TDR sensor, and eliminating the influence of temperature is vital to improve the detection accuracy of soil moisture content.

Moreover, the results in Figure 5 show that the output current generally increases with the increase of soil dry density. The output current of the sensor increases rapidly when the soil dry density increases from 1.21 g/cm^3 to 1.29 g/cm^3. With the same moisture content, the soil samples with high soil dry density have larger soil particle content per unit volume and lower air content than the soil samples with low soil dry density. Under the same temperature, the relative permittivity of soil particles is greater than that of air. Thus, the output current increases as the soil dry density



(a) (b)

Figure 3: Calibration results of sensor parameters: (a) dielectric constant; (b) magnetic permittivity.



(a) (b)

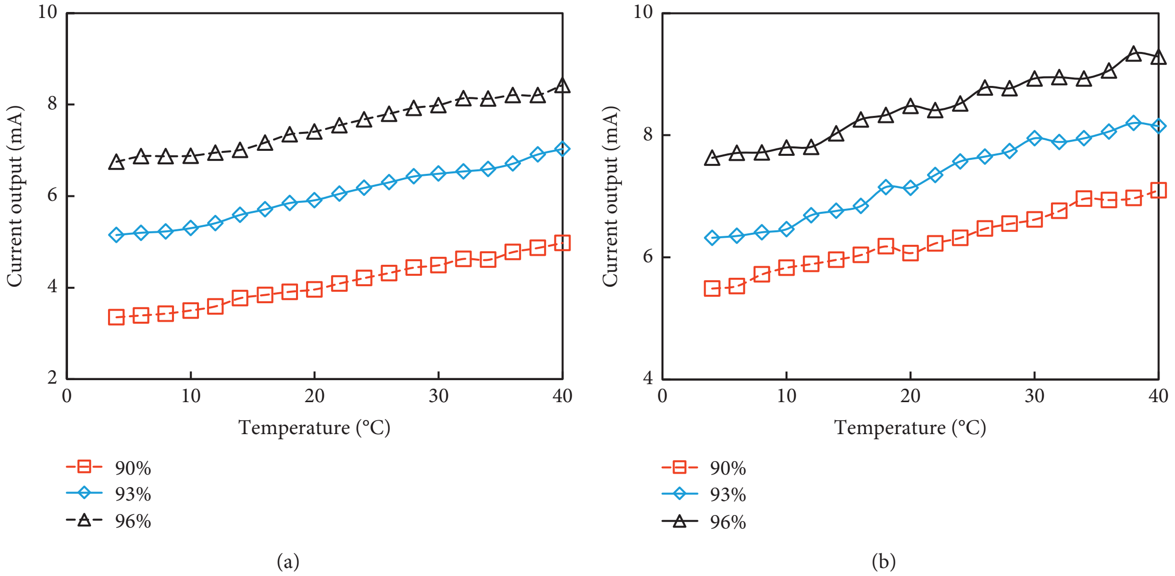
Figure 4: Testing results of (a) moisture content and (b) temperature in the laboratory.

increases. The studies about the samples with the other five moisture contents have similar conclusions. Under the same temperature, the output current increases with the increase of soil dry density.

4.4. Seasonal Variations in Moisture of Subgrade. The laboratory calibration test indicated that the moisture content measured by the TDR sensor has a good linear correlation with the actual one. The relevant parameters should be determined according to the formula of this research before burying the TDR sensor. Then, the actual moisture content of the subgrade structure can be obtained through the TDR sensor.

This test measures the depth of the slope and the top surface of the subgrade affected by precipitation under natural conditions. Two TDR sensors were buried in two layers in the subgrade with a filling height of 15 m, as shown in Figure 6(a). The sensor positions along the direction of the cross section of the subgrade are 1 and 2 m away from the subgrade slope. The initial moisture content of the in situ soil was taken while the two TDR sensors were being buried, and the initial data were taken after the instrument readouts have been stable for 4 hours. During the on-site monitoring, the subgrade structure of the test section has experienced the rainy season from June to August and the dry season from September to November. The moisture content of the subgrade changes with the seasons, as shown in Figure 6(b).

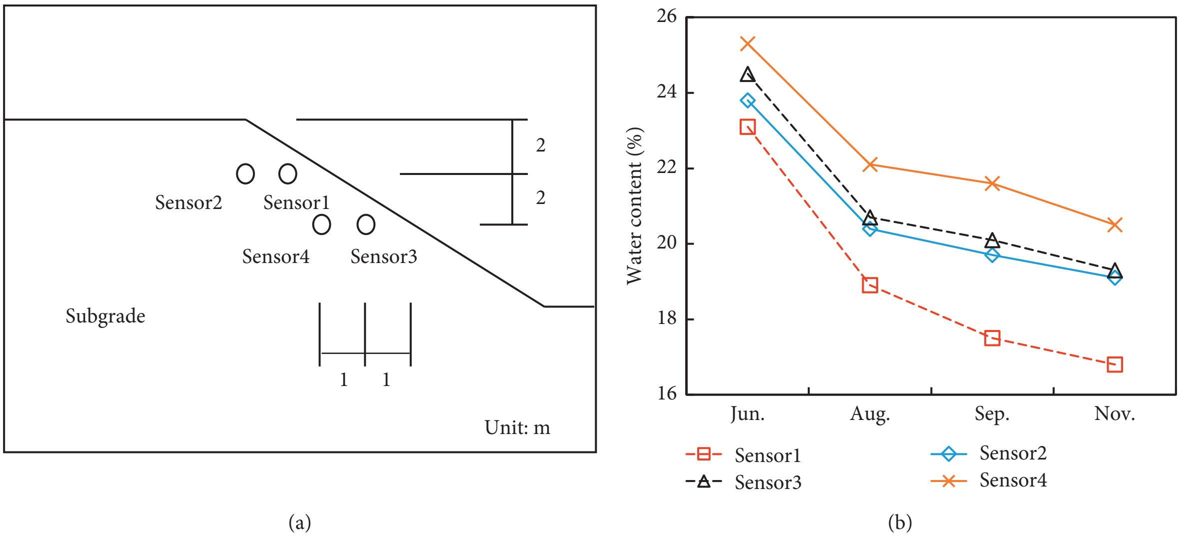
The monitoring data showed that the moisture content of the silt subgrade during the roadbed construction was large. After half a year of settlement, the soil was gradually drained and consolidated, and the moisture content of the subgrade section gradually decreased. The moisture content of observation points at a distance of 1 m from the slope is lower than that of observation points 2 m away from the slope because the soil near the slope surface is much susceptible to external weather conditions. These findings verified that the monitoring method determined by the laboratory calibration test is effective.



(a)

(b)

Figure 5: Influence of temperature on TDR sensor test results at the moisture of (a) 10.11%; (b) 18.83%.



(a)

(b)

Figure 6: Field (a) sensor layout plot and (b) moisture-time relationship of subgrade.

5. Conclusions

The structural strength and the agricultural productivity of soil are closely related to the moisture content. TDR sensors have been widely used in the agricultural production and service monitoring in the civil engineering. This study analyzed the influence of moisture content and dry density on the quality of testing sensors through laboratory calibration experiments. At the same time, taking a typical slope in the southern China as an example, a field study of the moisture content of the subgrade soil was carried out, and the periodic changes of the moisture content were tracked. The main findings of this paper are as follows:

(a) Changes in soil moisture content or dry density results in significant changes in soil dielectric constant and magnetic permeability. In TDR calibration, the dielectric constant and the electrical conductivity are used as intermediate variables. The results indicated that the coupling effect between the volumetric moisture content and the dry density of soil should be completely considered.

(b) Based on the principle of TDR, a calculation model for dielectric constant and electrical conductivity has been established. The model has a good fit effect and stability by comparing the calculated moisture content and actual results of soil samples.

(c) It provides a feasible means for the real-time monitoring of the moisture content on the side slope of the subgrade and has theoretical and engineering application significance. Through the model calibration, the influence law of moisture content and temperature on soil dielectric constant is analyzed. The quality of the model has been verified with the fitting goodness more than 90%.

(d) After half a year of settlement, since the soil was gradually drained and consolidated, the moisture content of the subgrade section gradually decreased. The test results shows that the soil near the surface of the slope was more susceptible to external weather conditions. It also verifies that the monitoring method determined by the laboratory TDR calibration test was successful.

Data Availability

The testing data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors gratefully acknowledge the National Key Research and Development Program of China (2019YFF0216804).

References

[1] J. Jiang, J. Wang, W. Wang, and W. Zhang, "Modeling influence of gas/liquid/solid three-phase boundary zone on cathodic process of soil corrosion," *Electrochimica Acta*, vol. 54, no. 13, pp. 3623–3629, 2009.

[2] J. Zhang, F. Li, L. Zeng, J. Peng, and J. Li, "Numerical simulation of the moisture migration of unsaturated clay embankments in southern China considering stress state," *Bulletin of Engineering Geology and the Environment*, vol. 80, no. 1, pp. 11–24, 2021.

[3] P. R. Ward, K. C. Flower, N. Cordingley, C. Weeks, and S. F. Micin, "Soil water balance with cover crops and conservation agriculture in a mediterranean climate," *Field Crops Research*, vol. 132, pp. 33–39, 2012.

[4] C. F. Chiu, W. M. Yan, and K.-V. Yuen, "Reliability analysis of soil-water characteristics curve and its application to slope stability analysis," *Engineering Geology*, vol. 135-136, pp. 83–91, 2012.

[5] W. Zhang, H. Zheng, F. Jiang, Z. Wang, and Y. Gao, "Stability analysis of soil slope based on a water-soil-coupled and parallelized smoothed particle hydrodynamics model," *Computers and Geotechnics*, vol. 108, pp. 212–225, 2019.

[6] Y. Lu and S. H. Liu, "Cracking in an expansive soil under freeze–thaw cycles," *Sciences in Cold and Arid Regions*, vol. 9, no. 4, pp. 392–397, 2018.

[7] Y. Yao, J. Ni, and J. Li, "Stress-dependent water retention of granite residual soil and its implications for ground settlement," *Computers and Geotechnics*, vol. 129, Article ID 103835, 2021.

[8] Z. Gao, Y. Zhu, C. Liu, H. Qian, W. Cao, and J. Ni, "Design and test of a soil profile moisture sensor based on sensitive soil layers," *Sensors*, vol. 18, no. 5, Article ID 1648, 2018.

[9] Q. Wang, X. e. Liu, S. Yang, M. Jiang, and J. Cao, "Non-destructive detection of density and moisture content of heartwood and sapwood based on X-ray computed tomography (X-CT) technology," *European Journal of Wood and Wood Products*, vol. 77, no. 6, pp. 1053–1062, 2019.

[10] Q. Kong, H. Chen, Y.-l. Mo, and G. Song, "Real-time monitoring of water content in sandy soil using shear mode piezoceramic transducers and active sensing-a feasibility study," *Sensors*, vol. 17, no. 10, Article ID 2395, 2017.

[11] X. Zhang, J. Zhang, L. Li, Y. Zhang, and G. Yang, "Monitoring citrus soil moisture and nutrients using an IoT based system," *Sensors*, vol. 17, no. 3, p. 447, 2017.

[12] K. Chandrasekaran and M. Senthilkumar, "Effect of herbal extract treatment on the moisture management properties of cotton knitted fabrics," *Journal of Natural Fibers*, vol. 17, no. 4, pp. 557–572, 2020.

[13] J. S. Whiteley, J. E. Chambers, S. Uhlemann, P. B. Wilkinson, and J. M. Kendall, "Geophysical monitoring of moisture-induced landslides: a review," *Reviews of Geophysics*, vol. 57, no. 1, pp. 106–145, 2019.

[14] Z. Yang, H. Cai, W. Shao et al., "Clarifying the hydrological mechanisms and thresholds for rainfall-induced landslide: in situ monitoring of big data to unsaturated slope stability analysis," *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 4, pp. 2139–2150, 2019.

[15] L. Ruiz Valero, V. Flores Sasso, and E. Prieto Vicioso, "In situ assessment of superficial moisture condition in façades of historic building using non-destructive techniques," *Case Studies in Construction Materials*, vol. 10, Article ID e00228, 2019.

[16] A. Ahmed, S. Hossain, M. S. Khan, and A. Shishani, "Data-based real-time moisture modeling in unsaturated expansive subgrade in Texas," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2672, no. 52, pp. 86–95, 2018.

[17] Y.-S. Yao, J.-L. Zheng, Z.-S. Chen, J.-H. Zhang, and Y. Li, "Field measurements and numerical simulations of temperature and moisture in highway engineering using a frequency domain reflectometry sensor," *Sensors*, vol. 16, no. 6, p. 857, 2016.

[18] E. Babaeian, M. Sadeghi, S. B. Jones, C. Montzka, H. Vereecken, and M. Tuller, "Ground, proximal, and satellite remote sensing of soil moisture," *Reviews of Geophysics*, vol. 57, no. 2, pp. 530–616, 2019.

[19] J. Li, J. Zheng, Y. Yao, J. Zhang, and J. Peng, "Numerical method of flexible pavement considering moisture and stress sensitivity of subgrade soils," *Advances in Civil Engineering*, vol. 2019, Article ID 7091210, 2019.

[20] J. Qian, Y. Yao, J. Li, H. Xiao, and S. Luo, "Resilient properties of soil-rock mixture materials: preliminary investigation of the effect of composition and structure," *Materials*, vol. 13, no. 7, p. 1658, 2020.

[21] Y. Yao, S. Luo, J. Qian, J. Li, and H. Xiao, "Soil-water characteristics of the low liquid limit silt considering compaction and freeze-thaw action," *Advances in Civil Engineering*, vol. 2020, Article ID 8823666, 2020.

[22] J. Pytka, P. Budzyński, M. Kamiński, T. Łyszczyk, and J. Józwik, "Application of the TDR soil moisture sensor for terramechanical research," *Sensors*, vol. 19, no. 9, Article ID 2116, 2019.

[23] G. C. Topp, J. L. Davis, and A. P. Annan, “Electromagnetic determination of soil water content: measurements in coaxial transmission lines,” *Water Resources Research*, vol. 16, no. 3, pp. 574–582, 1980.

[24] J. Ledieu, P. De Ridder, P. De Clerck, and S. Dautrebande, “A method of measuring soil moisture by time-domain reflectometry,” *Journal of Hydrology*, vol. 88, no. 3-4, pp. 319–328, 1986.

[25] F. Cui, Y. Du, J. Ni, Z. Zhao, and S. Peng, “Effect of shallow-buried high-intensity mining on soil water content in ningtiaota minefield,” *Water*, vol. 13, no. 3, p. 361, 2021.

[26] J. Zhang, A. Zhang, C. Huang, H. Yu, and C. Zhou, “Characterising the resilient behaviour of pavement subgrade with construction and demolition waste under Freeze-Thaw cycles,” *Journal of Cleaner Production*, vol. 300, Article ID 126702, 2021.

[27] J. Zhang, A. Zhang, J. Li, F. Li, and J. Peng, “Gray correlation analysis and prediction on permanent deformation of subgrade filled with construction and demolition materials,” *Materials*, vol. 12, no. 18, p. 3035, 2019.

[28] H. Bhuyan, A. Scheuermann, D. Bodin, and R. Becker, “Use of time domain reflectometry to estimate moisture and density of unbound road materials: laboratory calibration and field investigation,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2655, no. 1, pp. 71–81, 2017.

[29] G. Curioni, D. N. Chapman, A. C. D. Royal et al., “Time domain reflectometry (TDR) potential for soil condition monitoring of geotechnical assets,” *Canadian Geotechnical Journal*, vol. 56, no. 7, pp. 942–955, 2019.

[30] Z. Tian, T. Ren, Y. Kojima, Y. Lu, R. Horton, and J. L. Heitman, “An improved thermo-time domain reflectometry method for determination of ice contents in partially frozen soils,” *Journal of Hydrology*, vol. 555, pp. 786–796, 2017.

[31] J. Li, J. Zhang, G. Qian et al., “Three-dimensional simulation of aggregate and asphalt mixture using parameterized shape and size gradation,” *Journal of Materials in Civil Engineering*, vol. 31, no. 3, Article ID 04019004, 2019.

[32] IHSMT, *Test Methods of Soils for Highway Engineering (JTG 3430-2020)*, Beijing, China, 2021.