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TDR-200 Soil Moisture Meter: Measurement Accuracy Verification

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Abstract

This reference document describes a procedure that was employed to verify the accuracy of a time domain reflectometry (TDR) based soil moisture meter. The operating principles of this soil moisture meter are discussed, as well as the experimental setup and results. The results indicate that this soil moisture meter performs within the manufacturer's specifications when used in sand.

Résumé

Ce document de référence décrit une procédure utilisée pour vérifier l'exactitude d'un humidimètre de sol basé sur la réflectométrie temporelle (TDR). Les principes de fonctionnement de cet humidimètre de sol sont discutés, ainsi que le montage expérimental et les résultats. Les résultats indiquent que cet humidimètre de sol est conforme aux spécifications du fabricant lorsqu'il est utilisé dans le sable.

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1 Introduction

The TDR-200, manufactured by Spectrum Technologies, is a device that employs Time Domain Reflectometry (TDR) to measure the volumetric water content (VWC) of soils. The meter operates by sending an electrical pulse lengthwise along two metal probes and measuring the reflection time, τ, of the pulse. The TDR-200 comes with different probe lengths, which allows the meter to survey different soil depths.

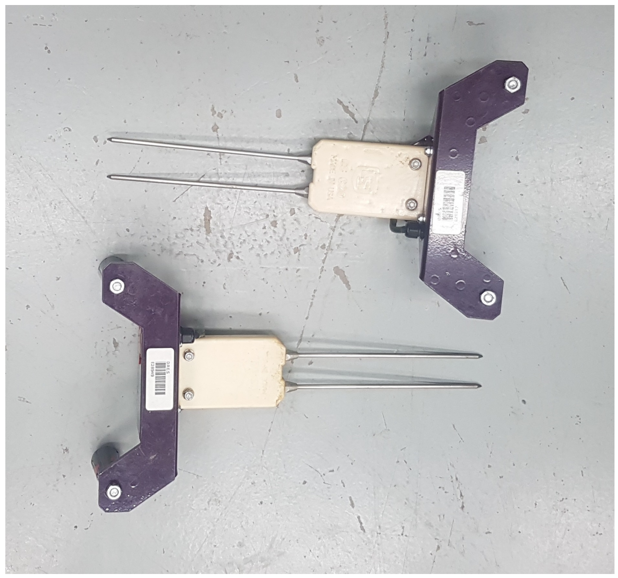

Figure 1: *Two TDR-200s, Top view.*

There is a requirement to use two TDR-200 meters, pictured in Figure 1, in support of explosive hazard detection projects. However, the soil moisture meters had not been used for many years and it was not known whether these meters still performed within the manufacturer's specifications.

In this report, TDR-200 VWC measurements were compared to VWC calculated by a gravimetric analysis of sand samples. The first trial tested the accuracy of the TDR-200 across a large range of VWC values, and the second trial tested the variability of the TDR-200 measurements with a relatively dry sand, 10 % VWC sand, and 20 % VWC sand. The TDR-200 readings were then compared to the ± 3 % VWC error listed in the device's specification sheet, where it was determined that the TDR-200s performed within these specifications when used in sand.

2 Theory

TDR technology has broad applications. For instance, it can be used in electrical systems to find faults or wiring problems. An electrical pulse can be sent along a transmission line, and reflections can be observed when the travelling wave encounters an impedance mismatch [1]. Large reflections may indicate that the transmission line is damaged. This concept has been used in aircraft wiring integrity verification [2].

TDR can also be used in soil water content measurement. If metallic probes are inserted into the soil, there is a high impedance mismatch where the metal contacts the soil. An electrical pulse can be sent along the probe and the reflection time of the pulse can be measured. This reflection time is dependent on the dielectric constant of the soil, which itself is dependent on soil characteristics such as water content.

For soils with a low conductivity, and when considering electromagnetic wave frequency on the order of 100 MHz, the wave propagation velocity along the metal probes, v, can be approximated by

$$\mathrm{v} = \frac{2L}{\tau} \cong \frac{1}{\sqrt{\mu \epsilon_{bulk} \mu_0 \epsilon_0}}, \tag{1}$$

where L is the probe length, τ is the time the pulse takes to travel 2L, μ_0 is the magnetic permittivity of free space, ϵ_0 is the dielectric permittivity of free space, μ is the relative permeability of the soil, and ϵ_{bulk} is the real part of the bulk dielectric permittivity of the material [3].

Since $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ [3], and the typical relative magnetic permeability of soil, μ, is 1 [4], equation (1) can be simplified to

$$\mathrm{v} \cong \frac{c}{\sqrt{\epsilon_{bulk}}}. \tag{2}$$

By combining equations (1) and (2), we obtain

$$\epsilon_{bulk} \cong \frac{c^2}{v^2} = \frac{c^2}{\left(\frac{2L}{\tau}\right)^2} = \frac{c^2 \tau^2}{4\mathrm{L}^2}. \tag{3}$$

In this way, the approximate real dielectric permittivity can be calculated when the probe length L and reflection time τ are known. Since dry soil typically has a dielectric permittivity of 3–5 and water has a dielectric permittivity of 81 [5], the dielectric permittivity of the water easily dominates the dielectric permittivity of wet soils [3].

A correlation can be therefore be drawn between dielectric permittivity and VWC, and this is how the TDR-200 is internally calibrated. Some calibrations take into account factors such as soil bulk density, soil texture, or temperature [3]. Other calibrations consider the soil a mixture of materials with different dielectrics, including solids, air, free water, and bound water [3].

3 Trial 1

3.1 Setup

The sand used in these trials was washed playsand, which is intended for use in sandboxes and playgrounds. First, this sand was prepared and placed in a bucket reservoir. Rocks larger than 7 mm were filtered out of the sand, and any clumps were crushed before being placed in the reservoir.

A 4 L glass jar was filled with sand from the reservoir. A jar of this size was chosen since its 25 cm height allows the 20 cm TDR-200 probes to fit while leaving a few centimetres of sand at the bottom of the jar to mitigate possible edge effects. A small 100 mL sand sample was extracted from the top of the jar, and this sample was weighed and heated at 110 °C in accordance with ASTM D2216-10 [6]. ASTM D2216-10 does not specify a drying time, so an 18 hour drying time was chosen, as it was convenient for scheduling purposes. The gravimetric water content (GWC) of this sample, u, was determined using the formula [7]

$$u = \frac{m_{initial} - m_{final}}{m_{initial}}, \tag{4}$$

where $m_{initial}$ is the initial soil sample mass and m_{final} is the mass of the baked soil sample.

VWC, θ, was calculated using the formula [7]

$$\theta = u\left(\frac{\rho_{sand}}{\rho_{water}}\right) = u\left(\frac{m_{sand}}{\mathrm{v}_{sand}}\right), \tag{5}$$

where ρ_{sand} is the measured bulk density of the sand, $\rho_{water} = 1.00$ is the density of water, m_{sand} is the mass of the sand in the jar, and v_{sand} is the volume of sand in the jar. For Trial 1, the density of the extracted sample was used in calculations instead of the bulk density of the sand in the jar.

The two TDR-200 meters were arbitrarily named "TDR A" and "TDR B." Measurements were taken with both meters using the built-in averaging function. This function allows the user to take multiple measurements, for which the TDR-200 calculates the average VWC to the nearest whole number. The TDR-200 was inserted in the sand, kept stationary, and the average value of 10 data points was taken. Then, the TDR-200 was removed and the sand jar was shaken to eliminate air gaps that could affect the next reading.

When required, a 10 mL graduated cylinder was used to add water to the jar. One TDR-200 measurement was taken for each added water value in the 0-520 mL range, and in the 570 mL-1020 mL range, two measurements were collected for each added water value. The new VWC, θ_{new}, was then extrapolated from the previous VWC, θ_{old}, using the formula

$$\theta_{new} = \theta_{old} + \frac{\mathrm{v}_{aw}}{\mathrm{v}_{s}},$$

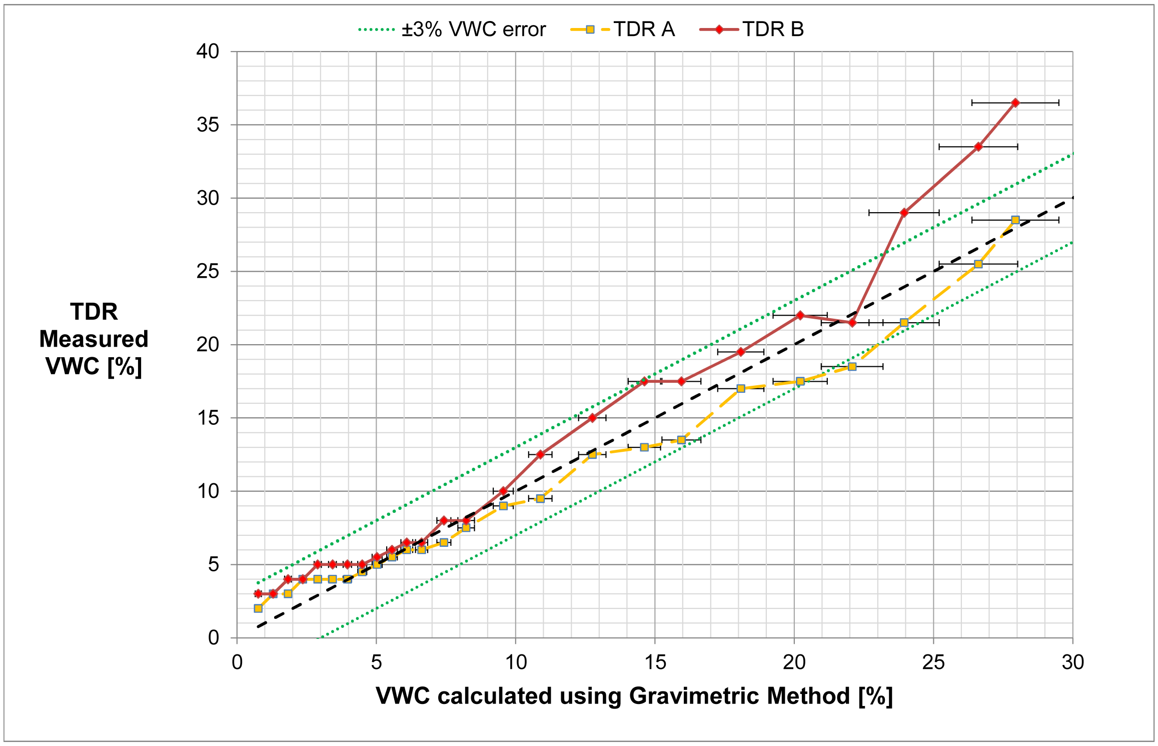

Figure 2: *TDR-200 VWC measurements as a function of calculated VWC for Trial 1.*

where v_{aw} is the volume of added water. Thus, calculated VWC was recorded and compared to the VWC reading of the TDR-200 meters.

3.2 Results and Analysis

The data collected in the first trial is tabulated in Table A.1. The results shown in Figure 2 indicate that, within the 0-20 % VWC range, both meters perform within the manufacturer reported specifications. However, the relative error of the calculated VWC values is high since the VWC value is extrapolated from a single GWC measurement. Also, no more than two VWC measurements were taken from each TDR-200, which meant that the variability of the TDR-200 measurements in a fixed VWC soil had not been characterized. A second trial was designed primarily to address these concerns.

Additionally, a number of sources of error in the first trial were addressed in Trial 2. TDR technology performs best in a homogeneous soil [8]. However, due to the fact that the 4 L glass jar had approximately 3.7 L of sand in it prior to the addition of any water, mixing by shaking or tumbling was difficult, so it was unknown whether the water was homogeneously distributed throughout the soil. In fact, it was observed that the water failed to permeate the outer layer of sand in the jar until 520 mL of water were added. Furthermore, the trial took approximately three hours, which would also promote water settling at the bottom of the jar, making the sand less homogeneous. The relatively long trial time could also promote water evaporation when the glass jar was exposed to the air. Moreover, when the 4 L jar had over 800 mL of added water, the jar lid failed to close properly, and shaking and mixing the jar led to a total loss of approximately 5 mL of water. An improved mixing method was used in the second trial to rectify this problem.

As far as determining the true initial VWC, the change in mass of the 100 mL dry sand sample was 0.76 g, which is a small value relative to the range of the scale that was used, which had a maximum capacity of 8000 g. A larger volume of sand was extracted for the drying procedure in the second trial to address this. Alternatively, a more accurate scale could be used in the future.

4 Trial 2

4.1 Setup

In this trial, 4 L glass jars full of dry sand, 10% VWC sand, and 20% VWC sand were prepared.

First, as before, sand was filtered for large rocks and clumps and placed in a large bucket reservoir. Then, 4 L of sand from this reservoir was added to a 15 L metal bucket, and the desired quantity of water was added. This bucket was tumbled for 6 minutes. The resulting homogenous sand was used to fill a 4 L glass jar, and measurements were taken with the TDR-200 meters. Afterwards, the first few inches of sand were removed to ensure that surface water evaporation did not contribute to a lower calculated VWC. Then, 300-500 mL samples were extracted from each sand jar, and the sand was heated at 110 °C for 18 hours. Additionally, after the samples were heated for 18 hours and weighed, they were heated a second time for another 24 hours to determine whether they could be dried further.

Six measurements were taken for each sand jar. Prior to each measurement, the 4 L jar was shaken to remove air gaps, the TDR-200 probes were inserted into the sand and one data point was collected by taking the average of 10 points using the TDR-200's built-in averaging function. The probes were then removed and the process was repeated for each subsequent measurement. The sand volume at the beginning and end of the trial was marked along the side of the glass jar, and the volume at these two points was measured by adding water to the jar and calculating how much water was added. The average of these two volume values was used in density calculations. The gravimetric and volumetric water content calculations were done in a similar manner as before. However, unlike in Trial 1, the bulk density of the sand in the jar was used for density calculations instead of the density of the extracted sand sample.

4.2 Results and Analysis

The measurements taken with the dry, 10% VWC, and 20% VWC sand are recorded in Table A.2. Figure 3 shows TDR measured VWC as a function of Gravimetric VWC. The results of this trial indicate that the TDR-200 meters are within the ±3 % VWC error specifications in the 0–20 % VWC range. The change in mass for the sand sample when the sand was allowed to dry for an additional 24 hours was negligible, which indicates that the 18 hour period was adequate. The sample masses listed in Table A.2 were measured after the first 18 hour drying period.

The methods used to measure the amount of water to be added to the sand jar could be improved. A 10mL graduated cylinder was used to measure and add water to the jar in the first trial, and in the second trial, water was weighed in a plastic cup and added to the jar. A pipette may be a more accurate way of measuring water volume, and could be used in the future.

Figure 3 shows TDR-200 VWC measurements as a function of VWC calculated using the gravimetric method.

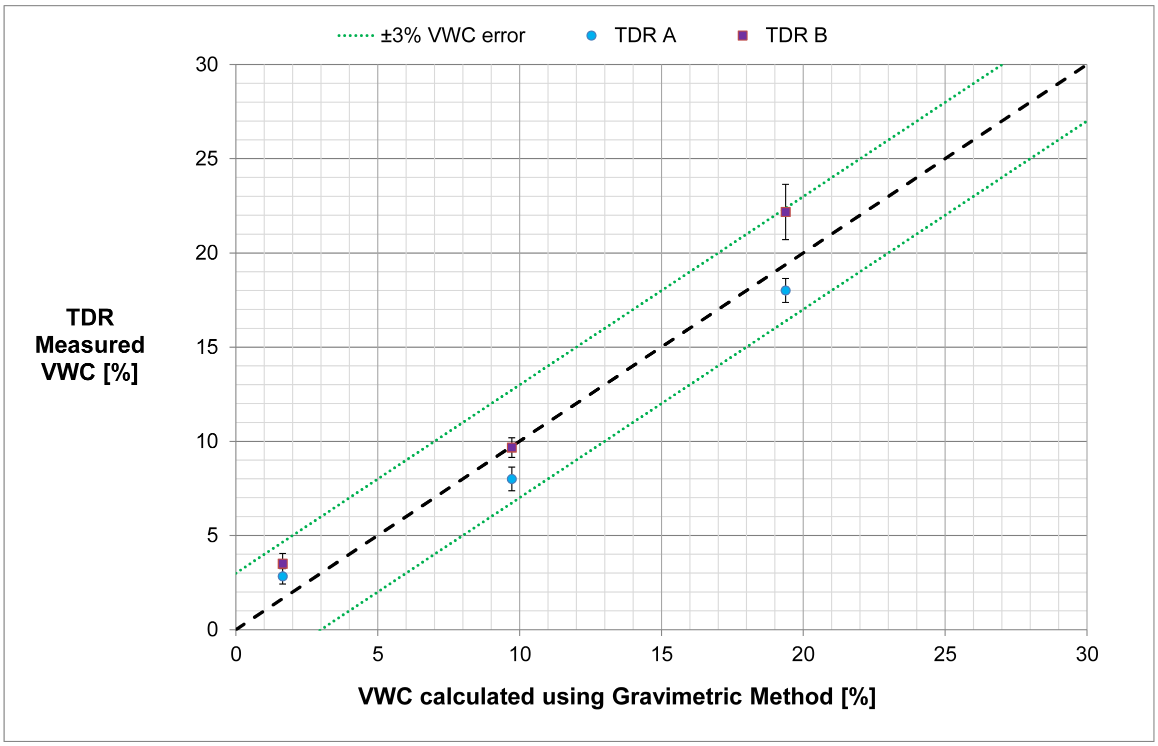

Figure 3: *TDR-200 VWC measurements as a function of calculated VWC for Trial 2.*

5 Conclusion

In this experiment, the manufacturer reported accuracy of two TDR-200 meters was verified by comparing VWC values measured using a TDR-200 soil moisture meter to VWC values calculated through gravimetric analysis of sand samples. It was determined that the two meters met the manufacturer's specifications when used in sand. If ±3 % accuracy is sufficient for the application, the TDR-200 meters are an appropriate choice. Future trials could investigate the behavior of the TDR-200 meters in other soils of interest, such as clay or loam.

A feature of interest in newer TDR-200 models is the period mode, in which the meter outputs the reflection time, τ, instead of VWC. The manual for the TDR-200 suggests preparing soil samples of known VWC, measuring the period with the device, and performing a linear regression in order to obtain a soil-specific calibration if high accuracy is needed. A calibration procedure could be created based on the trials performed in this experiment.

Future trials could investigate how meter and soil properties affect VWC measurement. Bent probes are known to cause lower VWC readings, as the probes create air gaps in the soil when inserted [9], but in our case, TDR B, which had slightly bent probes, had consistently higher readings than TDR A. The probes could be repaired prior to future trials or the impact of probe deformation could be examined. Additionally, temperature is known to be a significant factor in TDR soil moisture measurement [10]. This parameter was not accounted for in this trial series, and so the impact of temperature on measured VWC could be researched further.

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Annex A Data

Table A.1: *Trial 1 Results.*

Bold *indicates θ value measured according to the ASTM D2216-10 standard.*

Gravimetric Measurement				**TDR-200 VWC Measurements**			
v_{aw} [mL]	$\sigma_{v_{aw}}$ [mL]	θ [%]	σ_θ [%]	θ_A [%]	$\theta_A - \theta$	θ_B [%]	$\theta_B - \theta$
0.0	-	**0.76**	0.11	2	1.24	3	2.24
20.0	0.3	1.30	0.11	3	1.70	3	1.70
40.0	0.8	1.83	0.12	3	1.17	4	2.17
60.0	1.0	2.36	0.12	4	1.64	4	1.64
80.0	1.2	2.90	0.13	4	1.10	5	2.10
100.0	1.4	3.43	0.14	4	0.57	5	1.57
120.0	1.6	3.96	0.15	4	0.04	5	1.04
140.0	1.7	4.49	0.16	4	0.01	5	0.51
160.0	1.9	5.03	0.18	5	-0.03	5	0.47
180.0	2.0	5.56	0.19	5	-0.06	6	0.44
200.0	2.1	6.09	0.21	6	-0.09	6	0.41
220.0	2.2	6.63	0.22	6	-0.63	6	-0.13
220.0	2.2	6.63	0.22	5	-1.13	5	-1.13
250.0	3.8	7.43	0.25	6	-0.93	8	0.57
280.0	4.8	8.22	0.30	7	-0.72	8	-0.22
330.0	5.7	9.56	0.36	9	-0.56	10	0.44
380.0	6.4	10.89	0.42	9	-1.39	12	1.61
450.0	7.1	12.75	0.49	12	-0.25	15	2.25
520.0	9.3	14.62	0.58	13	-1.62	17	2.88
570.0	11.0	15.95	0.70	14	-1.95	18	2.05
570.0	11.0	15.95	0.70	13	-2.95	17	1.05
650.0	12.6	18.08	0.83	17	-1.08	20	1.92
650.0	12.6	18.08	0.83	17	-1.08	19	0.92
730.0	13.9	20.22	0.97	18	-2.22	22	1.78
730.0	13.9	20.22	0.97	17	-3.22	22	1.78
800.0	15.2	22.08	1.11	19	-3.08	21	-1.08
800.0	15.2	22.08	1.11	18	-4.08	22	-0.08
870.0	16.3	23.95	1.26	21	-2.95	29	5.05
870.0	16.3	23.95	1.26	22	-1.95	29	5.05
970.0	17.4	26.61	1.41	26	-0.61	33	6.39
970.0	17.4	26.61	1.41	25	-1.61	34	7.39
1020.0	18.4	27.94	1.56	28	0.06	37	9.06
1020.0	18.4	27.94	1.56	29	1.06	36	8.06

Table A.2: *Trial 2 results.*

(a) *Sand with no added water*

Gravimetric Measurement			**TDR-200 VWC Measurements**		
		±		TDR A	TDR B
Mass of sand in jar	6035.7 g	0.1 g		2	3
Mean sand volume in jar	3716.7 g	0.1 g		3	4
Density	1.624 g/mL	0.003 g/mL		3	3
				3	3
Sample, $m_{initial}$	867.7 g	0.1 g		3	4
Sample, m_{final}	858.9 g	0.1 g		3	4
Sample, Δm	8.8 g	0.1 g			
			Mean	2.83	3.50
GWC [%]	1.014 %	0.016 %	Standard deviation	0.41	0.55
VWC [%]	1.647 %	0.027 %			

(b) *10% VWC sand*

Gravimetric Measurement			**TDR-200 VWC Measurements**		
		±		TDR A	TDR B
Mass of sand in jar	5909.0 g	0.1 g		9	10
Mean sand volume in jar	3697.9 g	0.1 g		8	10
Density	1.598 g/mL	0.003 g/mL		8	9
				7	9
Sample, $m_{initial}$	603.79 g	0.02 g		8	10
Sample, m_{final}	567.04 g	0.02 g		8	10
Sample, Δm	36.75 g	0.03 g			
			Mean	8.00	9.67
GWC [%]	6.087 %	0.005 %	Standard deviation	0.63	0.52
VWC [%]	9.726 %	0.027 %			

Table A.3: *Trial 2 results, continued.*

(c) *20% VWC sand sample*

Gravimetric Measurement			**TDR-200 VWC Measurements**		
		±		TDR A	TDR B
Mass of sand in jar	6814.4 g	0.1 g		17	22
Average sand volume in jar	3726.8 g	0.1 g		18	23
Density	1.828 g/mL	0.003 g/mL		18	21
				18	24
Sample, $m_{initial}$	547.32 g	0.02 g		18	23
Sample, m_{final}	489.32 g	0.02 g		18	20
Sample, Δm	58.00 g	0.03 g			
			Mean	18.00	22.17
GWC	10.60 %	0.02 %	Standard deviation	0.63	1.47
VWC	19.38 %	0.05 %			

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