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Comparison of laboratory TDR soil water measurements

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ABSTRACT

Reliable soil moisture sensors are essential for agricultural application. Time Domain Reflectometry (TDR) is a useful method for nondestructive, continuous measurements of soil water content. Laboratory measurements of soil volumetric water content by the TDR 100 Time Domain Reflectometer were compared to gravimetric measurements in three soils, Clay Loam, Silt Loam and Sand soil. Comparison between original and homemade 10 cm and 20 cm rods was made. TDR 100 gave good results in Clay Loam and Silt Loam soil and over estimated VWC in Sand soil. Results showed little or no difference between original and homemade sensor measurements.

Key words: volumetric water content, soil moisture sensor, TDR

IZVLEČEK

PRIMERJAVA LABORATORIJSKIH MERITEV VODE V TALNEM SUBSTRATU S TDR

Zanesljivi senzorji za merjenje vlage v tleh so v kmetijstvu nujni. Time Domain Reflectometry (TDR) je metoda, ki omogoča kontinuirano merjenje vlage v tleh brez rušenja talnega profila. Laboratorijske meritve volumske vsebnosti vode, izvedene s TDR 100 Reflectometrom, smo primerjali z gravimetrično metodo v glinasto ilovnatih, meljasto ilovnatih ter peščenih tleh. Primerjali smo meritve narejene z izvirnimi ter doma narejenimi 10 cm in 20 cm sondami. TDR 100 je pokazal dobre rezultate v glinasto ilovnatih in meljasto ilovnatih tleh, v peščenih tleh so bile izmerjene vrednosti višje od standarda. Rezultati kažejo malo ali nič razlik med meritvami, opravljenimi z izvirnimi in doma narejnimi sondami.

Ključne besede: volumska vsebnost vode, senzor za merjenje vlage v tleh, TDR

1 INTRODUCTION

Many plant-soil-water and hydrological investigations depend on accurate measurement of soil water content. Often undergoing study of the processes requires continuous measurement. Time Domain Reflectometry (TDR) became known as a

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useful method for nondestructive, continuous measurements of soil water content and bulk electrical conductivity in the 1980s (Evett, 2000, Chandler et al, 2004). After being used for telecommunications industry, Topp et al (1980) applied the TDR method for measurement of the apparent dielectric constant of soil K_a, which is strongly dependent on water content. With TDR the apparent soil dielectric constant K_a is measured and related to soil volumetric water content (VWC) using a calibration equation (Chandler et al, 2004). Topp et al (1980) demonstrated that TDR could measure water content with an accuracy of better that 2% VWC and that a single calibration equation could be applied to nearly all soils (Baker and Allmaras, 1990). Automated TDR systems for water content measurement were described by Baker and Allmaras (1990), Heimovaara and Bouten (1990), Herkelrath et al (1991) and Noborio (2001).

TDR is an electromagnetic method in which the applied signal is guided along a transmission line though a soil sample. Most TDR systems currently used for soil measurements apply a fast rise time electromagnetic pulse to the soil transmission line. The time delay between the reflections of the pulse from the beginning and end of the soil transmission line is used to determine the velocity of propagation through the soil along the transmission line (Topp and Ferré, 2002).

In spite of the TDR method's long-standing presence on the market and application in practice, the equipment is still costly and the shipment time consuming. The aim of this study was to compare the measurements of the TDR 100 Time Domain Reflectometer using original and homemade parts.

2 MATERIALS AND METHODS

2.1 Materials

The TDR 100 Time Domain Reflectometer is a connector-type TDR sensor, which generates a very short rise time electromagnetic pulse that is applied to a coaxial system. The coaxial system includes a TDR probe for soil water measurements and samples and digitises the resulting reflection waveform for analysis or storage (Figure 1). The elapse travel time and pulse reflection amplitude contain information used by the on-board processor to quickly and accurately determine soil volumetric water contents (VWC) (Campbell Scientific, 2004). These sensors are reported to have the same area of influence and accuracy specifications as the buriable-type sensors, which are directly attached to a cable. The connector-type TDR sensors consist of two 6 mm diameter waveguides – steel rods - that are inserted from the soil surface. The rods are connected to the cable with clamps. Given the design and diameter of these waveguides, they could be inserted from the surface into undisturbed soil without pre-forming holes, even under relatively dry soil conditions.

The vertically inserted connector-type TDR sensors provide average soil moisture measurement over range of 0–10 and 0–20 cm, being the length of the waveguides used. While this technique can be automated, in this application measurements were made on experiment basis, simultaneously as measurements with other sensors.

Also, original steel rods of 10 and 20 cm length (TDR 100 10a and 20a), provided by the TDR 100 producer Soil Moisture were reproduced from the same material in exact same dimensions (TDR 100 10b and 20b).

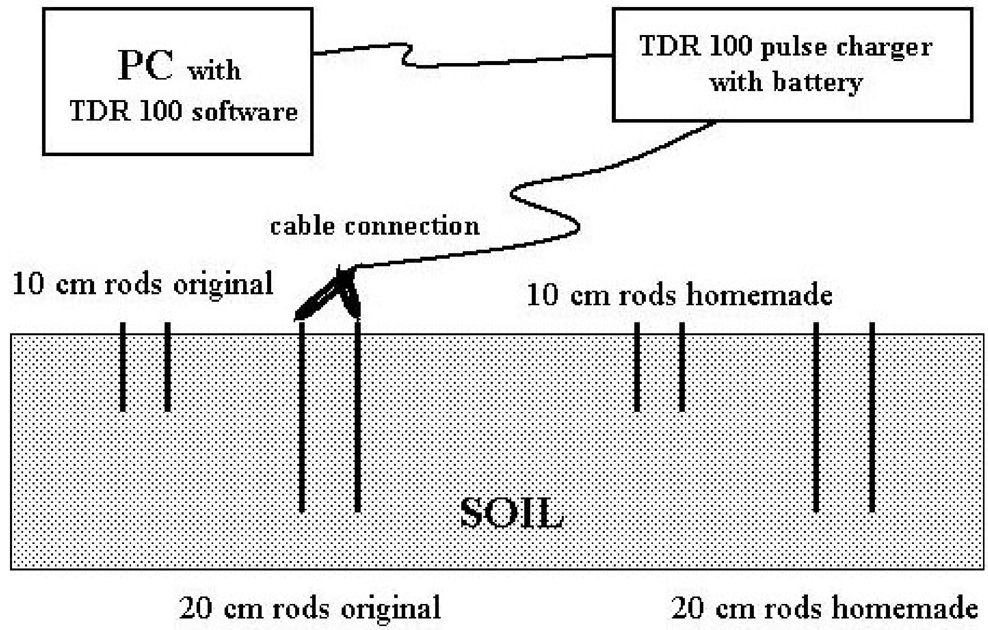

Figure 1: Scheme of TDR 100 experiment set, connections of PC with TDR 100 software via cable to TDR 100 pulse charger and battery to TDR rods via clasps.

2.2 Methods

The differentially driven probe rods form a transmission line with a wave propagation velocity that is dependent on the dielectric permittivity of the medium surrounding the rods. Nanosecond rise-times produce waveform reflections characteristic of an open-ended transmission line (Campbell Scientific, 2004). The TDR method relies on graphical interpretation of the waveform reflected from that part of the waveguide that is the probe (Figure 2) (Evett, 2000, Noborio, 2001). The return of the reflection from the ends of the rods triggers a logic state change, which initiates propagation of a new wave front.

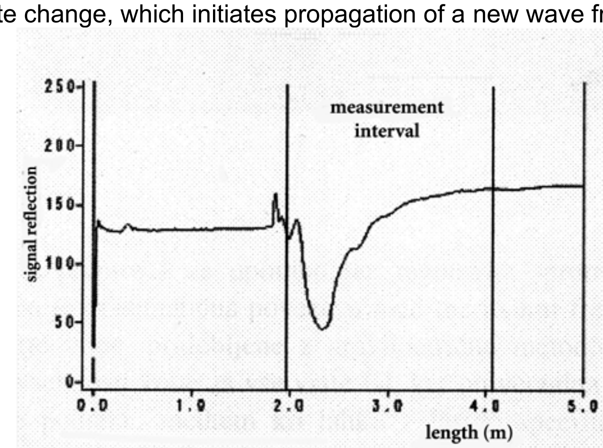

Figure 2: Graphic output on the PC screen for the TDR 100 Time Domain Reflectometer measurements. Lines define the measurement interval of the waveform as recommended by the producer (Campbell Scientific, 2004).

Since water has a dielectric permittivity significantly larger (ε_r (H_2O) ≈ 80) than other soil constituents, air (ε_r (Air) ≈ 0) and the solid phase (ε_r (Solid) ≈ 4) (Curtis and Defandorf, 1929), the resulting oscillation frequency is dependent upon the average water content of the medium surrounding the rods. Rods can be inserted from the surface or the probe can be buried at any orientation to the surface (Campbell Scientific, 2004). The measurement frequency for the water content reflectometer (WCR) varies with VWC and is generally between 15 and 45 MHz (Seyfried and Murdock, 2001).

Laboratory experiment was set at the Center for agricultural land management and agrohydrology, Biotechnical Faculty, University of Ljubljana, Slovenia. Three different soils were used, clay loam, silt loam soil and sand. Each soil was moistened on four different soil Volumetric Water Contents (VWC) and packed in a box. Rods were carefully inserted vertically in the soil 5 cm apart. For each VWC six consecutive readings were made.

3 RESULTS AND DISCUSSION

TDR 100 Reflectometer VWC measurements from 10 cm and 20 cm rods were evaluated, original and replicated, and compared the results with gravimetrically determined VWC (gVWC). Gravimetric method is a standard method for soil water content determination (Topp and Ferré, 2002). Tables 1 – 3 show results of soil VWC measurements in the three soils used in the experiment for the four different water contents (average VWC of six repetitive readings for every individual soil VWC, coefficient of variation (CV), standard deviation, min and max as well as range are given for each waveguide pair, with TDR 100 10a and 20a being labels for original rods; TDR 100 10b and 20b for homemade rods).

For interpretation of the TDR 100-10 waveguide for Clay Loamy Soil (Figure 2), broader measurement interval than manufacturer’s recommendation was taken. Measurement interval determination for individual soil type is extremely important (Evett, 2000) and the TDR 100 sensor construction enables manual manipulation. For the measurement interval determination tangent crossings on the waveguide, best representing the beginning and final pulse reflection, were used.

10b gave the best results for the first measurement (15.9% gVWC ±0.84). Original 20a rods showed the biggest deviation from the gVWC (±4.4%). All the rods 10 and 20 cm underestimated VWC in the second measurement (21.1% gVWC ±1.74) as well as in the third measurement (22.3% gVWC ±1.07), thou 10a and 10b gave better results. For the fourth measurement, the best agreement with (37.1% gVWC ±1.87) showed 10a rods (Table 1).

Table 1: Measurements of soil VWC TDR 100 Time Domain Reflectometer for four different soil water contents with average VWC, coefficient of variation (CV), standard deviation, min and max as well as range for Clay Loam soil.

	Measurement	TDR 100-10a	TDR 100-10b	TDR 100-20a	TDR 100-20b
Average VWC	1	16.81	18.58	7.82	11.57
	2	15.88	19.30	14.04	15.20
	3	20.75	20.91	17.10	17.80
	4	36.34	39.56	32.99	34.54
CV	1	0.02	0.39	0.00	0.05
	2	3.05	0.47	0.01	0.02
	3	0.62	0.11	0.01	0.03
	4	0.02	0.02	0.01	0.00
Standard deviation (VWC)	1	0.15	0.62	0.03	0.22
	2	1.75	0.69	0.09	0.14
	3	0.79	0.33	0.11	0.16
	4	0.14	0.13	0.10	0.06
Minimum	1	16.61	18.00	7.79	11.40
	2	14.89	18.66	13.96	15.08
	3	20.18	20.67	16.98	17.66
	4	36.13	39.39	32.84	34.45
Maximum	1	16.97	19.52	7.86	11.94
	2	19.00	20.07	14.14	15.45
	3	22.14	21.47	17.27	18.00
	4	36.50	39.72	33.06	34.61
Range	1	0.36	1.52	0.07	0.54
	2	4.11	1.41	0.18	0.37
	3	1.96	0.80	0.29	0.34
	4	0.37	0.33	0.22	0.16

In Silt Loam soil all probes gave satisfactory results for the first measurement (13,5% gVWC ±2.49), 10b being the exception with 5.3% VWC deviation. For the second measurement (21% gVWC ±2.03) the best results gave 10a rods with only 1.2% VWC deviation. In the third measurement (34.1% gVWC ±1.25) all rods gave lower values than those determined by Gravimetric method. 10a rods deviated for 1.8% VWC and 10b 2.8% VWC and 20a 2% VWC. 20a rods showed big standard deviation ±1.61. Both 10a and 10b gave good results for the fourth measurement (42.6% gVWC ±0.45). 10a deviated for 0.7% VWC and 10b for 1.7% (Table 2).

Table 2: Measurements of soil VWC TDR 100 Time Domain Reflectometer for four different soil water contents with average VWC, coefficient of variation (CV), standard deviation, min and max as well as range for Silt Loam soil.

	Measurement	TDR 100-10a	TDR 100-10b	TDR 100-20a	TDR 100-20b
Average VWC	1	13.57	18.75	9.54	12.47
	2	22.21	23.84	17.53	18.84
	3	32.28	32.03	32.08	31.67
	4	43.23	44.28	35.07	35.08
CV	1	0.82	0.07	0.01	0.01
	2	0.04	0.01	0.00	0.01
	3	0.47	0.04	2.59	0.13
	4	0.01	0.02	0.09	0.01
Standard deviation (VWC)	1	0.91	0.26	0.09	0.09
	2	0.21	0.08	0.05	0.08
	3	0.69	0.20	1.61	0.36
	4	0.08	0.12	0.30	0.10
Minimum	1	12.96	18.72	9.44	12.37
	2	21.97	23.76	17.47	18.76
	3	31.91	31.94	31.17	31.28
	4	43.18	44.15	34.93	35.02
Maximum	1	13.20	18.91	9.54	12.57
	2	22.40	23.94	17.51	18.90
	3	33.44	32.27	34.93	31.73
	4	43.34	44.23	35.03	35.08
Range	1	0.24	0.19	0.10	0.20
	2	0.43	0.18	0.04	0.14
	3	1.53	0.33	3.76	0.45
	4	0.16	0.08	0.10	0.06

For Sand soil the results were less satisfactory. In the first measurement (4.2% gVWC ±0.46) 10a rods' results deviated for 6.6% VWC, 10b deviated for 6.3% VWC. Standard deviations were low for all the rods with exception for 10b with standard deviation of ±0.47. In the second measurement (9.2% gVWC ±0.7) all rods highly overestimated the VWC, 10a for 4.5% VWC and 10b for 4.6% VWC. The rods overestimated the VWC in the third measurement (16.4% gVWC ±1.26) as well, 10a giving the highes estimated and deviated for 5.2% VWC (Table 3).

Table 3: Measurements of soil VWC TDR 100 Time Domain Reflectometer for four different soil water contents with average VWC, coefficient of variation (CV), standard deviation, min and max as well as range for Sand soil.

	Measurement	TDR 100-10a	TDR 100-10b	TDR 100-20a	TDR 100-20b
Average VWC	1	10.56	9.62	6.78	6.66
	2	15.38	15.20	12.81	12.29
	3	19.30	21.27	18.51	18.55
	4	37.97	37.86	33.24	33.42
CV	1	0.22	0.02	0.03	0.00
	2	0.06	0.01	0.09	0.00
	3	0.01	0.03	0.01	0.01
	4	0.01	0.01	0.01	0.02
Standard deviation (VWC)	1	0.47	0.15	0.18	0.06
	2	0.24	0.12	0.30	0.04
	3	0.08	0.16	0.07	0.12
	4	0.08	0.11	0.07	0.13
Minimum	1	9.76	9.42	6.66	6.56
	2	15.15	15.03	12.33	12.24
	3	19.20	21.00	18.40	18.40
	4	37.87	37.74	33.18	33.32
Maximum	1	10.93	9.75	7.09	6.72
	2	15.76	15.35	13.04	12.34
	3	19.40	21.40	18.59	18.65
	4	38.07	37.98	33.36	33.65
Range	1	1.17	0.33	0.43	0.16
	2	0.61	0.32	0.71	0.10
	3	0.20	0.40	0.19	0.25
	4	0.20	0.24	0.18	0.33

Results of VWC measurements of original and replicated rod sets were compared with gravimetrically determined VWC (Figures 3 – 14). Compared is the distribution of the TDR measurements against gVWC (dotted line is 1:1 line, which represents ideal situation). For Clay Loam soil original and replicated rods produced very similar results, thou there was some scattering along 1:1 line. Both 20 cm rods underestimated the VWC of Clay Loamy soil (dots under the 1:1 line) (Figures 3 – 6).

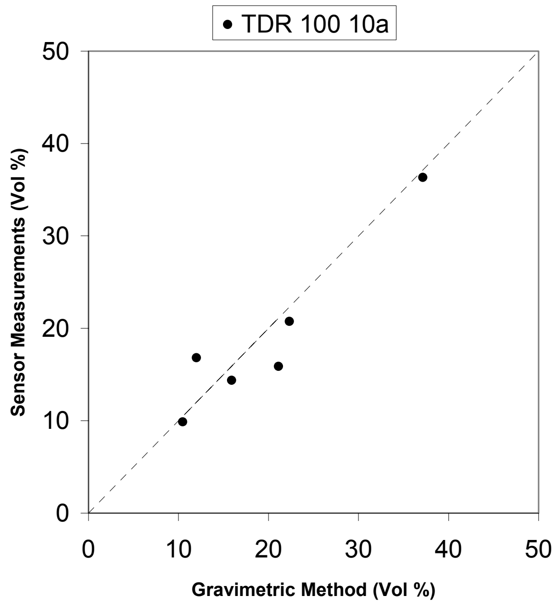

Figure 3: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for TDR 100 10 cm original rods for Clay Loamy soil. The dotted line is 1:1 line.

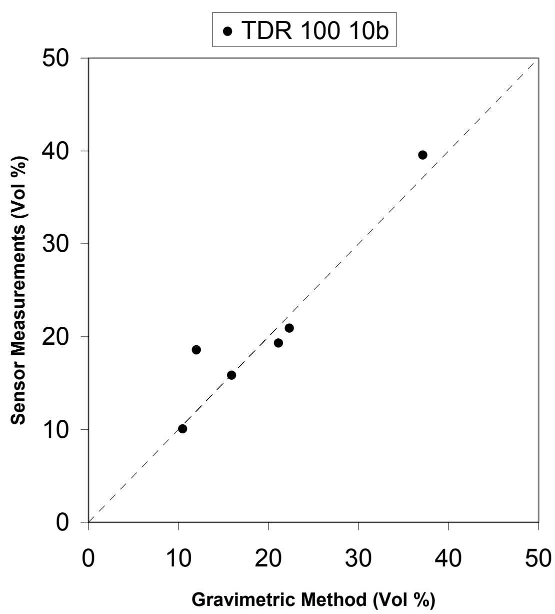

Figure 4: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for TDR 100 10 cm homemade rods for Clay Loamy soil. The dotted line is 1:1 line.

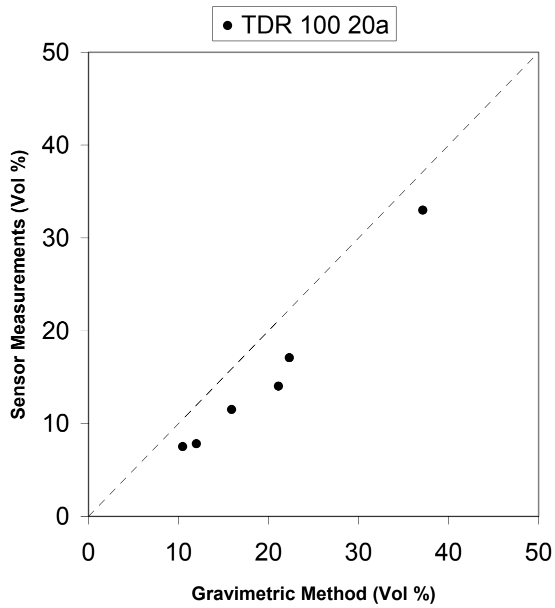

Figure 5: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for TDR 100 20 cm original rods for Clay Loamy soil. The dotted line is 1:1 line.

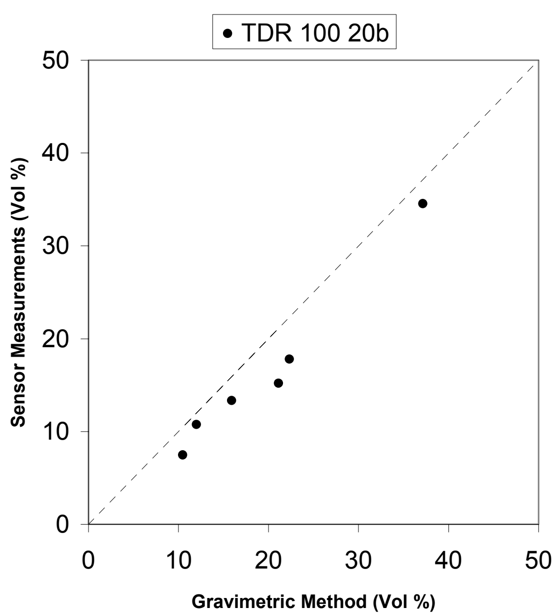

Figure 6: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for TDR 100 20 cm homemade rods for Clay Loamy soil. The dotted line is 1:1 line.

Comparison of the TDR 100 measurements and gravimetrically determined VWC (Figure 4) for Silt Loamy soil shows the best agreement with Gravimetric method for 10 cm original rods, whereas replicated 10 cm rods slightly over and underestimated VWC. Both original and replicated 20 cm rods underestimated the VWC of silt Loamy soil (dots under the 1:1 line) (Figures 7 – 10).

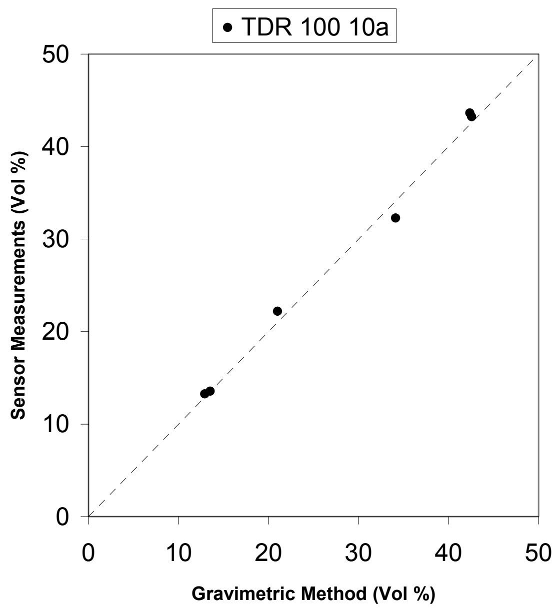

Figure 7: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 10 cm original rods for Silt Loamy soil. The dotted line is 1:1 line.

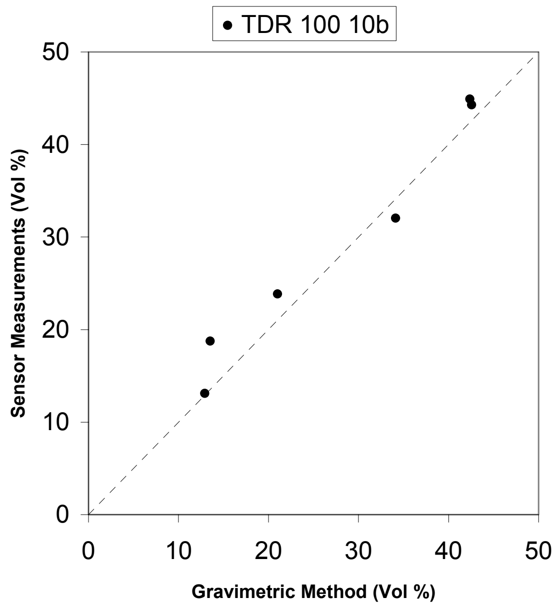

Figure 8: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 10 cm homemade rods for Silt Loamy soil. The dotted line is 1:1 line.

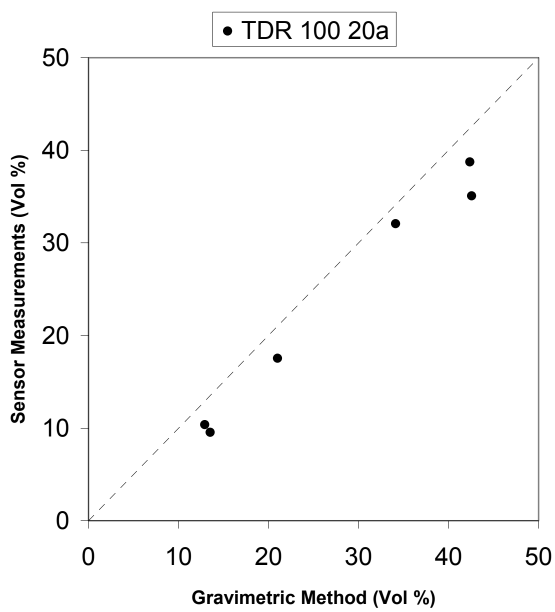

Figure 9: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 20 cm original rods for Silt Loamy soil. The dotted line is 1:1 line.

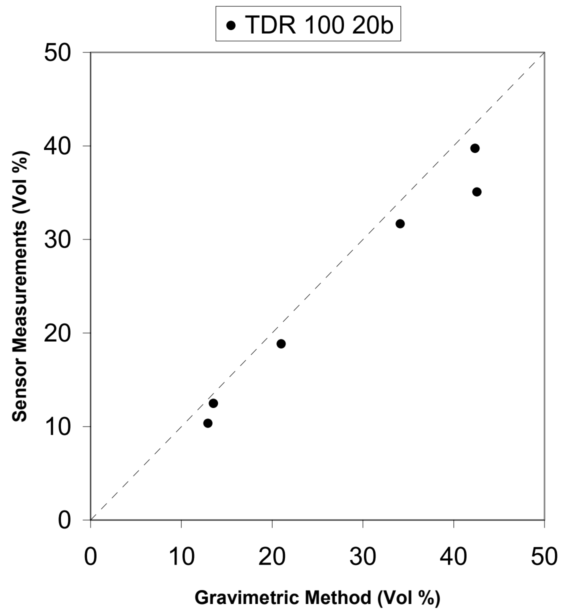

Figure 10: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 20 cm homemade rods for Silt Loamy soil. The dotted line is 1:1 line.

TDR 100 measurements in Sand soil strongly deviated from gravimetrically determined VWC (dots above the 1:1 line). The deviation was significant for both original (a) and replicated (b) rods, TDR sensors overestimating the VWC (Figures 11 – 14).

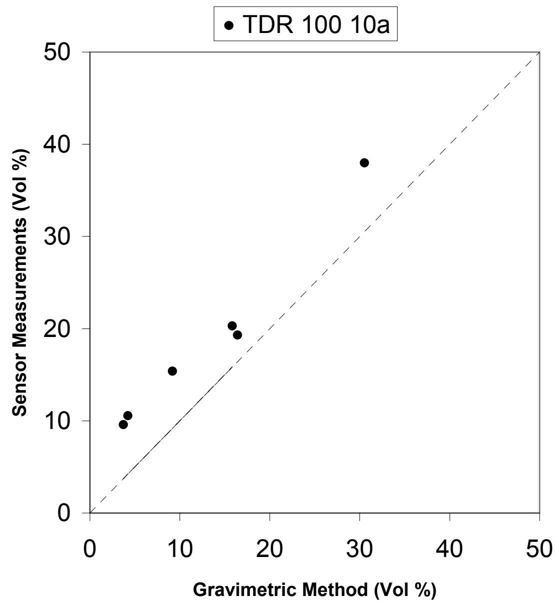

Figure 11: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 10 cm original rods for Sand soil. The dotted line is 1:1 line.

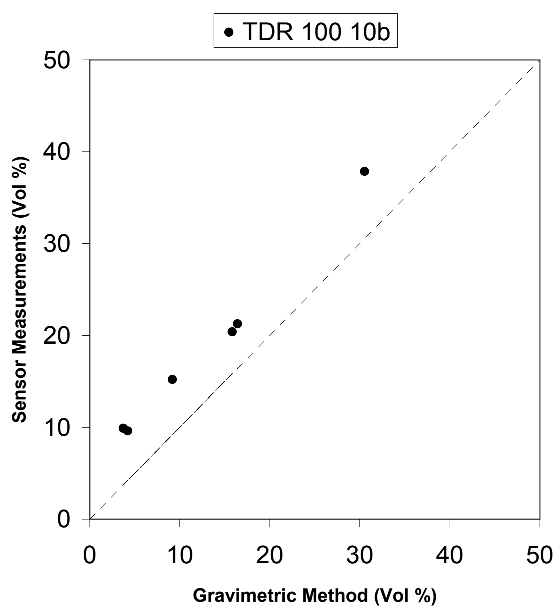

Figure 12: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 10 cm homemade rods for Sand soil. The dotted line is 1:1 line.

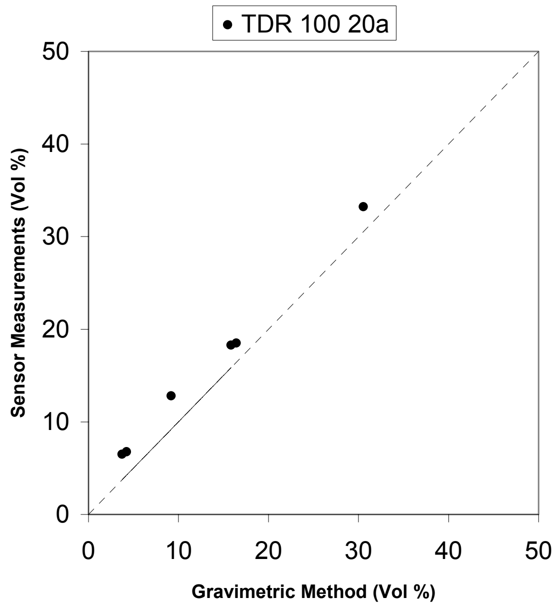

Figure 13: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 20 cm original rods for Sand soil. The dotted line is 1:1 line.

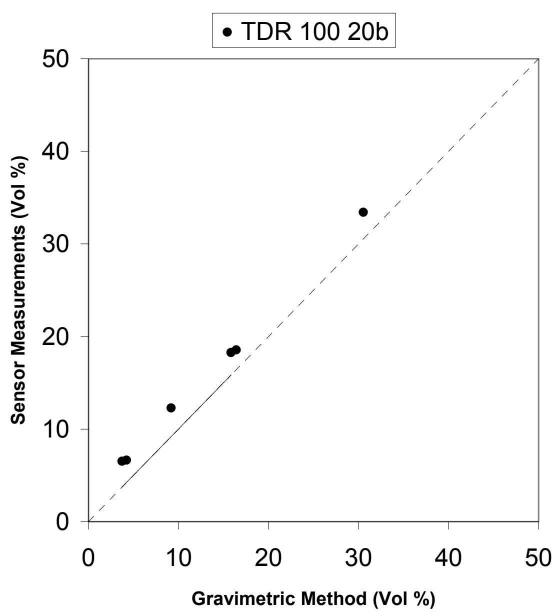

Figure 14: Comparison of Gravimetric method vs. TDR 100 Water Content Reflectometer measurements of soil volumetric water content for 20 cm homemade rods for Sand soil. The dotted line is 1:1 line.

4 CONCLUSIONS

TDR 100 Reflectometer measurements were compared to gravimetrically determined soil VWC, the latter taken as a standard (Topp and Ferré, 2002). During the experiment the importance of waveguide form interpretation and determination was shown to be of extreme importance, which agrees with findings of Evett (2001) and Noborio (2001). Manual interpretation of waveguide's form enabled better readings, adapting the analysis to each reading.

TDR 100 10 cm rods gave better results in both Clay Loam and Silt Loam soil, comparing to 20 cm results, which underestimated VWC. The difference can be contributed to the fact that shorter rods are more suitable for soil VWC measurements, due to their form, length and rod distance (Noboria, 2001). All TDR 100 Reflectometer measurements showed substantially higher VWC in Sand soil as Gravimetric method.

The results comparison of soil VWC measurements showed differences between original steel rods and homemade steel rods to be minimal and negligible. The one exception were 10 cm rods measurements in Silt Loam soil.

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