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The Studding of Accuracy of Soil Moisture Measurement by Time Domain Reflectometry (TDR)

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ABSTRACT

Time domain reflectometry (TDR) method is increasingly have used for estimation of soil water content. With TDR, soil dielectric constant (K) is measured and related to soil volumetric water content (VWC) using a calibration equation. The main objective of this study was to compare of the TDR measurements and gravimetrically determined VWC and determine the relationship between soil water content obtained from these two methods are based on mathematical equations (Linear, quadratic and cubic) for Clay, Loamy and Sandy soil texture in 10 moisture range. The studied experimental models in this research were Topp *et al* (1980), Roth *et al* (1992) and Jacobsen and Schjonning (1993). Results showed that mean soil VWC measurements of TDR method was 3% less than gravimetrically measurements for clay soil texture and mean soil VWCs measurement of TDR method were 0.3% and 2.5% greater than gravimetrically measurements for Loamy and Sandy soil texture. The results indicate cubic model is the best model and the weakest ones were belonged to Roth *et al* (1992) for Clay, Loamy and Sandy soil texture. It is concluded that with increasing soil clay content, the accuracy of measurement by TDR was decreased and the maximum and minimum measurement accuracy relate to sandy and clay soil texture respectively. Also it is concluded that the accuracy of measurement by TDR was greater than Topp *et al* (1980), Roth *et al* (1992) and Jacobsen and Schjonning (1993) and less than Linear, quadratic and cubic mathematical equations.

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INTRODUCTION

Soil moisture measurement and control is one of the necessary components for optimal management methods to reduce water consumption. Although the direct methods of soil moisture measuring have high accuracy as well as low cost, But with regard to direct methods of soil moisture measuring is time consuming procedure, thus, soil moisture estimation based on parameters that are easily measured may play an important role in saving time. Time domain reflectometry method was introduced in 1980 to measure soil moisture *(Topp et al., 1980*). In this method, soil volumetric moisture content of the soil is estimated based on the speed of electromagnetic waves. Dielectric constant in addition soil moisture content depends on the solution electrolytes and soil clay content (Liaghat *et al*, 1998). The first relationship between dielectric constant and volumetric moisture content by Topp *et al*., (1980) is presented as follows:

$$\theta_V = -5.3\times10^{-2} + 2.92\times10^{-2}\kappa - 5.5\times10^{-4}\kappa^2 + 4.3\times10^{-6}\kappa^3$$

Where, θ_V , is volumetric moisture percentage & k, is soil dielectric constant. Additional relationships between dielectric constant and volumetric moisture content by Roth *et al*., (1990) and Herkelrath *et al*., (1991) were presented. In recent years, extensive research has been done on TDR (Roth *et al*, 1992; Dasberg and Hopmans, 1992, Jacobsen and Schjonning; 1993; Dirksen and Dasberg, 1993; Ponizovsky *et al*., 1999; Topp *et al*., 2003, Robinson *et al*, 1999, 2002, 2003; Yoshikawa *et al*, 2004*)*.

Research results by Roth *et al*., (1992) were a third-degree polynomial calibration equation. Jacobsen and Schjonning, 1993, were studied effects of soil texture and bulk density on the calibration curve. Kup *et al*., 2011

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Journal of Applied Science and Agriculture, 9(2) Febuary 2014, Pages: 707-711

were calibrated the time domain reflectometry (TDR) method in Turfan sandy soils. Tanriverdi, 2005, was calibrated the TDR instrument for different soils that results showed TDR is a suitable method for measuring soil moisture content. Research by Biteli *et al*., (2007), showed that the major problem of using TDR is gradual and slow reduction of soil moisture. Noboria, 2001, at the same time measured the soil water content and electrical conductivity using developed TDR instrument. Pumpanen *et al*., 2005, were calibrated the time domain reflectometry (TDR) method in homogeneous and undisturbed humus soils Turfan sandy soils. Serrarens *et al*., 2000, were assessed the accuracy of TDR multilevel probes. Their research showed that soil contact with the probe and soil compaction is important for TDR evaluation (Serrarens, *et al*., 2000).

Also Research by Maroufpoor *et al*., 2009 showed that with increasing clay content, the accuracy in the estimation of volumetric soil moisture measured by TDR decreases. So, soil moisture estimates underestimated at the heavier soil texture. The main objective of this study was to compare of the TDR measurements and gravimetrically determined VWC and determine the relationship between soil water content obtained from these two methods are based on mathematical equations (Linear, quadratic and cubic) for Clay, Loamy and Sandy soil texture in 10 moisture range.

MATERIAL AND METHOD

In this study, according to preliminary information of soils and perform preliminary experiments, three regions with textures of sandy, loamy and clay were selected at the Mahabad region (West Azarbaijan). In each of these, soil sampling was conducted. Experiment on each of the three types of soil texture (Clay, Loamy and Sandy) was conducted in the 10 moisture range between air-dried to saturation soil with three replications. Therefore, soil moistures were measured using TDR and gravimetrically method. Quantitative comparison of volumetric soil moisture amounts of TDR and gravimetrically method should always be, therefore the linear, quadratic and cubic model were used. Iin addition, empirical equations included Topp *et al*., (1980), Roth *et al*., (1992) and Jacobsen and Schjonning, (1993) models evaluated as follows:

$$\theta = -0.053 + 0.0292\varepsilon - 0.00055\varepsilon^2 + 0.0000043\varepsilon^3$$ Topp *et al*., (1980)

$$\theta = -0.0728 + 0.0448\varepsilon - 0.00195\varepsilon^2 + 0.0000361\varepsilon^3$$ Roth *et al*., (1992)

$$\theta = -0.0701 + 0.0347\varepsilon - 0.00116\varepsilon^2 + 0.000018\varepsilon^3$$ Jacobsen and Schjonning, (1993)

In order to data analysis the Correlation Coefficient (R), Root Mean Square Error (RMSE), Maximum Error (ME), Mean Bias Error (MBE), Mean Absolute Error (MAE), Relative Error (RE), Standard Error (SE), Coefficient of Determination (CD), Coefficient of Variation (CV), coefficient of residual mass (CRM) and Modeling efficiency (EF) used as follows:

$$ME = \max\left|P_i - O_i\right|_{i=1}^{n}$$

$$MBE = \sum_{i=1}^{n}[(P_i - O_i)/n]$$

$$MAE = \sum_{i=1}^{n}\left[\left|P_i - O_i\right|/n\right]$$

$$RE = (MAE/\overline{O}) \times 100$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{1/2}$$

$$SE = \left[\frac{1}{n-1}\sum_{i=1}^{n}(P_i - \overline{O})^2\right]^{1/2}$$

$$CD = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2}{\sum_{i=1}^{n}(P_i - \overline{O})^2}$$

$$C.V = (SE/\overline{O}) \times 100$$

$$CRM = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i}$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$$

Where, P_i, The estimated values (volumetric soil moisture amounts of TDR method, mathematical models and empirical equations), O_i, The observed values (volumetric soil moisture amounts of gravimetrically method), $\overline{O}$, mean of observed (measured) values and n, number of samples.

Results:

The results of the volumetric soil moisture content measured by gravimetric method and the volumetric soil moisture content using TDR (mean of three replicates) for the different soil texture is presented (Table 1).

Table 1: The results of the volumetric soil moisture content measured by gravimetric method (θ_W) and TDR (θ_{TDR}) for the different soil texture

Clay soil texture			Loamy soil texture			Sandy soil texture		
Bd(gr/cm^3)	θ_W	θ_{TDR}	Bd(gr/cm^3)	θ_W	θ_{TDR}	Bd(gr/cm^3)	θ_W	θ_{TDR}
1.29	54.2	53.5	1.41	48.2	50.0	1.62	40.2	43.4
1.36	46.0	45.6	1.37	45.1	44.4	1.48	37.8	38.0
1.28	39.9	38.5	1.38	41.2	39.2	1.52	35.1	35.3
1.27	36.1	35.9	1.30	37.1	36.4	1.53	33.5	34.7
1.30	31.0	26.6	1.56	31.3	32.1	1.45	25.2	25.0
1.33	26.2	26.0	1.40	28.1	29.1	1.60	22.8	23.2
1.28	22.2	20.4	1.42	25.8	27.6	1.49	15.0	13.8
1.35	15.9	17.7	1.36	17.1	16.6	1.53	11.2	11.8
1.29	7.1	5.1	1.41	8.2	7.6	1.54	6.7	8.0
1.25	0	0	1.34	0	0	1.58	0	0

The results comparison of soil VWC measurements showed differences between TDR and gravimetrically measurements. Table 1 shows the volumetric moisture content from TDR method is less than the gravimetrically method in clay soils (Average 3%) but the volumetric moisture content from TDR method is greater than the gravimetrically method in loamy and sandy soils (respectively, an average of 0.3% and 2.5%), Which is consistent with the results of other investigators, as Research by Maroufpoor *et al*., 2009 showed that with increasing clay content, the accuracy in the estimation of volumetric soil moisture measured by TDR decreases. So, soil moisture estimates underestimated at the heavier soil texture, probably the reason is specific surface of clay and its mineralogy. Since the TDR device is sensitive to water content is kept around bars, accumulation of air bubbles around bars causes that devices underestimated the soil moisture, so underestimated soil moisture in the clay soils.

Dasberg and Hopmans, 1992, correlation coefficient between soil moisture amounts of TDR and gravimetrically method were reported 0.91 and 0.99 for sandy loam and silty loam soils respectively. Research by Vesna *et al*., 2005 showed that the TDR method is suitable for clay loam and silty loam soils, but in sandy soils but the volumetric moisture content from TDR method indicate larger amounts than the gravimetrically method in sandy soils. In order to data analysis the different statistics used included Correlation Coefficient (R), Root Mean Square Error (RMSE), Maximum Error (ME), Mean Bias Error (MBE), Mean Absolute Error (MAE), Relative Error (RE), Standard Error (SE), Coefficient of Determination (CD), Coefficient of Variation (CV), coefficient of residual mass (CRM) and Modeling efficiency (EF). Data analysis of volumetric soil moisture amounts of TDR (θ_{TDR}, dependent variable) and gravimetrically (θ_W, independent variable) method concluded using mathematical equations (linear, quadratic and cubic) as follows (table 2). Iin addition, empirical equations included Topp *et al*., (1980), Roth *et al*., (1992) and Jacobsen and Schjonning, (1993) models evaluated as follows (table 2):

Table 2: The results of different statistics of mathematical & empirical equations

Equation	R	RMSE	MBE	MAE	ME	RE	CRM	SE	CV	CD	EF
Clay soil texture											
Linear	0.996	0.0154	0.0000	0.0118	0.0347	4.238	0.0000	0.1615	57.95	1.009	0.009
Quadratic	0.996	0.0152	0.0000	0.0114	0.0322	4.096	0.0000	0.1615	57.96	1.009	0.009
Cubic	0.996	0.0152	0.0000	0.0115	0.0322	4.140	0.0000	0.1615	57.96	1.009	0.009
Topp *et al*.	0.992	0.0261	-0.0118	0.0205	0.0544	7.345	0.0423	0.1727	62.00	0.882	-0.134
Roth *et al*.	0.804	0.3311	0.1099	0.1344	1.0352	0.246	-0.3944	0.4414	158.4	0.135	-6.405
Jac & Sch	0.904	0.1244	0.0069	0.0697	0.3715	0.009	-0.0248	0.2499	89.70	0.421	-1.374
Loamy soil texture											
Linear	0.997	0.0116	0.0000	0.0099	0.0219	3.527	0.0000	0.1501	53.22	1.006	0.006
Quadratic	0.997	0.0116	0.0000	0.0099	0.0219	3.524	0.0000	0.1501	53.22	1.006	0.006
Cubic	0.997	0.0111	0.0000	0.0103	0.0188	3.663	0.0000	0.1502	53.24	1.005	0.009
Topp *et al*.	0.995	0.0239	0.0063	0.0184	0.0571	6.538	-0.0223	0.1675	59.37	0.808	-0.237
Roth *et al*.	0.801	0.2595	0.1005	0.1030	0.8021	0.524	-0.3563	0.3568	126.5	0.178	-4.613
Jac & Sch	0.912	0.0991	0.0114	0.0545	0.3007	0.319	-0.0404	0.2141	75.90	0.495	-1.021

Sandy soil texture										
Linear	0.997	0.0099	0.0000	0.0082	0.0192	3.618	0.0000	0.1328	58.38	1.006	0.006
Quadratic	0.998	0.0083	0.0000	0.0076	0.0124	3.357	0.0000	0.1329	58.43	1.004	0.004
Cubic	0.999	0.0070	0.0000	0.0056	0.0146	2.471	0.0000	0.1330	58.46	1.003	0.003
Topp *et al*.	0.993	0.0178	0.0016	0.0127	0.0429	5.595	0.0072	0.1410	61.99	0.892	-0.121
Roth *et al*.	0.976	0.0339	0.0157	0.0215	0.0914	9.450	-0.0689	0.1386	60.90	0.924	-0.082
Jac & Sch	0.990	0.0276	-0.0196	0.0240	0.0441	0.570	0.0860	0.1284	56.44	1.076	0.070

The results presented in Table 2 indicate cubic model with the highest correlation coefficient and lowest root mean square error is the best model and the weakest ones were belonged to Roth *et al* (1992) for Clay, Loamy and Sandy soil texture. It is concluded that with increasing soil clay content, the accuracy of measurement by TDR was decreased and the maximum and minimum measurement accuracy relate to sandy and clay soil texture respectively. The results presented in Table 2 indicate Topp *et al*., (1980) model is the better model for Sandy soil texture than Loamy and clay soil texture, because this model is obtained in Sandy soil texture.

Also it is concluded that the accuracy of measurement by TDR was greater than Topp *et al* (1980), Roth *et al* (1992) and Jacobsen and Schjonning (1993) and less than Linear, quadratic and cubic mathematical equations. The results presented in Table 2 indicate cubic model with the highest correlation coefficient and lowest root mean square error is the best model among the mathematical equations (linear, quadratic and cubic) and Topp *et al* (1980) model with the highest correlation coefficient and lowest root mean square error is the best model among the empirical equations (Topp *et al*., (1980), Roth *et al*., (1992) and Jacobsen and Schjonning, (1993)) for Clay, Loamy and Sandy soil texture. Also Oleszczuk *et al*., (2004) found similar results, so Topp *et al*., (1980) model has the best fit with the measured values for Clay soil texture. This result is consistent with the Kargas and Kerkides (2008).

Roth *et al* (1992) model estimated soil VWC measurements greater than gravimetrically measurements for Clay, Loamy and Sandy soil texture. With the results of Robinson *et al*., 2003 is consistent.
Jacobsen and Schjonning (1993) estimated soil VWC measurements less than gravimetrically measurements for Sandy soil texture and greater than gravimetrically measurements for Loamy and Clay soil texture. Topp *et al* (1980) model estimated soil VWC measurements greater than gravimetrically measurements for Loamy and Sandy soil texture and less than gravimetrically measurements for Clay soil texture.

Discussion:

Research showed that with increasing clay content, the accuracy in the estimation of volumetric soil moisture measured by TDR decreases. So, soil moisture estimates underestimated at the heavier soil texture, probably the reason is specific surface of clay and its mineralogy. The results indicate cubic model with the highest correlation coefficient and lowest root mean square error is the best model and the weakest ones were belonged to Roth *et al* (1992) for Clay, Loamy and Sandy soil texture. Roth *et al* (1992) model estimated soil VWC measurements greater than gravimetrically measurements. Jacobsen and Schjonning (1993) estimated VWC greater than gravimetrically measurements for Loamy and Clay soil texture, and Topp *et al* (1980) model estimated soil VWC measurements greater than gravimetrically measurements for Loamy and Sandy soil texture.

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