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Original Research

The studying effect of soil clay content and bulk density on moisture measuring accuracy by TDR

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ABSTRACT:

Time domain reflectometry has been used for measuring water content in soil that in this method water content is measured based on the relationship between water content and dielectric constant (K). The aim of this research is to compare of the TDR measurements and gravimetrically determined soil water content and determine the relationship between soil water content obtained from these two methods based on mathematical equations (linear, quadratic and cubic) for five soil texture (Clay, Sandy Clay Loam, Loam, Sandy Loam and Sandy) in 15 moisture ranges. Also the other objectives of this study were to investigate the influence of soil bulk density and clay content on TDR measurements. Soil samples were taken from five areas with different textures (sand, sandy loam, loam, sandy clay loam and clay). All physical properties of the soil, including clay, silt and sand contents were specified. The impact of soil bulk density and clay content on the accuracy of TDR is an undeniable fact. The high amounts of clay and low amounts of Soil bulk density caused an underestimation of water content. The multivariate linear regressions equation obtained from data is *(R^2 = 0.98):*

$$\theta = 0.121 + 0.160\varepsilon - 0.137\frac{\rho_b}{\rho_s} - 0.001\%\text{clay} + 0.000029\%\text{silt}$$

where 'ϑ', is the volumetric water content, 'ε' is the soil dielectric constant, 'ρ_b' is the soil bulk density (g cm^{-3}), 'ρ_s' is the soil density (g cm^{-3}), '% clay' is the percentage of clay-sized particles, and '% silt' is the percentage of silt-sized particles (P<0.01).

Keywords:

Bulk density, clay content, soil moisture, soil texture and TDR

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INTRODUCTION

Time Domain Relectometry (TDR) method has emerged as a widely applicable method in determination of soil volumetric water content (θ_v) in a fast, precise and non-destructive manner. The relationship between θ_v and apparent dielectric constant (K) of soils was used in order for estimating the soil 'θ_v' . For guaranteeing the accuracy of the measurement of using TDR technique, an attention should be paid to the selections of θ_v- K relationship.

The use of dielectric measurements is so common in many contexts, such as environmental study (Janik *et al.,* 2014), and other soil properties, as well as investigation of remote soil measurements (Usowicz *et al.,* 2014), researches focusing on the water infiltration (Pastuszka *et al.,* 2014), quality assurance of agricultural products (Sosa-Morales *et al.,* 2010), agrophysics (Lamorski *et al.,* 2014) and other fields linked to the environment.

Time domain reflectometry method was introduced in 1980 to measure moisture (Topp *et al.,* 1980). In this method, 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).

Investigation of the plants' roots distribution and the pattern of water absorption by the roots is so essential for development of modern irrigation systems (Clothier and Green, 1994). The soil moisture regulates the exchange of apparent and latent heat between earth surface and atmosphere. So, the soil moisture has a great impact on evaporation process and agricultural activities. The moisture percent is known as a keyword in the various fields, including environmental, hydrological, climate and agricultural studies (Walker, 1999; Silberstein and Sivapalan, 1999).

It is believed that a series of factors, including soil bulk density, temperature, texture and organic matter (OM) content have an impact on measurements done using TDR method (Roth *et al.,* 1990; Gong *et al.,* 2003). Topp *et al.* (1980) showed that their proposed equation performed well, as the bulk density value varied from 1.00 g cm-3 to 1.78 g cm^{-3}. Moreover, further studies were performed with a main focus on TDR (Topp *et al.,* 2003, Robinson *et al.,* 2002; Robinson *et al.,* 2003; Yoshikawa *et al.,* 2004). Another study accomplished by Bittelli *et al.,* (2007) demonstrated that gradual and slow reduction of soil moisture must be regarded as the main disadvantage of TDR technique.

The main aim of this study was to investigate the effect of soil clay content and bulk density on moisture measuring accuracy by TDR and determine the relationship between soil water content using application of mathematical equations (linear, quadratic and cubic) for various soil texture.

METHODOLOGY

The case study of the present research is chosen among from the fields located at Mahabad city, West Azerbaijan Province, Iran. For this purpose, totally five textures, including clay, sandy clay loam, loam, sandy loam and sandy were investigated. Experiments were performed in 15 moisture ranges betwixt air-dried and saturation soil along with replications which are presented in Table 1. For measurement of soil moistures, gravimetrically and TDR methods were utilized. For quantitative assessment of amounts of volumetric soil moisture by TDR, the gravimetrically determined data was used along with other metrics and standards, including Maximum Error (ME), Mean Bias Error (MBE), Mean Absolute Error (MAE), Relative Error (RE), Root Mean Square Error (RMSE), Standard Error (SE), Coefficient of Variation (CV), Coefficient of Determination (CD), Modeling Efficiency (EF) and Coefficient of Residual Mass (CRM), whose formulas presented as follows (Siosemarde *et al.,* 2014):

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

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

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

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

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

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

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

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

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

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

where, 'O_i' and 'P_i' refers to the observation and estimation values, respectively. 'n' represents the number of samples and '$\bar{O}$' is mean of observation values (Siosemarde *et al.,* 2014).

RESULTS AND DISCUSSION

Table 1 presents the results related to the volumetric soil moisture obtained using gravimetric and TDR method for above-mentioned five soil textures. According to Table 1, it can be concluded that the measured volumetric moisture content for clay, sandy clay loam and loam soil textures using TDR method is less the one which is measured using gravimetrically method for the same soil textures. For sandy loam and sandy soil, the high value of volumetric moisture content is associated with TDR method.

Table 2 contains the values of various statistics between gravimetrically (θ_w, independent variable) method and TDR (θ_{TDR}, dependent variable) method. The results showed that quadratic model is the best model with the best values of correlation coefficient and root mean square error for Clay, Sandy Clay Loam, Loam, Sandy Loam and Sandy soil textures. It is concluded that the TDR method had the highest accuracy in Sandy soil texture and the lowest accuracy in Clay soil texture.

Soil bulk density and clay content impact the accuracy of TDR. High clay contents and low Soil bulk density caused an underestimation of soil water content in the moisture range. The following multivariate linear regressions equation obtained from on data (R2 = 0.98):

$$\theta = 0.121 + 0.160\varepsilon - 0.137\frac{\rho_b}{\rho_s} - 0.001\%\text{clay} + 0.000029\%\text{silt}$$

where 'θ,' is the volumetric water content, 'ε' is the soil dielectric constant, 'ρ_b' is the soil bulk density (g cm^{-3}), 'ρ_s' is the soil density (g cm^{-3}), '% clay' is the percentage of clay-sized particles, and '% silt' is the percentage of silt -sized particles ($P<0.01$).

Table 1. Results of measured volumetric soil moisture for five soil textures

Clay texture		Sandy Clay Loam texture		Loam texture		Sandy Loam texture		Sandy texture	
θ_W	θ_{TDR}	θ_W	θ_{TDR}	θ_W	θ_{TDR}	θ_W	θ_{TDR}	θ_W	θ_{TDR}
51.6	50.5	40.0	39.5	36.6	36.5	34.7	35.0	33.8	33.9
48.1	46.2	38.6	37.9	33.3	33.4	31.4	31.6	31.6	31.7
45.2	43.8	36.7	35.8	30.6	30.4	29.6	29.9	29.9	29.9
43.1	42.6	34.8	34.2	28.9	27.8	27.8	27.1	26.6	26.6
39.5	37.6	31.1	30.8	26.6	26.5	25.6	26.9	24.4	24.5
37.3	35.1	28.0	27.9	24.8	24.7	21.8	22.1	21.3	21.5
34.4	32.9	25.6	25.1	21.9	21.8	19.9	20.0	20.9	21.1
30.2	28.8	22.1	22.1	19.2	19.3	17.8	17.8	18.2	18.6
27.8	26.9	19.1	19.0	17.6	17.1	16.6	16.5	15.9	16.0
23.4	22.8	17.6	15.1	14.6	14.5	14.5	14.9	13.2	13.2
18.4	17.6	15.9	15.1	11.9	11.8	11.9	11.0	11.9	12.0
14.6	12.6	14.5	13.9	8.8	8.9	9.6	9.9	10.8	10.8
10.4	9.9	10.8	9.9	6.9	6.5	7.7	7.8	8.9	9.0
7.9	7.8	7.8	7.5	3.4	3.4	4.9	4.9	5.8	5.8
3.6	3.5	3.5	3.4	1.6	1.6	3.3	3.3	4.6	4.6

Table 2. The statistical significant differences between water contents estimated with different equations

Equation	R	RMSE	MBE	MAE	ME	RE	CRM	SE	CV	CD	EF
Clay texture											
Linear	0.999	0.0057	0.000	0.005	0.012	1.595	0.000	0.149	51.32	1.001	0.002
Quadratic	0.999	0.0053	0.000	0.004	0.012	1.365	0.000	0.149	51.33	1.001	0.091
Cubic	0.999	0.0176	0.016	0.016	0.023	5.584	-0.056	0.156	53.92	0.907	-0.102
Sandy Clay Loam texture											
Linear	0.999	0.0059	0.000	0.004	0.019	1.659	0.000	0.112	45.51	1.003	0.003
Quadratic	0.999	0.0058	0.000	0.004	0.019	1.685	0.000	0.112	48.51	1.003	0.003
Cubic	0.999	0.0941	0.079	0.079	0.166	34.26	-0.343	0.181	78.43	0.384	-1.606
Loam texture											
Linear	0.999	0.0029	0.000	0.002	0.009	1.065	0.000	0.107	55.92	1.001	0.001
Quadratic	0.999	0.0029	0.000	0.002	0.009	1.015	0.000	0.107	55.92	1.001	0.001
Cubic	0.999	0.0098	-0.007	0.007	0.022	3.857	0.038	0.101	52.75	1.125	0.111
Sandy Loam texture											
Linear	0.999	0.0046	0.000	0.003	0.011	1.612	0.000	0.096	51.81	1.002	0.002
Quadratic	0.999	0.0046	0.000	0.003	0.011	1.598	0.000	0.096	51.81	1.002	0.002
Cubic	0.999	0.0207	0.017	0.017	0.041	8.988	-0.090	0.109	59.14	0.769	-0. 300
Sandy texture											
Linear	0.999	0.0010	0.000	0.001	0.003	0.405	0.000	0.091	48.97	1.000	0.000
Quadratic	0.999	0.0009	0.000	0.001	0.002	0.367	0.000	0.091	48.98	1.000	0.000
Cubic	0.999	0.0063	-0.005	0.005	0.011	2.842	0.028	0.087	47.23	1.075	0.070

Figure 1 shows the RMSE values to soil bulk density to soil density ratio (ρ_b / ρ_s). According to Figure 2, the accuracy in the estimation of volumetric soil moisture measured as the TDR increases with increase of ρ_b/ρ_s,. Figure 2 shows the RMSE values to Clay percentage. Moreover, Figure 2 shows that with increasing clay percentage, the accuracy of TDR device decreases

The results of this study showed that with increasing clay amounts, the TDR method accuracy decreases which also shown by Maroufpoor *et al.* (2009), in which they demonstrated that high clay content leads to reduction in estimation accuracy of the volumetric moisture. Hence, the estimations related to the soil moisture for clay soil texture are underestimated mainly due to the specific surface of clay and its mineralogy. With regard to the obtained results, for sandy soil texture all estimations of the soil moisture by TDR are overestimated, which was also verified by Zupanc *et al.,* (2005) for sandy soil texture.

CONCLUSION

The obtained results indicate that an increase in the clay content of the soil leads to increase in the dielectric constant which is due to the increase of specific soil surface and reduction of boundary layer. As a result, the accuracy of the measurement device will be decreased

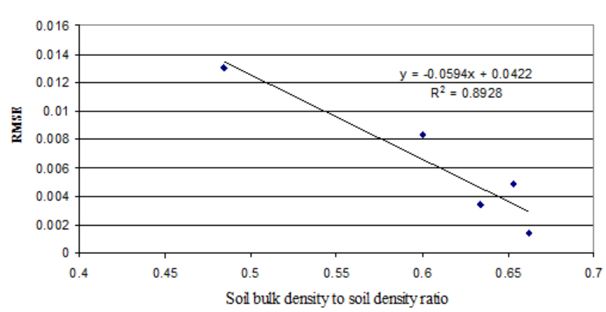

Figure 1. The RMSE values to soil bulk density to soil density ratio (ρ_b/ρ_s).

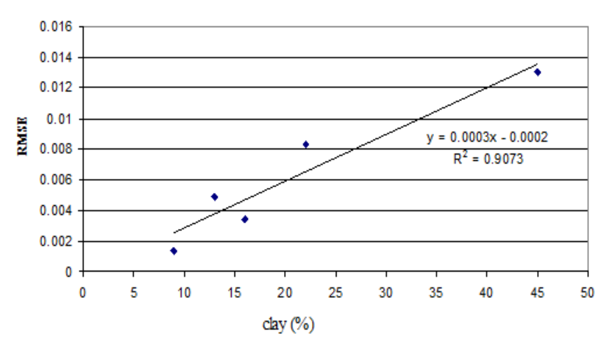

Figure 2. The RMSE values to clay percentage

significantly and the reduction in measurement accuracy associated with low moisture area is higher than the areas with high moisture amount. Moreover, TDR device showed higher amount of moisture for heavy soil textures, compared to the gravimetrically method. It can be concluded that, any reduction in the moisture of the soil, will lead to increase in accuracy of TDR device during the measurement of moisture.

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