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Full Length Research Paper

Evaluation of dielectric constant by clay mineral and soil physico-chemical properties

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Time domain reflectometry (TDR) has capability of distinguishing the dielectric property of solid, air and liquid phases of the soils and has become increasingly popular for determining the soil water content (SWC). The purpose of this study was to find a relationship between soil bulk density (BD), clay content, clay mineralogy with dielectric constant. The latter is a function of SWC. For this purpose 10 soil samples were taken from five areas with different textures and depths (from topsoil, 0 to 0.3 m and subsoil, 0.3 to 0.6 m), The BDs were varied from 1.18 to 1.65 Mg m^{-3}. Soil physical and chemical properties such as organic matter, clay, silt, and sand percentages as well as clay minerals were measured. Results showed that high clay contents underestimated the SWC in the low moisture range and overestimated the SWC in the high moisture range. Results also showed that soils with similar clay content but different minerals had different impact on dielectric constant. Soils with high BD, or low porosity, had higher dielectric constant value than soils with low BD and high porosity.

Key words: Clay mineralogy, dielectric constant, bulk density, soil water content, time domain reflectometry.

INTRODUCTION

To investigate the effect of bulk density (BD) on the soil dielectric constant, the soil columns were prepared at different level of BD, and constant level of soil water content (SWC). The effect of soil BD and clay content on TDR soil moisture measurements have been reported by many researchers. This effect is primarily caused by changes in soil and water dielectric constant when soil compaction and clay content are changed (Wyseure et al., 1997). The effect of clay content is important when the accurate measurement of water content is needed. High clay contents underestimate the SWC in the low moisture range but causes overestimation in the high moisture range. Ledieu et al. (1986) reported that the calibration equation between dielectric constant value (K_a) and volumetric water (θ_v) could be improved by considering soil bulk BD. The denser the soil, the greater the volume ratio of solid particles to air and the larger, the dielectric constant of dry soil (K_s) (Yuanshi et al., 2003). The liquid phase in soil can be subdivided into a free water phase and a bound water phase. Free water phase is able to rotate freely following an alternating electric field (Sun, et al., 2000). In contrast, the bound water phase consists of water molecules that are bound to the soil surface by adhesive, cohesive and osmotic forces (Hilhorst et al., 2001). The rotation of bound water molecules which follow electric field is restricted, resulting in less polarization as compared to free water, and a low dielectric constant. The electrical conductivity (EC) of clay soil imposes a great impact on soil water content measurement using TDR (Topp et al., 1980; Malicki et al., 1994; Sun et al., 2000; Namdar-Khojasteh et al., 2010). The soil EC comes from the electrolytes in soil solution and the electrical charged clay colloid surface. The elevated EC increases the apparent dielectric constant (Sun et al., 2000; Topp et al., 2000), acting counter to that of bound water in TDR soil water content measurement, and making TDR less sensitive to soil

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Abbreviations: TDR, Time domain reflectometry; **SWC,** soil water content bulk; **BD,** density.

Figure 1. Shows a general scheme of the zone measurements.

texture (Sun, et al., 2000). The effects of clay content on dielectric constant are because of the following:

Bound water

The polarization of bound water molecules is impeded by high electrostatic attraction from the negatively charged clay particle surface (Shang, 1994). Reduced polarization will result in much lower dielectric constant. For bound water that is directly attached to the soil particle surface, the dielectric constant is nearly 3.2 times that will lead to a faster propagating velocity and shorter time delay of electromagnetic (EM) waves in TDR. Therefore, it underestimates the soil water content (Sun, et al., 2000).

The bulk soil electrical conductivity (EC_b)

The effect of EC_b on TDR measurement has been reported by many researchers (Topp et al., 1980; Malicki et al., 1994; Sun et al., 2000; Namdar-Khojasteh et al., 2010). The elevated EC_b causes dispersion of the reflected signal, resulting in longer rise time. The study showed that there is a rise time related measurement error (Hook and Livingston, 1995). The signal is attenuated by energy dissipation through current flow making the detection of final reflection signal very difficult, if it is still possible (White et al., 1994). The elevated EC_b also increases the apparent dielectric constant, leading to an overestimated SWC (Sun et al., 2000). O'Konski (1955) described that in a colloid a semi-conducting surface can arise due to a distribution of charge density and induce extra polarization.

The BD affects dielectric constant (K_a) since when it is high porosity is low, leading to that the amount of the mineral phase present in the soil increases. It is expected that soils with high BD, or low porosity, will have a larger K_a value than soils with low BD and high porosity (Sun et al., 2000):

$$\theta_v = \frac{K_a^{0.5} - K_s^{0.5}}{K_w^{0.5} - 1} \qquad (1)$$

Where K_s, $K_a^{0.5}$ and K_w are dielectric constant in solid, total and liquid phase, respectively.

Malicki et al. (1996) studied the influence of a soil solid phase on the dielectric constant of the soil over a range of water contents. They found the following relationship between the square root of the dielectric constant and soil BD.

MATERIALS AND METHODS

Soil sampling

Soil samples from five areas were taken in this study. Areas were placed in Karaj and Ghazvin in Iran. Figure 1 shows a general scheme of these studied areas. Soil samples were taken from the both topsoil (0 to 0.3 m depth) and subsoil (0.3 to 0.6 m depth). Therefore, totally ten soil samples were collected. The BD of soil samples varied between 1.18 to 1.65 Mg m^{-3}. Soil physical and chemical properties were also determined for each soil samples. These properties were by organic matter, clay, silt, sand content and clay minerals. These properties are presented in Tables 1 and 2.

Soil samples were air-dried and passed through a 5 mm sieve and then divided into subsamples (15 to 20) that were mixed with water. The soil was then packed into polyvinyl Cl (PVC) cylinders (0.18 m long and 0.19 m in diameter) and TDR measurements were taken using two rod probes connected to a Trace system I, model 6050X1 (Soil Moisture Equipment Corp., Santa Barbara, CA). Then samples were removed from the cylinders, spread in a thin layer for obtaining the next desired moisture content. The procedure was repeated until the water content was close to saturation in each subsample. Three TDR measurements were recorded and averaged. In total 203 subsamples were analyzed. Gravimetrical method was used to determine the sample water content by an oven at 110°C during 48 h. The water content ranged from 0.075 to 0.606 m^3 m^{-3}. All TDR measurements were taken at the constant temperature of 17°C. Dielectric constant was calculated by $(ct/2L)^2$, where L is the length of the rod, t is the two-way transit time in the probe, and c is the light speed in free space (Namdar-Khojasteh et al., 2010). Results are shown in Figure 2.

RESULTS AND DISCUSION

The effect of soil bulk density

The relationship between soil bulk density (BD) and dielectric constant (K_a) is shown in Figure 3. The linear relationship indicates that the increase in K_a would result an increase in solid particles mass per unit volume, due to the fact that solid phase posses a higher dielectric

Table 1. Properties of the soils.

Location	Depth	Clay	Silt	Sand	Organic matter	Bulk density	Texture
				g kg^{-1}		Mg m^{-3}	
Takestan	Topsoil (0-30)	286	292	412	22.3	1.29	Clay loam
	Subsoil (30-60)	566	252	181	19.3	1.52	clay
Soltan	Topsoil (0-30)	316	172	466	18.6	1.44	Sandy clay
	Subsoil (30-60)	391	242	366	13.4	1.45	Clay loam
Shal	Topsoil (0-30)	616	257	126	18.6	1.18	Clay
	Subsoil (30-60)	576	247	176	12.6	1.58	Clay
Gharasan	Topsoil (0-30)	318	352	266	14.9	1.38	Clay loam
	Subsoil (30-60)	396	417	186	6.7	1.49	Silty clay
M. Danesh	Topsoil (0-30)	260	480	260	23.3	1.41	loam
	Subsoil (30-60)	260	400	340	11.2	1.65	loam

Table 2. The minerals of the soils.

Location/depth (0-30)	Illite (%)	Smectites (%)	Kaolinite (%)	Cholorite (%)	Mixed clays (%)	Vermiculite (%)	Palygoreskite (%)
Takestan	30	20	10	30	-	10	-
Soltan	40	10	10	30	10	-	-
Shal	30	30	10	30	-	-	-
Gharasan	-	90	-	10	-	-	-
M. Ddanesh	30	10	10	30	10	10	-

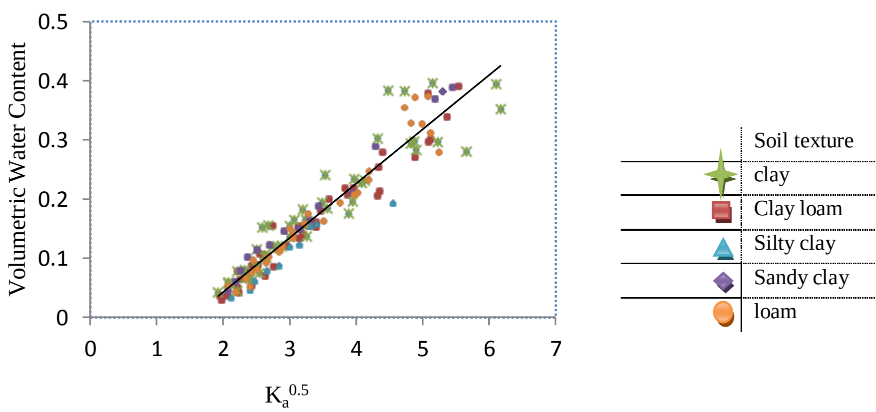

Figure 2. Result total data for relation between dielectric constant and $K_a^{0.5}$.

constant than other phases. Jacobsen and Schjonning (1993), Yuanshi et al. (2003) obtained the same conclusion in their experiments.

According to the calibration graph in Figure 3, the K_a value changes 0.414 for each 0.1 Mg m^{-3} increase in soil BD, that result in 0.0054 m^3 m^{-3} error in measurement of soil water content (by applying Equation 1) if a proper calibration was not considered. The results are in

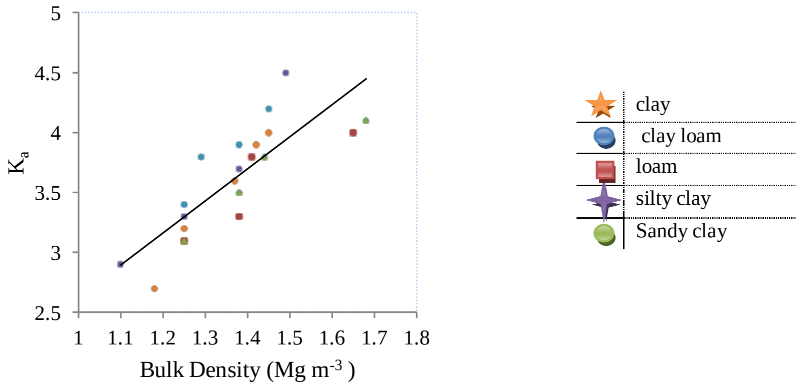

Figure 3. The relationship between soil bulk density and its corresponding K_a.

Table 3. The $K_a^{0.5}$ at different soil water content and bulk density calculated using three equations at two bulk densities.

Whalley's equation		Calibration from Figure 3 and Equation (1)		Malicki's equation		Water content (m^3 m^{-3})
1.5 Mg m^{-3}	1 Mg m^{-3}	1.5 Mg m^{-3}	1 Mg m^{-3}	1.5 Mgm^{-3}	1 Mg m^{-3}	
2.193	1.976	2.130	1.950	1.840	1.590	0.047
2.667	2.450	2.540	2.290	2.322	2.041	0.100
3.561	3.324	3.338	3.188	3.216	2.890	0.200
4.555	4.230	4.132	3.982	4.110	3.733	0.300

agreement with the experimental results of Jones and Friedman (2000). Table 3 compares the calculated square root of dielectric constant at different BDs using the Malicki's equation and using the calibration from Figure 3, Equation (1) and Whalley's Equation (1993). As soil water content of 0.1 m^3 m^{-3}, the calculated $K_a^{0.5}$ values using above equations were similar. The increase in $K_a^{0.5}$ was 0.282, 0.15, and 0.217 using the Malicki's equation, calibration from Figure 3, Equation 1, and Whalley's model, respectively. At soil water content of 0.3 m^3 m^{-3} the increase was 0.477, 0.15, 0.225 for the Malicki's equation, the calibration from Figure 3, and Equation 1, and Whalley's model, respectively, as soil BD going up from 1.0 Mg m^{-3} to 1.5 Mg m^{-3}. However, there was a substantial difference when soil water content was low. The rate of increase in $K_a^{0.5}$ as soil BD increases as predicted by the Malicki and Whalley equations are faster than that of shown in Figure 3. At 0.2 m^3 m^{-3} soil water content Malicki's equation predicts a 0.326 increase in $K_a^{0.5}$ as the soil BD goes up from 1.0 to 1.5 Mg m^{-3} for dry soil .This results also show that with an increase in water content (from 0.047-0.3 m^3 m^{-3}) the effect of BD is increased. Yuanshi et al. (2003) obtained the same conclusion in their experiments.

The effect of clay content

Table 4 shows that the slope of the linear relationship between $K_a^{0.5}$ and $\frac{1}{K_w^{0.5}-1}$. When the clay content increases, the amount of offset decreases thereby the slope increases (Yuanshi et al, 2003). The slope for loamy soil was not significantly different from silty clay, clay loam and sandy clay. However, the slope for two textures of clay loam and silty clay were significantly different. Results showed a high decrease in slope of clay loam and silty clay T-Gharasan and S-Gharasan. The amount of dielectric constant is different from other soils. This might be because of high salinity or clay minerals. With increase in the amount of clay content in all soils (except T-Gharasan) the dielectric constant decreased, because of increase in surface area of solid particles and the amount of bound water.

Figure 4 shows two clay texture soils with 61.64 and 56.64 percent clays having nearly similar minerals. With increase in clay percentage of the soil, dielectric content is decreased (Figure 5). The soil clay content might have a considerable effect on time delay of EM waves and soil water content.

Firstly, the bound water of clay particles has a much lower dielectric constant than free water. This allows the faster movement for EM waves, and therefore underestimates the water content, especially in the low moisture range where the ratio of bound water to free water is high. Secondly, clay soils usually possess higher bulk EC than loamy soils. The bulk EC comes from the ionic concentration in soil solution and the charged

Table 4. Dielectric constant for soils with different textures.

Location	Texture	Clay content (%)	Slope	Dielectric constant of soil water (K_w)
T-Daneshghah	Loam	26.0	0.1272	78.52
S- Daneshghah	Loam	26.0	0.1271	78.63
T-Takestan	Clay loam	28.6	0.1277	77.98
T-Soltan	Sandy clay	36.1	0.1278	77.87
T-Gharasan	Clay loam	38.1	0.1170	91.14
S- Soltan	clay loam	39.1	0.1275	78.20
S-Gharasan	Silty clay	39.6	0.1171	91.00
S-Takestan	Clay	56.6	0.1278	77.87
S-Shal	Clay	57.6	0.1312	74.33
T-Shal	Clay	61.6	0.1370	68.87

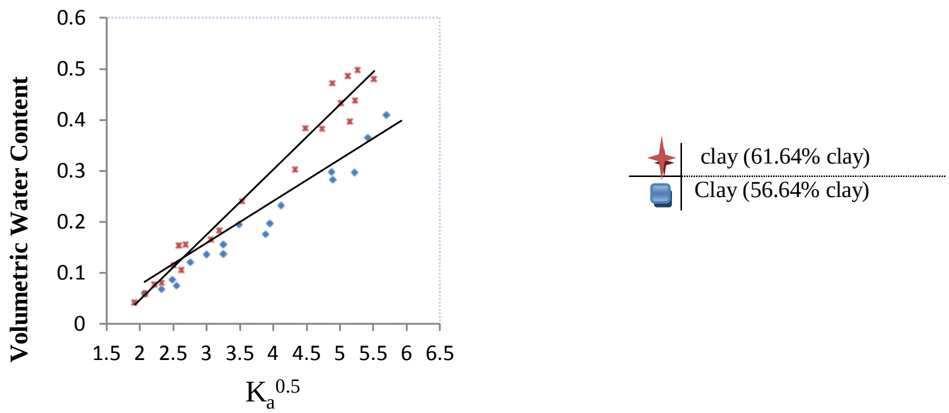

Figure 4. The effect of clay content on dielectric constant in clay texture with 56.64 and 61.64 clay percent.

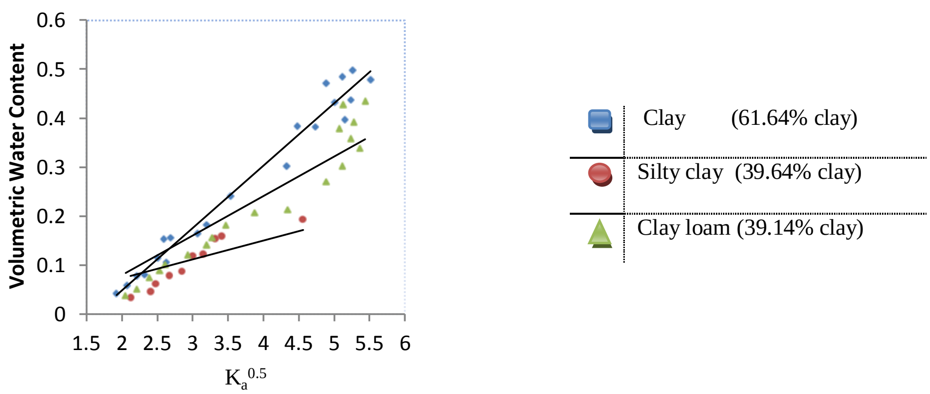

Figure 5. The effect of clay content on dielectric constant in different clay, silty clay and clay loam texture.

particle surface. The EC would cause signal attenuation and an overestimation of water content, especially in the high water content range where the EC is high and the ratio of bound water to free water is low (Sun et al.,

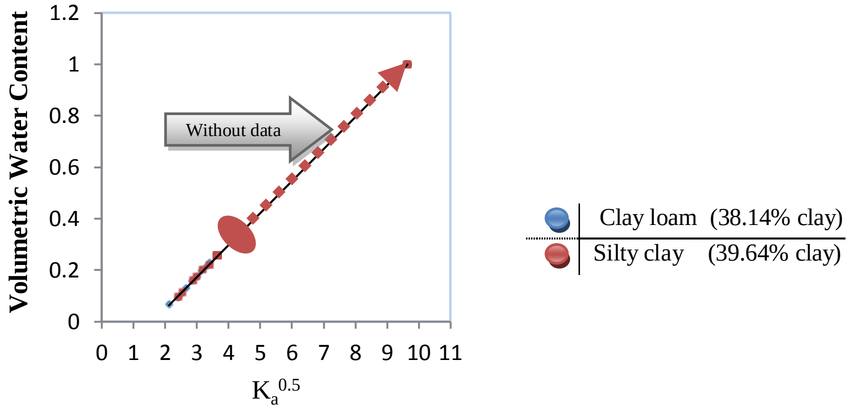

Figure 6. The effect of clay content on dielectric constant in clay with smectite mineral.

2000). The results also show that soil with high surface area such as Smectite had more effect on dielectric constant than other clays such as Chlorite and Illite to decrease dielectric constant. Results showed that only at very high moisture level, where the volume fraction of bound water to total water is very small, the effect of bound water can be neglected. In low moisture level the effect of bound water is significant (Yuanshi et al., 2003).

Figure 6 shows the relationship between water content and $K_a^{0.5}$. In this soil, the dielectric constant before specific point (0.22 m^3 m^{-3}) increased and after this point the amount of dielectric constant was unchanged. For following soils with increasing the number of replicates for different level of salinity the results will be nearly the same. When clay minerals of the soils S-Gharasan and T-Gharasan examined the results showed that they are different from other soils because of having about 95 percent Smectite (Table 2). Early in 1968, Mitchell and Arulanandan (1068) described that clay mineral affected on frequency of TDR. This study showed that the amount and type of clays in soils have significant effects on dielectric constant. This effect was due to the influence of clay mineral on the wave frequency of TDR which can finally affect dielectric constant in natural clay soils and water–clay mixtures that has been already studied by Hoesktra and Delaney (1974), Hipp (1974), Campbell (1990), Arulanandan (1991), Wensik (1993), Zerwer and Santamarina (1994), Fam and Santamarina (1996), Saarenketo (1998), and Ishida et al. (2000). Experimental results showed that in the high frequency range [50 MHz–1.3 GHz], Smectite group has a more dielectric dispersion than other clay groups (Arulanandan, 1991; Saarenketo, 1998; Ishida et al., 2000 and Santamarina, 2001). However, the microscopic phenomena associated to the dielectric dispersion of clays are still a subject of considerable debate.

Conclusion

The effect of soil bulk density and clay content on TDR measurements has been discussed. The time delay of EM waves of TDR and the square root of the apparent dielectric constant of soil are both increased linearly with soil bulk density. For soil with high clay contents, TDR underestimate soil water content in the low moisture range because the bound water effect is dominant. Thus, for calibration of TDR for measuring soil water content the effect of soil bulk density and clay content have important roles on the accuracy of the measurements.

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