Development of a Real-Time Soil Moisture Meter using Oscillation Frequency Shift Method

K. B. Kim, N. H. Lee, J. W. Lee, S. S. Lee, S. H. Noh

Abstract: The objective of this study was to develop a real-time soil moisture meter using RF impedance. The impedance such as capacitance and resistance (or conductance) was analyzed using parallel cylinder type capacitance probe (C-probe) and Q-meter (HP4342). The capacitance and conductance of soil increased as volumetric water content increased. The 5 MHz of modified Colpitts type crystal oscillator was designed to detect the capacitance change of the C-probe with moist soil. A third order polynomial regression model was proposed to describe the relationship between RF impedance and volumetric water content. The prototype real time moisture meter consisted of the C-probe, sample container, oscillator, frequency counter and related signal processing units. The calibration equation for measurement of volumetric moisture content of soil was developed and validated. The correlation coefficient and root mean square error between measured volumetric water content by oven method and predicted values by prototype moisture meter for unknown soil samples were 0.984 and 0.032 cm^3cm^{-3}, respectively.

Keywords: Volumetric water content, Crystal oscillator, Oscillation frequency shift, Parallel cylinder type C-probe, Real-time soil moisture meter

Introduction

Real-time measurement of soil moisture content has been a research concern for efficient irrigation and drainage management. Traditionally, soil moisture sensors such as the potentiometer and gypsum block have been widely used. These are simple and inexpensive method. However, the potentiometer has some measurement errors caused by variations of hydraulic pressure in soil and the gypsum block methods should be changed frequently because of corrosion (Hillel, 1980).

The time-domain reflectometry (TDR) technique has been developed using the electromagnetic properties such as dielectric constant, loss factor and conductivity of soil. The principle of TDR is based on a propagation velocity variation of electromagnetic wave on a transmission path containing the dielectric materials such as soil (Topp et al., 1982). Because the dielectric constant of water (more than 80) is much higher than that of dry soil, the property can be used to measure soil moisture content. The relationship between dielectric constant of soil and volumetric water content was correlated as a third order polynomial function (Topp et al., 1980). However this TDR measurement depends on soil types (Campbell, 1990) requiring special types of TDR probe, transmission line tester, signal generator and oscilloscope to measure the amplitude and phase shift of the reflected wave from soil. Thus the initial cost of a TDR device is high (Gardner et al., 1991).

A technique using the dielectric constant directly evaluates the capacitance of an electrode type soil moisture sensor (Tomer and Anderson, 1995, Ruth, 1999, Rial and Han, 2000) or measures the resonant frequency shift as the capacitance change of the capacitive sensing of moist soil samples (Wobschall, 1978). This method requires simple implementation and low cost compared with TDR method. Mostly, since the shape of the sensor is parallel plate or concentric cylinder type, the sensitivity is higher than any other type of the sensor but it may be unfavorable for the

(Submitted in March 2001; Reviewed in May 2001; Approved in June 2001)
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water potential flow in soil.

Theoretically, permittivity (or dielectric properties) of a material depends on the concentration and activity of permanent electric dipole molecules and ionic bonded molecules, and on the degree of dipole alignment to the changes in electromagnetic field applied. The relative complex permittivity is often represented by the complex number $\varepsilon = \varepsilon' - j\varepsilon''$, where, ε', is usually associated with the ability of a material to store electric-field energy, the imaginary part, ε'', represents the loss of electric field energy in the material and is related to conductivity.

The dielectric properties of soil are highly affected by moisture concentration in the soils. Other factors affecting the dielectric constant of soil are frequency, ionic conductivity, soil compactness, mineral contents and various soil types (Campbell, 1990, Wobschall, 1977, 1978, Hallikainen, 1984).

In this paper, the RF impedance such as capacitance and resistance (or conductance) are presented with parallel cylinder type capacitance probe and Q-meter at 5 to 30 MHz. Prototype real time soil moisture meter using the dielectric property of soil is then proposed.

Materials and Methods

1. Soil sample preparation

Three types of moist soil samples were used for this study. The compositions of all soil types in terms of sand, silt and clay percentages and particle sizes are shown in Fig. 1. These compositions are based on the USCS (United Soil Classification System). The soil type II was pure graded sand and non-plastic. The characteristic of soil type I and III showed from well-graded sand to silty sand and were non-plastic. The specific weights of soil type I, II and III were 2.66, 2.69 and 2.73, respectively. All soil samples were dried thoroughly at air oven and hence the effects of organic matters in soil samples on electrical measurements were not considered.

In order to make various water content levels of soil samples, distilled water was added to dry soil and thoroughly mixed. And the mixture moist soil samples were stored at a constant temperature and humidity chamber for one week. The ranges of volumetric water content of soil type I, II and III were 0.019-0.404 cm^3cm^{-3}, 0.015-0.587 cm^3cm^{-3} and 0.016-0.696 cm^3cm^{-3}, respectively. Soil samples were filled into the rectangular sample container with arbitrary densities.

The volumetric water content was determined by the forced-air oven method (24-hours, 105℃) and are expressed as;

$$\theta = \frac{V_W}{V_T} \quad \cdots\cdots (1)$$

where, θ is the volumetric water content (cm^3cm^{-3}), V_W is volume of water (cm^3) and V_T is total volume of soil (cm^3).

All experiments were conducted at ambient temperature of 21±1℃.

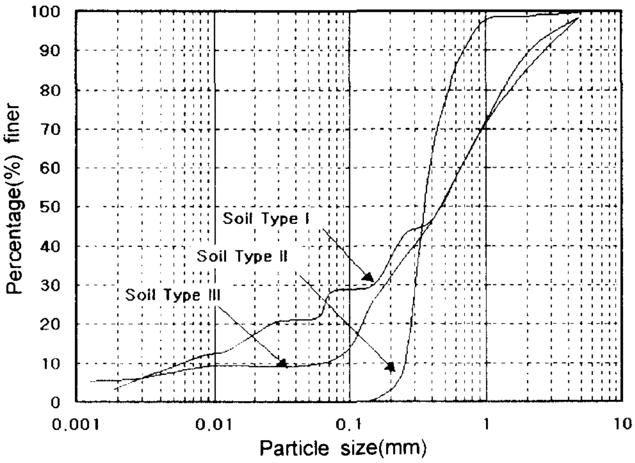


Fig. 1 Grain size distribution of soil samples.

2. Capacitive soil moisture sensor

As a soil moisture sensor, parallel cylinder type capacitance probe (C-probe) was fabricated as is shown in Fig. 2 and have been mainly used for TDR soil moisture meter. The length, L and radius of cylinder, a are 50 mm and 5 mm, respectively. The distance between centers of cylinders, b is 11 mm. From the geometry of the C-probe, the theoretical capacitance (Cc) of the C-probe with soil of which dielectric constant is ε'_S is expressed as following equation (Baxter, 1997) ;

$$C_C = \frac{\pi\varepsilon_o\varepsilon_S'}{\ln\left\{\frac{b+\sqrt{b^2-4a^2}}{2a}\right\}}L \quad \cdots\cdots (2)$$

where ε_o is the permittivity of free space(8.854×10^{-12} F/m).

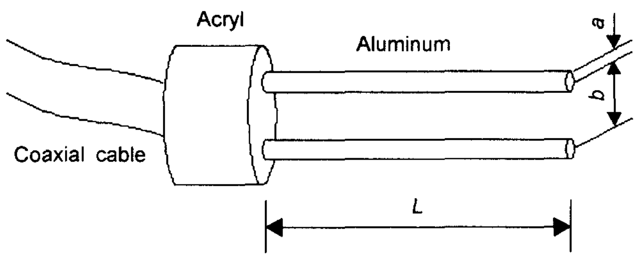


Fig. 2 Parallel cylinder type soil moisture sensor.

3. RF impedance measurement system

RF impedance of soil type I was characterized by using the Q-meter (HP4342) as is shown in Fig. 3. The C-probe was inserted to rectangular sample cell of which volume is 175 cm^3 filled with soil. The range of the measuring frequency was selected from 5 to 30 MHz because at low frequency (less than 1 MHz), the impedance of soil may be affected by the ionic conductivity and the mineral content in soil samples (Wobschall, 1977, Campbell, 1990). From the Q-meter measurement system, the capacitance of the sample cell containing soil samples and the C-probe (C_C) is expressed as;

$$C_C = C_O - C_O' \quad (3)$$

where, C_O is capacitance (pF) at first resonance point of Q-meter without sample cell and C_O' is capacitance at second resonance point of Q-meter with sample cell.

The resistance of the sample cell with soil samples (R_C) is expressed as;

$$R_C = \frac{1}{2\pi f C_O}\left(\frac{1}{Q_O'} - \frac{1}{Q_O}\right) \quad (4)$$

where, f is measuring frequency in *MHz*, Q_O' is the Q value of the Q-meter at second resonance point with sample cell and Q_O is the Q value of the Q-meter at first resonance point without sample cell.

From the equations of (2), (3) and (4), it may be assumed that the impedance of sample cell including soil and C-probe is proportional to the dielectric properties of the soil as;

$$\varepsilon_S' \propto C_C \quad (5)$$

$$\varepsilon_S'' \propto (1/R_C) = G_C \quad (6)$$

where, ε'' is dielectric loss factor and G_C is conductance (*mho*) of the sample container with the soil and C-probe.

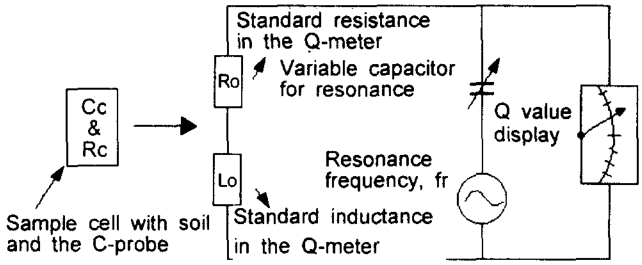


Fig. 3 RF impedance measurement system using Q-meter (HP4342).

4. Design and construction of a prototype real time soil moisture meter

5 MHz of crystal oscillator with frequency counter method was used to detect the RF capacitance change of the C-probe (Fig. 4). The design criteria of the electronic circuit were stability of oscillating wave shape, temperature compensation, noise minimization and linearity of frequency generation within the capacitance range of the C-probe containing various conditions of soil.

The electrical oscillator coupling the C-probe was constructed by modification of Colpitts type oscillator using NAND gate, the crystal and the C-probe (Fig. 4). The fabricated oscillator has good temperature stability. After the 5MHz of initial frequency was adjusted by variable capacitor to 5.000 ∓ 0.002MHz, the sample cell including soil samples and the C-probe was connected to the oscillator by the relay (Fig. 5).

When the C-probe is connected to the crystal oscillator with parallel, the oscillation frequency of the oscillator is shifted by the capacitance (C_C) of the C-probe as;

$$f_r' = f_r - \Delta f \quad (7)$$

where, f_r is the oscillation frequency without the C-probe, f_r' is the oscillation frequency change with the C-probe, Δf is oscillating frequency variation due to the capacitance change of the C-probe including soil samples.

A prototype soil moisture meter as is showin Fig. 5 was constructed with the C-probe, soil sample container (50 by 30 by 30 cm), 5 MHz of oscillator, frequency counter, microprocessor, EEPROM and LCD module. The calibration equation for volumetric moisture content is built in ROM of microprocessor. After the binary counts of oscillation frequency are converted to real frequency unit in MHz by the program stored in the ROM of microprocessor, the volumetric water content is displayed on LCD.

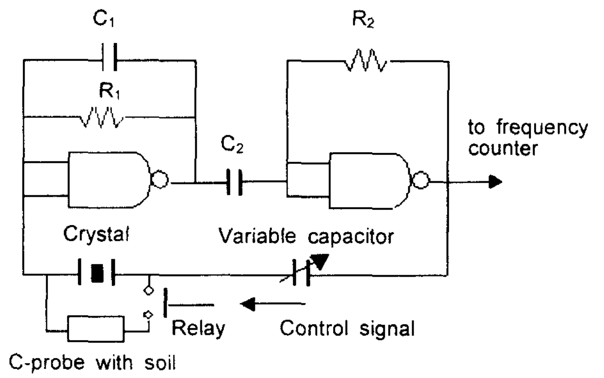


Fig. 4 Circuit diagram of electric oscillator.

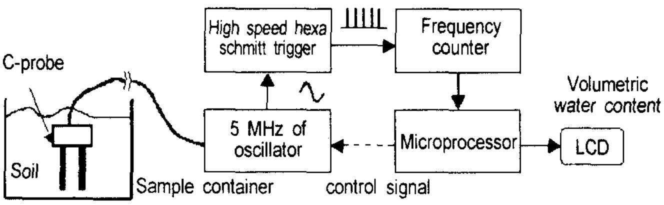


Fig. 5 Block diagram of the prototype real time soil moisture meter.

Results and Discussion

1. RF impedance of soil

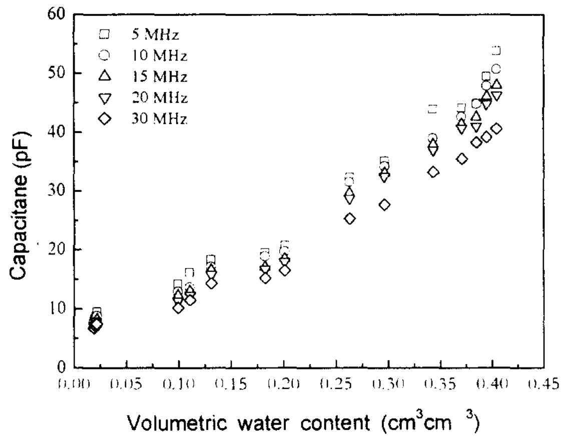
The impedance of the C-probe of soil type I with various volumetric water contents(0.019-0.404 cm^3cm^{-3}) were determined by using Q-meter. The capacitance and conductance was illustrated in Fig. 6. The capacitance and conductance at each measuring frequency increased as volumetric water content increased with polynomial relationships, respectively. Because the water content in soil samples mainly affects the permittivity, the capacitance and conductance increase. However the frequency dependence was not significant to volumetric water content.

Based on the relationship between impedance and volumetric water content, the third order of polynomial regression model was assumed and analyzed for soil type I;

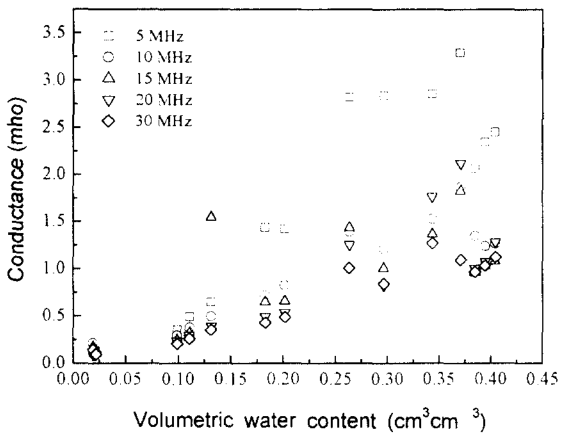
$$\theta = aC_C^3 + bC_C^2 + cC_C + d \quad \cdots\cdots (8)$$

$$\theta = aG_C^3 + bG_C^2 + cG_C + d \quad \cdots\cdots (9)$$

where, *a*, *b*, *c* and *d* are coefficients specific to each regression.



(a) Capacitance vs. volumetric water content



(b) Conductance vs. volumetric water content

Fig. 6 RF impedance vs. volumetric water content (cm^3cm^{-3}) of the soil type I at indicated frequency levels and ambient temperature of 21±1℃.

The statistical analysis results are summarized in Table 1. The volumetric water content is highly significant to capacitance of the C-probe with correlation coefficients of greater than 0.98 regardless of the measuring frequency. From the results of equation (8), it may be concluded that the capacitance of the C-probe containing soil samples is good promising factor for measurement of volumetric water content of soil.

Table 1 Regression analysis results between the impedance of the C-probe and volumetric water content of soil type I (Eqn. (8) and (9)) at different frequencies and ambient temperature of 211℃

Dependent variable	Frequency (MHz)	5	10	15	20	30
Capacitance	Correlation coefficient	0.983	0.987	0.992	0.992	0.993
	Root mean square error	0.023	0.026	0.021	0.021	0.020
Conductance	Correlation coefficient	0.950	0.963	0.957	0.973	0.978
	Root mean square error	0.051	0.044	0.041	0.038	0.034

2. Measurement of volumetric water content with prototype soil moisture meter

The oscillation frequency change of the prototype soil moisture meter for soil samples (soil type II and III in Table 1) was analyzed. Fig. 7 shows representative results for the effect of volumetric water content on oscillator output frequency.

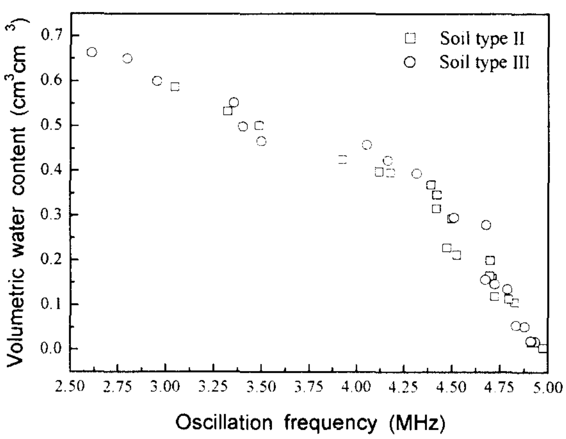


Fig. 7 Oscillation frequency changes of the oscillator depending on volumetric water content of soil type II and III at initial frequency of 5 MHz and ambient temperature of 21±1℃.

Regression analysis to determine the relationship between the volumetric water content and oscillation fequency change was made with the following polynomial model as;

$$\theta = af_r'^3+bf_r'^2+cf_r'+d \quad \cdots\cdots\cdots\cdots (10)$$

Table 2 presented that the coefficients of determination and root mean square errors of each soil sample were 0.979 and 0.028cm^3cm^{-3} for soil type II and 0.983 and 0.033 cm^3cm^{-3} for soil type III, respectively. For all samples, coefficient of determination and root mean square error were 0.979 and 0.031cm^3cm^{-3}, respectively. Hence, it may be possible to express one calibration equation between volumetric water content and oscillation frequency change regardless of soil type.

Based on the above results, the calibration equation for determination of volumetric water content for all soil samples was developed as;

$$\theta = -0.1066\times f_r'^3+1.1135\times f_r'^2-3.9952f_r'+5.4218 \cdots (11)$$

The calibration equation (11) was built in the ROM of microprocessor of prototype soil moisture meter and then the performance was tested with soil type II and III having unknown volumetric water content. Results are shown in Fig. 8, the measured values by oven method are in good agreement with the predicted

Table 2 Regression analysis expressing the volumetric water content dependence of the oscillation frequency at initial frequency of 5 MHz and ambient temperature of 21±1℃

Soil type	Regression coefficients				Determination coefficient	Root mean square error
	a	*b*	*c*	*d*		
II	-0.0969	1.0194	-3.7174	5.1846	0.979	0.028
III	-0.1425	1.5070	-5.3904	7.0271	0.983	0.033
All samples	-0.1066	1.1135	-3.9952	5.4218	0.979	0.031

Model: $\theta = af_r'^3+bf_r'^2+cf_r'+d$

values by prototype soil moisture meter. The correlation coefficient and the root mean square error were 0.987 and 0.032 cm^3cm^{-3}, respectively.

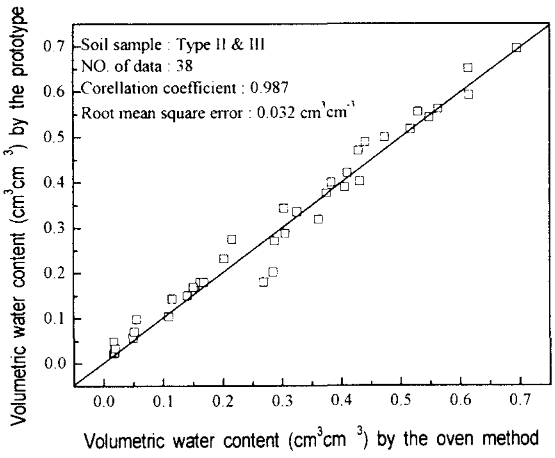


Fig. 8 Performance test results of prototype soil moisture meter for unknown volumetric water content of soil type II and III at ambient temperature of 21±1℃.

Conclusions

Based on preliminary results presented in this paper, the following conclusions can be made.

The impedance of the C-probe containing the soil samples increased as volumetric water content increased in the range of 5 to 30 MHz. The third order polynomial relationship was presented between volumetric water content and RF impedance of the C-probe including soil samples for all measuring frequencies. The volumetric water content is highly significant to capacitance of the C-probe with correlation coefficients of greater than 0.98 regardless of the measuring frequency.

The 5 MHz of oscillator with frequency counter method was used to detect the RF capacitance change of the C-probe. The third order polynomial model including the oscillation frequency shift as independent variable and volumetric water content as dependent variable was developed.

A prototype soil moisture meter was constructed and its performance was tested. As a result, its correlation coefficient and the root mean square error were 0.987 and 0.032 cm^3cm^{-3} as compared with the oven method. The technique for volumetric water content measurement based oscillation frequency shift method may provide a promising method for devleopment of a practical insturments in sensing soil moisture content. However the additional studies such as *in-situ* measurement and characterizing the effect of organic matters and soil temperature are required.

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