12.3: Contributions to the Measured Capacitance by the Dielectric Properties of Water in Insulated Electrode Soil Moisture Sensors

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Abstract
In a soil/water matrix, water has a much higher dielectric constant than that of the other soil components. Capacitance measurement methods are often used to measure the soil water content. Many capacitance soil moisture sensors employ a probe consisting of two electrodes of which one or both are insulated from the matrix. The capacitance between the probes varies as a function of water content. Theoretical analysis of a sensor arrangement employing two electrodes with an insulating coating is performed and compared to experimentally derived data. Both show that conduction effects within the matrix mask the contribution to the measured capacitance by the dielectric properties of water.

INTRODUCTION
Soil water sensors relying on changes in capacitance due to soil water content are commonplace. Several probes, one or more being insulated, are embedded in the soil and some form of circuitry used to measure the capacitance between the probes. Many use the capacitance to vary the frequency of oscillation of a multivibrator or some other form of oscillator [1-3]. Others such as Time or Frequency Domain Reflectometry measure the effect on a RF pulse due to soil impedance.

In sensors operating at mid frequencies the effective capacitance seen across the probes is influenced by both the dielectric and conductivity properties of the soil/water matrix. With decreasing frequency (DC to kHz) the conductivity properties become increasingly important, while conversely at higher frequencies (>10MHz) the dielectric effects become the important property.

Where one or more of the probes is insulated from the soil/water matrix and the probe is operated at mid frequencies the measured capacitance depends on:

1. The dielectric constant and thickness of the insulation
2. The effective area contacting a conducting medium(soil/water)
3. The conductivity of the conducting medium
4. The effective area contacting a high dielectric constant medium(water as dielectric WAD)

The possibility therefore exists that measurements of water content may be distorted by variations in soil/water conductivity.

Both the impedance component due to the water as dielectric (WAD) and the resistive component due to soil/water conductivity are proportional to the probe separation and inversely proportional to the probe surface areas. The ratio between these is therefore only frequency dependant and independent of probe configuration. The impedance component due to the insulation is dependent on insulation thickness, dielectric constant, surface area and frequency but not soil/water conductivity.

In a patent for a soil moisture monitor [1] it is pointed out that the WAD component is swamped by the conductivity of the soil/water matrix.

A sensor being designed uses the probe capacitance as part of a RC network and measures the charge and discharge times of the network.

By varying the initial charge stored on the WAD component of the probe capacitance and analyzing the discharge curves it should be possible to determine the soil/water conductivity and water content using one probe.

The following model and experimental results support this idea but only for very low conductivity. At higher conductivity the WAD component is masked completely.

Modeling
In the probe arrangement used by this sensor and others where an insulating coating covers the probes a circuit is formed between the two probes(Figure 1) by the soil/water matrix. The resulting network can be regarded as effectively 3 series capacitors with the middle capacitor (C3) bridged by a resistance (R2) dependant on the matrix conductivity. The resulting charge/discharge characteristic of this network is therefore dependent on both water content and water conductivity. Capacitor C2 (series C2a and C2b) is dependent on the proportion of conductive material contacting the probe areas. If it is assumed that most soil components are poor conductors then the connection that the plates make with the water component determine the value of C2. Capacitor C3 is dependent on water content through the dielectric properties of water. C1 is made up of stray circuit capacitance.

If water content is to be determined from the overall capacitance of the probe/soil/water system without consid-
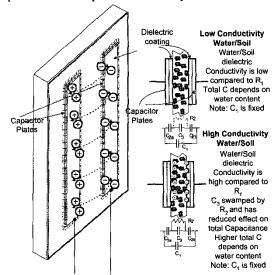

Figure 1 Model of probes in soil.

eration of soil conductivity, errors will result where the value of R2 is sufficiently high to allow C3 to effect the circuit operation, i.e. in very low conductivity soil/water matrixes.

The present work aims to determine the range of soil/water conductivity for which C3 can safely be ignored and so the measured water content is a simple function of C2. It also aims to develop methods to separate values for conductivity and water content from the short-term charge /discharge behavior of the network and how this is effected by the parallel R2//C3 component.

For long (>>RC) charging pulses applied to the network, the time taken to charge the network comprising the sensor and soil/water matrix should equal the time taken to discharge that network. This is because any charge stored on C3 will be dissipated in R2 in the long term, however if a discharge cycle is begun earlier during the charge cycle then some charge will remain on C3 and the time taken to discharge the network will reflect this. By varying the time allowed for charging (t1) and measuring the time taken to discharge (t2) as a function of t1, it should be possible to determine the R2 and C3 components.

Capacitance C3 should only be proportional to water content and R2 inversely proportional to conductivity (σ) and water content. The time constant of these two components is proportional to $1/\sigma$.

The first step in this process is to model the behavior of the network for different allowed charging times, water content and conductivity and compare the results to experiment.

Mathematical Modeling and Simulation

Initially the circuit including electronics was modeled with circuit simulation software to check for agreement across a range of values. Values for C1, C2 and C3 were estimated from measurements made with the probes in air, in saturated saline solution and in distilled water. The Spice simulations for different water contents were made by scaling the values of C2, C3 and R2 by a fraction representing the water content fraction. This assumes that these 3 components are similarly effected by water content. The charge and discharge times produced in the simulation were similar to the experimental results.

The three differential equations for the sensor probe and soil/water combination were then solved symbolically using Laplace transforms to obtain three functions for the 3 current loops. These functions were used to find the currents flowing in the network as a function of time, soil/water matrix conductivity and water content. The calculations were performed in Mathcad and automated using a Visual Basic Macro running in Excel.
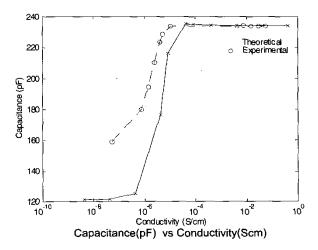

Figure 2 Comparing Theory to Experiment

The results of these calculations indicate that the charge and discharge times obtained for various values of water content is effected by conductivity less than 10^{-5}Scm (Figure 2) i.e. the dielectric effect of C2 becomes masked by the effects of the conductivity (R2) and can be disregarded.

Plots (Figure 3) of the ratio of the charge time to discharge time for a range of high R2 values show a region where it should be possible to measure both conductivity and water content. For lower values the ratios remain constant over a wide range R2 values and it will not be possible to measure conductivity using this information. This is the region covering normal soil/water conductivity. This is yet to be confirmed by experiment.
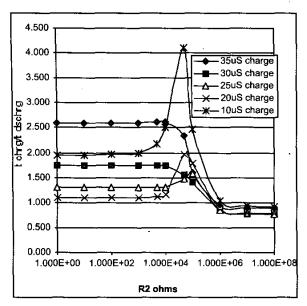
Figure 3 Charge to discharge times ratio for five different allowed charging times versus R2

Transient Analysis.

By combining C2a and C2b as C2 the following network (Figure 4) can be used to represent the probe/soil system where V is applied at t=0.
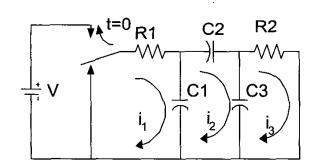

Figure 4 Lumped impedance model of probe.

$$R_1 \cdot i_1 + \frac{1}{C_1} \int_0^{t_1} i_1 \, dt - \frac{1}{C_1} \int_0^{t_1} i_2 \, dt = V \cdot u(t)$$

$$\frac{-1}{C_1} \cdot \int_0^{t_1} i_1 \, dt + \frac{1}{C_1} \cdot \int_0^{t_1} i_2 \, dt + \frac{1}{C_2} \cdot \int_0^{t_1} i_2 \, dt$$

$$+ \frac{1}{C_3} \cdot \int_0^{t_1} i_2 \, dt - \frac{1}{C_3} \cdot \int_0^{t_1} i_3 \, dt = 0$$

$$R_2 \cdot i_3 - \frac{1}{C_3} \cdot \int_0^{t_1} i_2 \, dt + \frac{1}{C_3} \cdot \int_0^{t_1} i_3 \, dt = 0$$

The three simultaneous equations have the following Laplace transformations where the term $q_n(0)$ represent the charge on capacitor C_n at t=0

$$R_1 \cdot I_1(s) + \frac{1}{C_1} \left(\frac{I_1(s)}{s} + \frac{q_1(0)}{s} \right) - \frac{1}{C_1} \left(\frac{I_2(s)}{s} \right) = \frac{V}{s}$$

$$\frac{-1}{C_1} \left(\frac{I_1(s)}{s} \right) + \frac{1}{C_1} \left(\frac{I_2(s)}{s} - \frac{q_1(0)}{s} \right) + \frac{1}{C_2} \left(\frac{I_2(s)}{s} + \frac{q_2(0)}{s} \right)$$

$$\left. \right\} + \frac{1}{C_3} \left(\frac{I_2(s)}{s} + \frac{q_3(0)}{s} \right) - \frac{1}{C_3} \left(\frac{I_3(s)}{s} \right) = 0$$

$$R_2 \cdot I_3(s) + \frac{-1}{C_3} \cdot \left(\frac{I_2(s)}{s} \right) + \frac{1}{C_3} \left(\frac{I_3(s)}{s} - \frac{q_3(0)}{s} \right) = 0$$

$$I_1(s) = \frac{d \cdot s + f}{a \cdot s^2 + b \cdot s + c}$$

$$I_2(s) = \frac{u \cdot s^2 + v \cdot s + w}{a \cdot s^2 + b \cdot s + c}$$

$$I_3(s) = \frac{1}{C_2} \frac{n \cdot s + p}{a s^2 + b \cdot s + c}$$

Solutions to the simultaneous equations

where

$$a = R_2 \cdot C_3 \cdot R_1 \cdot C_2 + R_2 \cdot C_3 \cdot R_1 \cdot C_1 + R_2 \cdot R_1 \cdot C_1 \cdot C_2$$

$$b = R_2 \cdot C_2 + R_1 \cdot C_2 + R_1 \cdot C_1 + R_2 \cdot C_3$$

$$c = 1$$

$$\left| d = \left(-R_2 \cdot C_3 \cdot q_1(0) + C_3 \cdot C_1 \cdot R_2 \cdot V - R_2 \cdot C_3 \cdot q_2(0) - R_2 \cdot q_3(0) \cdot C_2 \right.\right.$$
$$\left.\left. + R_2 \cdot C_1 \cdot V \cdot C_2 + R_2 \cdot C_3 \cdot V \cdot C_2 - R_2 \cdot C_2 \cdot q_1(0) \right) \right.$$

$$\left| f = -q_2(0) + C_1 \cdot V - q_1(0) + V \cdot C_2 \right.$$

$$n = \left(R_1 \cdot C_1 + C_2 \cdot R_1 \right) q_3(0) + q_1(0) \cdot C_2 \cdot R_1 - R_1 \cdot C_1 \cdot q_2(0)$$

$$p = -q_2(0) + V \cdot C_2 + q_3(0)$$

$$u = \left(C_3 \cdot q_1(0) \cdot C_2 \cdot R_2 \cdot R_1 - C_3 \cdot q_2(0) \cdot R_2 \cdot R_1 \cdot C_1 \right.$$
$$\left. - C_1 \cdot q_3(0) \cdot C_2 \cdot R_2 \cdot R_1 \right)$$

$$v = \left(-R_2 \cdot C_3 - R_1 \cdot C_1 \right) q_2(0) + q_1(0) \cdot C_2 \cdot R_1 - R_2 \cdot q_3(0) \cdot C_2$$
$$+ R_2 \cdot C_3 \cdot V \cdot C_2$$

$$w = V \cdot C_2 - q_2(0)$$

Finding the inverse Laplace transforms

$$i_1(t) = \frac{d \cdot x_1 + f}{a \cdot (x_1 - x_2)} \cdot e^{x_1 \cdot t} + \frac{d \cdot x_2 + f}{a \cdot (x_2 - x_1)} \cdot e^{x_2 \cdot t}$$

$$i_2(t) = \frac{u}{a} \cdot dirac(t) + \frac{\left(v + u \cdot \frac{-b}{a}\right) \cdot x_1 + \left(w + u \cdot \frac{-c}{a}\right)}{a \cdot (x_1 - x_2)} \cdot e^{x_1 \cdot t}$$

$$+ \frac{\left(v + u \cdot \frac{-b}{a}\right) \cdot x_2 + \left(w + u \cdot \frac{-c}{a}\right)}{a \cdot (x_2 - x_1)} \cdot e^{x_2 \cdot t}$$

$$i_3(t) = \frac{n \cdot x_1 + p}{a \cdot (x_1 - x_2)} \cdot e^{x_1 \cdot t} + \frac{n \cdot x_2 + p}{a \cdot (x_2 - x_1)} \cdot e^{x_2 \cdot t}$$

where

$$x_1 = \frac{\frac{-b}{a} + \left[\left(\frac{b}{a}\right)^2 - 4 \cdot \frac{c}{a}\right]^{0.5}}{2} \quad x_2 = \frac{\frac{-b}{a} - \left[\left(\frac{b}{a}\right)^2 - 4 \cdot \frac{c}{a}\right]^{0.5}}{2}$$

The voltages appearing across the probes as a function of time were calculated in MathCad from the loop currents. The voltages were solved for ranges of C2, C3, R2 and varying charging times. The MathCad calculations were called from a Visual Basic macro running in Excel.

Further calculations were made using these results to find the expected output pulse length from the sensor electronics (a HCMOS Schmidt trigger NAND gate)

Experimentation

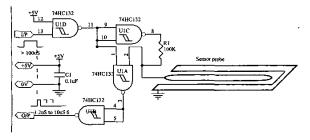A probe was fabricated on printed circuit board and an

Figure 5 Probe test circuit

insulating coating applied over the probes. A square wave with a period much greater than the probe time constant was applied to one electrode through a 100Kohm resistor. The other electrode connected to system ground (Figure 5). A HCMOS Schmidt trigger NAND gate was used to measure the delay between removal of the pulse and the discharge of the probe system.

The probes were placed in water samples of increasing conductivity. Small increases in conductivity caused by the addition of NaCl initially increases the sensor reading but ceases to have any appreciable effect beyond around 10^{-5}Scm (Figure 2). It only took a very small increase in conductivity to cause a large change in reading when the water was very pure. i.e. a couple of drops of 100g/l saline in 200ml of distilled had a very noticeable effect on probe capacitance.

Conclusion

In conclusion, the measurement of capacitance for soil moisture using this type of sensor is independent of variations in soil conductivity in conductive soil/water matrixes. There is a possibility of measuring both conductivity and water content together in soils of very low conductivity.

REFERENCES

[1] Bireley, R.L., Soil Moisture Monitor. 1989, USA Patent 4850386

[2] Feniger, I.G.A.F.N., Soil Moisture Sensor. 1995, USA Patent 5424649

[3] P.J.Ross, A water level sensor using a capacitance to frequency converter. J.Phys.E: Sci. Instrum., 1983. 16: p. 827-828.