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Research Article

Influence of Electrical Double Layer in the Electrical Model for Capacitance-based Soil Moisture Sensor on Measuring Soil Moisture

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Abstract: The reasonable electrical model for Capacitance-Based Soil Moisture Sensor (CBSMS), namely relationship between soil moisture and sensor output voltage, is the basic requirement of soil moisture measurements. In the present study, two CBSMS (PA-1 for the self-developed CBSMS and EC-5 for decagon company's CBSMS) were employed to assess influence of electrical double layer in the electrical model for CBSMS on measuring soil moisture based on 15 soil samples with moisture ranging from 2.6~30%. Results showed that significant deviations of experimental results and estimated values were determined mainly in dependence on the electrical models (Model-1: with electrical double layer, Model-2: without electrical double layer), soil moisture range and sensor itself. Significant deviations were observed in the moisture range of 2.6~6%, 22~30% for EC-5 and of 2.6~10%, 22~30% for PA-1 with Model-2, whereas the deviations did not exist for both CBSMS in the moisture range of 2.6~10% with Model-1. For both CBSMS, in the moisture range of 22~30%, the deviation between estimated values from Model-1 with experimental results was obviously less than that from Model-2. These results suggest that the electrical double layer should be considered in the electrical model for CBSMS, especially for measuring low soil moisture.

Keywords: Capacitance-based sensor, electrochemical, equivalent electrical model, soil moisture sensing

INTRODUCTION

Measurement of soil moisture is essential for evaluation and selection of agro-systems and for the reasonable use of water resources (Gnecchi *et al*., 2008; Kitić and Crnojević-Bengin, 2013). The Capacitance-Based Soil Moisture Sensor (CBSMS) is widely used sensor for soil moisture measuring because the capacitance method can measure soil water content in situ in real time at a low cost and has a wide measurement range (Ma and Ma, 2002; Sánchez *et al*., 2004; Bogena *et al*., 2007).

Accuracy is the basic requirement of soil moisture measurement. To make accurate measurements it is necessary to establish valid and accurate relationship between soil moisture and sensor output voltage, namely reasonable electrical model (Xu *et al*., 2013). When the electrodes are inserted into the soil, it is expected to form an electrical double layer at the interface soil and the electrode surface according to the electrical double layer theory in electrochemistry (Guan *et al*., 2005). It is essential to take the effect of electrical double layer into consideration for realistic modeling (Biswas *et al*., 2005). However, few published studies consider the effect of electrical double layer on soil moisture prediction (Johnson *et al*., 2002; Sánchez *et al*., 2004; Biswas *et al*., 2005; Bogena *et al*., 2007; Gnecchi *et al*., 2008). Biswas *et al*. (2005) and Xu *et al*. (2013) considered the effect of electrical double layer in the modeling of capacitance-based sensors with electrodes inserting into a variety of solution but not soil. The proposed model by Gnecchi *et al*. (2008) included the contact capacitance and contact resistance caused by the electrical double layer, but this model was eventually ignored in real calculation. Therefore, the suitable electrical model in which the effect of electrical double layer at the interface soil and the electrode surface shall be developed in order to make accurate measurements employing CBSMS. The current study aims to investigate the influence of electrical double layer in the electrical model for CBSMS on measuring soil moisture.

THE PROPOSED ELECTRICAL MODEL

The equivalent circuit of the electrical double layer could be reduced to a capacitance paralleled with a resistance (Guan *et al*., 2005). In the present study,

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employing electrical double layer theory in the electrochemical field to analyze contact resistance and contact capacitance at the interface soil and the electrode surface and establishing the formula for the relationship between the contact capacitance and the relative soil permittivity and then the proposal electrical model for CBSMS on measuring soil moisture including the contact resistance and contact capacitance at the interface soil and the electrode surface was presented.

Studies have shown that the dielectric properties of moist soil may be represented by a frequency-dependent complex dielectric response function (ε) of the following form (Sánchez *et al*., 2004):

$$\varepsilon\ (\omega) = \varepsilon_r\ (\omega) + j\varepsilon_i\ (\omega) \tag{1}$$

where,

ε_r : Real part of ε
ε_i : Imaginary part of ε
ω : Angular frequency
j : $\sqrt{-1}$

ε_r is a measurement of the energy stored in the dipoles aligned in an applied electromagnetic field and thus can be regarded as a quantity that is determined by the amount of water in the medium. ε_i is a measurement of the rate of energy dissipation in the medium and therefore can be determined by the conductivity of the medium. Although both ε_r and ε_i are influenced by soil moisture content, ε_r is determined in a predictable manner by soil moisture, whereas ε_i is not. A specific frequency band should be chosen for measurement, in which the influence of soil conductivity and dielectric relaxation on soil dielectric properties is less than other bands. In this frequency band, soil dielectric properties satisfy the following equations (Ma and Ma, 2002; Zhao, 2009; Xing *et al*., 2010):

$$\varepsilon_r \approx \varepsilon_0,\ \varepsilon_i \approx 0 \tag{2}$$

$$\varepsilon \approx \varepsilon_r \approx \varepsilon_0 \tag{3}$$

ε_0 is the free-space permittivity, usually referred to as the soil relative permittivity. ε_0 significantly depends on how much moisture is in the soil, the soil relative permittivity turns greater as the proportion of water in the soil increases. The difference between ε_0 of the driest soil and the wettest soil can reach almost 30 (Filho and Portela, 1988; Li and Taishi, 2010; Radonić *et al*., 2010). The relation between the soil water content and soil relative permittivity was calculated using the empirical relation derived by Topp *et al.* (1980):

$$\theta = -5.3*10^{-2} + \varepsilon_0*2.92*10^{-2} - \varepsilon_0^2*5.5*10^{-4} + \varepsilon_0^3*4.3*10^{-6} \tag{4}$$

where, θ is the soil volumetric water content. ($m^3*m^{-3}*100\%$). As Eq. (4) demonstrates, the change of soil water content leads to the change of soil relativity, which further leads to the change of capacitance between the sensor electrodes inserted in the soil. So the soil water content can be calculated based on the measurement of the capacitance between the electrodes.

In the present study, two CBSMS (PA-1 for the self-developed CBSMS and EC-5 for decagon company's CBSMS) were employed to investigate the influence of electrical double layer in the electrical model for CBSMS on measuring soil moisture based on 15 soil samples with moisture ranging from 2.6 to 30%. According to the electrical double layer theory in electrochemistry, when different phases come together, there would be an electrical double layer formed at the phase interface (Guan *et al*., 2005). When the electrodes are inserted into the soil, as the electrodes and the soil are different phases, according to the electrical double layer theory, there must be an electrical double layer formed at the interface, which equivalent circuit consists of a contact resistance and contact capacitance between the electrodes and the soil. The soil itself also has soil resistance and soil capacitance. Considering all the above, the electrical model represented by Model-1 in the following sections is established as shown in Fig. 1. It consists of R1, C1, R2, C2 which are caused by the electrical double layer and Rs, Cs. R1, C1 are, respectively the contact resistance and contact capacitance at interface soil and surface of electrode 1. R2, C2 are, respectively the contact resistance and contact capacitance at interface soil and surface of electrode 2. Rs, Cs are respectively soil resistance and soil capacitance. Because the external surface of two electrodes is made of insulating material, R1 and R2 can be ignored (Biswas *et al*., 2005).

The capacitance method of measuring soil water content is based on the relation of capacitance between the electrodes and soil water content, the soil water content can be predicted after measuring capacitance between the electrodes and the soil. Electrode 1 and 2 are of the same material shape and size, namely they are symmetrical; therefore Eq. (5) is valid. The property of the electrical double layer is different from that of the soil. The relation between the contact capacitance caused by the electrical double layer and the soil relative permittivity is determined by physical electric and electrochemistry. When analyzing the electrical double layer, we assumes the soil solution is dilute and adopts the diffuse electrical double layer model fitting the dilute solution given by Gouy and Chapman. Gouy-Chapman has established the basic equation to determine the surface charge density of the diffuse electrical double layer (Li, 2006), which is Eq. (6). The capacitance caused by the electrical double

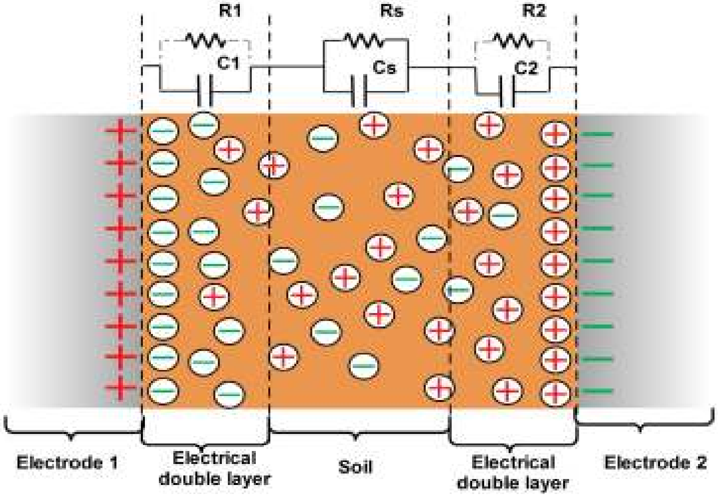

Fig. 1: The electrical model model-1 proposed in this study

layer, which is the contact capacitance, is the partial differential of the surface charge density σ_0 over surface potential φ_0 (Zhang, 2010), which is Eq. (7). As Eq. (7) demonstrates, the relationship between the contact capacitance $C_{contact}$ and the soil relative permittivity ε_0 doesn't follow parallel plate capacitor formula; $C_{contact}$ is linearly proportional to the square root of ε_0 when other parameters are kept constant. The constant coefficient k_1 is employed to represent all the other parameters. The relation between soil capacitance Cs and soil relative permittivity ε_0 follows parallel plate capacitor formula, which is Eq. (8) and in the circumstance that other parameters are kept constant, this relation is linear, the constant coefficient k is employed to represent all the other parameters. Because the size of the electrodes keeps constant and the electrodes are fully inserted into the soil, soil resistance Rs changes only with soil conductivity. According to the analysis of the relation between soil conductivity and soil moisture (Li, 2008), the relation between soil resistance Rs and soil moisture θ is established, which is Eq. (9). Soil impedance Z_T is constituted by $C_{contact}$, Cs and Rs, the expression of Z_T is shown as Eq. (10):

$$C1 = C2 = C_{contact} \tag{5}$$

$$\sigma_0 = \left(\frac{2C_e\varepsilon_0 kT}{\pi}\right)^{\frac{1}{2}} * \sinh\left(\frac{Ze\varphi_0}{2kT}\right) \tag{6}$$

$$C_{contact} = d\sigma_0/d\varphi_0 = \frac{2kT}{Ze} * \left(\frac{2C_e\varepsilon_0 kT}{\pi}\right)^{\frac{1}{2}} * \cosh\left(\frac{Ze\varphi_0}{2kT}\right) = k_1\varepsilon_0^{\frac{1}{2}} \tag{7}$$

$$Cs = \frac{\varepsilon_0 S}{4\pi d} = k_2\varepsilon_0 \tag{8}$$

$$Rs = b\theta^{-2} \tag{9}$$

$$Z_T = \frac{1}{j\omega(C_{contact}/2)} + Rs \,//\, \frac{1}{j\omega C_s} \tag{10}$$

where,

σ_0 = The surface charge density of colloidal ($C*m^{-2}$)
C_e = The electrolyte concentration ($mol*L^{-1}$)
ε_0 = The soil relative permittivity
k = Boltzmann constant ($1.3807*10^{-23} J\cdot K^{-1}$)
T = Thermodynamic temperature K
Z = Valence of the counter-icon
e = The charge of an electron (C)
φ_0 = The surface potential (V)
S = The face to face area of the electrodes (m^2)
d = Distance of the two electrodes (m)
θ = The soil volume water content ($m^3*m^{-3}*100\%$)

in this study the unit of capacitance is F, the unit of resistance is Ω k_1 k_2 b are all unknown constants. From Eq. (1) to (10), the relation between θ and Z_T could be derived. The relation between Z_T and sensor output voltage was specifically elaborated in previous studies (Bogena *et al*., 2007; Xu *et al*., 2013) and will not be discussed here. Thus θ can be predicted from sensor output voltage based on the electrical model established in this study.

METHODOLOGY

Soil preparation: Soil utilized for laboratory tests was collected from the campus of University of Chinese Academy of Sciences in Beijing city in China. It was determined by Chinese Academy of Agriculture Sciences to be sandy loam with specific characteristics given in Table 1. The soil was dried, crushed and sieved with a 2 mm sieve. The volume water content of the treated soil was then measured to be 2.6% by the gravimetric method. Deionised water was added over the treated soil and 15 samples were generated with soil moisture content respectively of 2.6, 4, 6, 8, 10, 12, 14,

Table 1: Specific characteristics of the soil utilized for the experiment

Soil utilized in this study				
		Particle size distribution[1]		
pH	Organic matter content g/Kg	Sand (%)	Silt (%)	Clay (%)
8.67	25.1	71	15.9	13.1

[1]: Textural classes are according to international classification

Fig. 2: Physical map of EC-5 and PA-1 CBSMS

Fig. 3: The experiment scene

16, 18, 20, 22, 24, 26, 28 and 30%, respectively. The soil becomes fully saturated at greater water contents. The procedure for soil preparation has been described in previous studies (Manna and Chowdhuri, 2007; Liang *et al*., 2011; Dean *et al*., 2012).

Measurement of soil moisture: Soil samples were measured respectively with EC-5 CBSMS and PA-1 CBSMS. Both sensors are powered by PSS-2005 power supply made by Gwinstek Company in Taiwan with the supply voltage of 2.5 V. Sensors' output voltage was read by GDM-451 Multimeter made by Gwinstek Company in Taiwan. For each CBSMS, experiments were repeated three times, mean value of the three sets of sensor- output- voltage- V_o- soil- moisture-θ experimental data were calculated for estimation of the equivalent circuit parameters. Physical map of the two CBSMS and experiment scene are respectively shown in Fig. 2 and 3.

Estimation of the equivalent circuit parameters from the experiment data: Mean value of the experimentally measured data of sensor output voltage and soil moisture θ for two CBSMS at different soil volume water content have already been recorded. From these results, the values of k_1, k_2 and b can be estimated by solving Eq. (1) to (10), numerically. The three unknown parameters k_1, k_2 and b were evaluated by solving nonlinear simultaneous equations iteratively with applying Universal Global Optimization Algorithms based on st Opt. The iterative solution takes 16-100 steps to converge with an error less than 0.1%.

RESULTS AND DISCUSSION

The inferred values of k_1, k_2, b in four cases:

- **Employing EC-5 CBSMS and model-1:** With electrical double layer
- **Employing EC-5 CBSMS and model-2:** Without electrical double layer
- Employing PA-1 CBSMS and Model-1
- Employing PA-1 CBSMS and Model-2

were given in Table 2. k_1 is the coefficient between the contact capacitance $C_{contact}$ and $\sqrt{\varepsilon}$. k_2 is the coefficient between soil capacitance C_s and ε. b is the coefficient between soil moisture R_s and θ^{-2}. Electrical double layer is not considered in Model-2, so the equivalent circuit parameters of Model-2 are only k_2 and b, without k_1.

For EC-5 CBSMS, RMSE according to Model-1 is 7.8 mV, obviously less than that according to Model-2, which is 10.47 mV. For PA-1 CBSMS, RMSE according to Model-1 is 59.15 mV, far less than that according to Model-2, which is 113.11 mV. For both CBSMS, Model-1 fits better with the experimental results compared to Model-2. k_1 for PA-1 CBSMS is 0.0946 pF, 0.0846 pF greater than that for EC-5 CBSMS. k_2 for PA-1 CBSMS is respectively 3.1151 and 6.8548 pF less than that of EC-5 CBSMS from Model-1 and Model-2. The difference between the two CBSMS inferred parameters is probably due to the

Table 2: The fitting parameters and the Root Mean Square Errors (RMSES) of Model-1 and Model-2 respectively for EC-5 CBSMS and PA-1 CBSMS

EC-5				
Model	k1 (pF)	k2 (pF)	b	RMSE (mV)
Model-1	0.0100	6.8585	0.94E06	7.80
Model-2	-	3.1312	4.60E06	10.47
PA-1				
Model	k1 (pF)	k2 (pF)	b	RMSE (mV)
Model-1	0.0946	0.0037	1.00E03	59.15
Model-2	-	0.0161	1.91E03	113.11

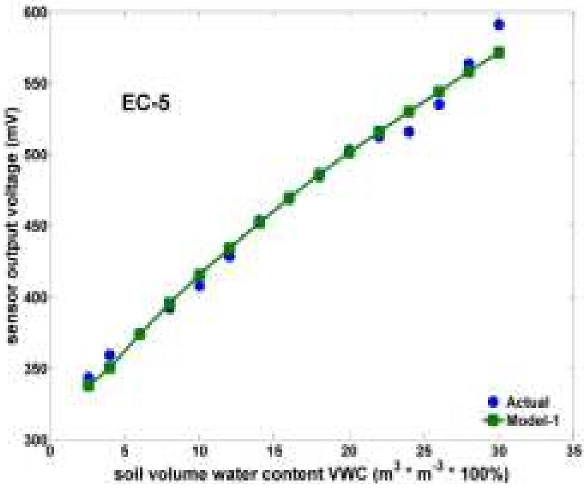

Fig. 4: The comparison of estimated values from model-1 and experimental results in soil moisture range 2.6~30% for EC-5

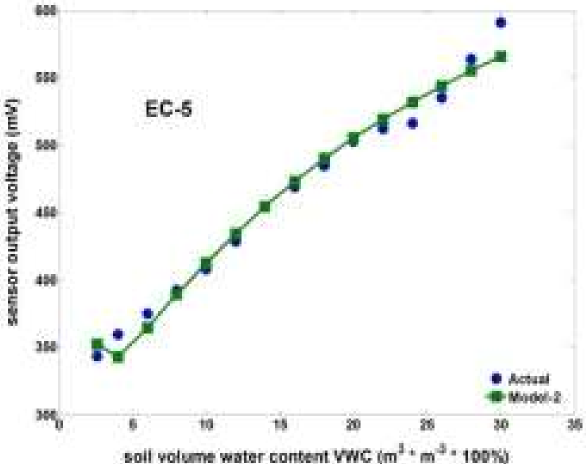

Fig. 5: The comparison of estimated values from model-2 and experimental results in soil moisture range 2.6~30% for EC-5

difference of electrode size, circuit design and measurement frequency.

The estimated values of sensor output voltage V_o from Model-1 and experimental values of V_o at different soil volume water content for EC-5 CBSMS have been plotted in Fig. 4. The estimated values match to the experimental values at soil water content 2.6~20%, Model-1 fits well with the experimental results in this range. At soil water content range 22~30%, fluctuations occur between estimated value and experimental value. At range 22~26%, estimated V_o is greater than experimental V_o at the same soil moisture, the maximum deviation occurs at soil water content 24, which is 15.22 mV. At range 28~30%, estimated V_o is less than experimental V_o at the same soil moisture, the maximum deviation occurs at soil water content 30%, which is 13.95 mV. This further means that Model-1 will underestimate soil moisture at range 22~26% with the maximum error 1.81% (the sensitivity of EC-5 is 8.4 mV/%) (Decagon Devices, Inc., 2008) at soil water content 24% and overestimate soil moisture at range 28~30% with the maximum error 1.66% at soil water content 30%. The estimated values of V_o from Model-2 and experimental values of V_o at different soil volume water content for EC-5 CBSMS have been plotted in Fig. 5. It can be observed that there is marginal variation between estimated and experimental values at soil moisture ranging from 2.6~6%. At soil water content 2.6%, estimated V_o is greater than experimental V_o, at soil water content 4 and 6%, estimated V_o is less than experimental V_o. At soil moisture range 22~26%, the estimated values of V_o are greater than experimental V_o at the same soil water content, the maximum deviation is 41.92 mV at soil water content 24% which will cause an underestimate of 5%. At soil moisture range 28 and 30%, the estimated values of V_o are less than experimental V_o at the same soil water content, the maximum deviation is 44.97 mV which will cause a overestimate of 5.35% at soil water content 30%.

Figure 6 and 7 has respectively given the comparison of estimated values of the two models and experimental values for PA-1 CBSMS. Model-1 fits experimental well with experimental results at soil moisture range 2.6~20%, at soil moisture greater than 20%, fluctuations occur between estimated and experimental values. The maximum underestimate error is 2.38% (the sensitivity of PA-1 is 60.86 mV/%) at soil water content 22% and the maximum overestimate error is 1.85% at soil water content 30%. As for Model-2, at soil moisture range 2.6~10%, estimated V_o are greater than experimental V_o under the same soil water content which will cause underestimate, the maximum underestimate error is 2.78% at soil moisture 6%. At soil moisture range 14~30%, fluctuations occur between estimated values and experimental values with the maximum overestimate error of 2.07% at soil water content 14% and the maximum underestimate error of 3.08% at soil water content 30%.

In summary, no matter for EC-5 CBSMS or PA-1 CBSMS, RMSE from Model-1 is obviously less than that from Model-2, Model-1 has better goodness of fit than Model-2 at soil moisture 2.6~20% and the fluctuation margin between estimated values and experimental values from Model-1 at soil moisture range 22~30% is significantly less than that from Model-2. Therefore, Model-1 fits better with

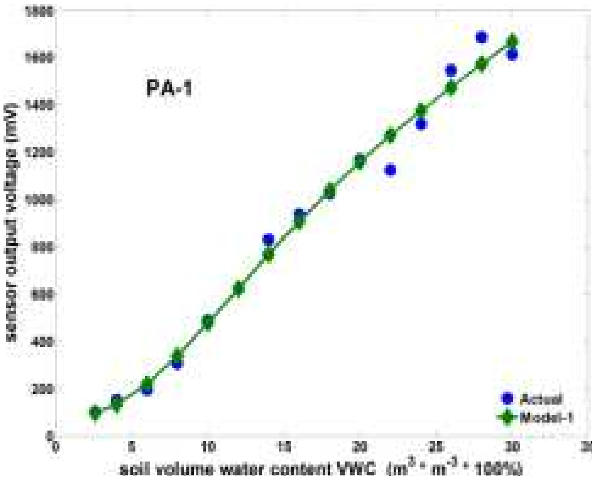

Fig. 6: The comparison of estimated values from model-1 and experimental results in soil moisture range 2.6~30% for PA-1

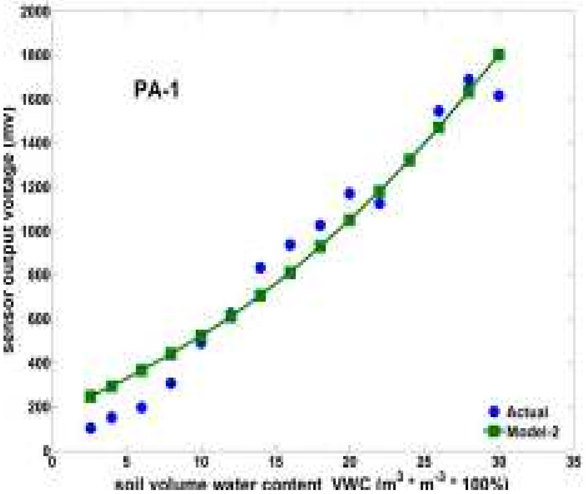

Fig. 7: The comparison of estimated values from model-2 and experimental results in soil moisture range 2.6~30% for PA-1

experimental results. The superiority of Model-1 is especially reflected in low soil moisture samples (2.6~10%).

Based on the previous work reported by IIyas *et al*. (2013), it is speculated in this paper, that the main factor causing the electrical double layer is the bound water in soil, the contact capacitance C_{contact} in the equivalent circuit of Model-1 considering the electrical double layer functions as an added permittivity term for bound water. Both soil bound water and free water content can be predicted from Model-1 while only the latter can be predicted from Model-2. It is suggested that the electrical double layer should be considered in the electrical model for capacitance-based soil moisture sensor for measuring low soil moisture.

CONCLUSION

This study investigated the influence of electrical double layer on capacitive soil moisture sensing by establishing an equivalent circuit model Model-1 which consists of the contact capacitance caused by the electrical double layer and comparing Model-1 with Model-2 without considering electrical double layer. EC-5 CBSMS and PA-1 CBSMS were employed to get sensor-output-voltage-V_o-soil-moisture-θ experimental data in soil samples with water content 2.6~30%. Fitting parameters and estimated sensor output voltage of the two models corresponding to different soil moisture were estimated by solving nonlinear simultaneous equations iteratively combined with the experimental data. Results have shown that compared to Model-2, the goodness of fit of Model-1 is obviously better. The superiority of Model-1 is especially reflected in low soil moisture samples.

Field test will be carried on in future. The relationship between soil texture and electrical double layer will be investigated and the influence of soil texture on capacitive soil moisture sensing will be further studied.

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