Journal of Engineering Science and Technology
Vol. 13, No. 6 (2018) 1514 - 1522

A NEW PROPOSED MODEL OF DIELECTRIC ANALYSIS FOR MEASUREMENT OF SOIL MOISTURE WATER CONTENT

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Abstract

Electromagnetic methods have been widely used in the measurement of the water content of the soil. These methods utilise the permittivity as electrical properties of the soil, to determine the moisture content of the soil. Since the measurements are carried out indirectly, a calibration between permittivity and the water content of the soil is needed. Generally, the calibration method generated by using an empirical and mixing model. This study presents a new method of calibration by using a normalisation approach to calibrate the value of the permittivity of the water content of the soil. Secondary data was used to compare new calibration with other methods from previous studies. This calibration provides satisfactory results when compared to other methods.

Keywords: ECVT, Permittivity, Volumetric water content.

1. Introduction

The water content in soil is an important study, employing several areas of knowledge. The study of soil water content can be applied and implemented in the various cases, especially in the area of soil studies. In soil slope stability analysis, soil water content has a very large contribution to the level of sensitivity of the safety factor [1]. Besides, the process of the irrigation of agricultural land also requires information on the soil water content. Water content is also used to calculate effective stress parameters in order to predict the shear strength of unsaturated soil [2].

Among the methods of measuring soil water content widely used today is the electromagnetic method. Through this method, soil water content is determined

Nomenclatures

V_a	Volume of air
V_s	Volume of solid
V_t	Total volume of soil
V_v	Volume of void
V_w	Volume of water in the soil
Greek Symbols	
θ	Volumetric soil water content
θ_r	Residual soil water content
θ_s	Saturated soil water content
Θ	Degree of saturation of soil
ε	Permittivity
ε_N	Normalised permittivity
ε_{res}	Permittivity of soil in residual states
ε_{sat}	Permittivity of soil in saturation states
η	Porosity of soil

by measuring the electrical properties of the soil such as the capacitance [3] and permittivity [4]. However, most of it uses the properties of the permittivity of soil to determine soil water content.

A variety of equations for the relationship between permittivity and water content have been proposed by previous researchers. These equations indicate a need for a calibration between the permittivity of the soil and the soil water content. As for the method used for the calibration of permittivity and water content, it can generally be divided into two methods, the empirical method [5] and mixing or composite models [6-7]. In the empirical method, the calibration process is generated from several water contents and permittivity measurements. Alternatively, the mixing model takes the fraction of soil composition (solid, air and water) and their relationship with permittivity.

2. Theory and Method

A Volumetric water content is defined as the amount of water contained in the soil, which is mathematically expressed as follows,

$$\theta = \frac{V_w}{V_t} \tag{1}$$

where V_w is the volume of water in the soil and V_t is the total volume of soil. The degree of saturation obtained from the maximum and minimum values of water that can be stored in the soil. Mathematically, the degree of saturation is defined in Eq. (2).

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

where θ is the volumetric soil water content, θ_r the residual soil water content, and θ_s the saturated soil water content. In terms of volume, the degree of saturation of the soil can also be defined as a ratio between the volume of water and volume of the void.

By following the form of Eq. (2), the normalised permittivity is defined as follows

$$\varepsilon_N = \frac{\varepsilon - \varepsilon_{res}}{\varepsilon_{sat} - \varepsilon_{res}} \tag{3}$$

where ε is the permittivity of the soil, ε_{res} and ε_{sat} are the permittivities of soil in residual and saturation states respectively.

In order to obtain the relationship between the normalised water content and normalised permittivity, we propose the following three-equations model

$$\Theta = \varepsilon_N^{\ 0.5} \qquad \text{(a)}$$
$$\Theta = \varepsilon_N \qquad \text{(b)} \tag{4}$$
$$\Theta = \varepsilon_N^{\ 2} \qquad \text{(c)}$$

Secondary data from Topp et al. [8] and Roth et al. [9] are plotted with three models in Eq. (4) and the models of Topp et al. [8], Roth et al. [7] and Malicki et al. [10] as shown in Fig. 1.

The equations of Topp et al. [8], Roth et al. [7] and Malicki et al. [10] are shown in Eqs. (5), (6) and (7) respectively.

$$\varepsilon = 3.03 + 9.3\theta + 146.0\theta^2 - 76.7\theta^3 \tag{5}$$

$$\theta = \frac{\varepsilon^\gamma - (1-\eta)\varepsilon_s^\gamma - \eta\varepsilon_a^\gamma}{\varepsilon_w^\gamma - \varepsilon_a^\gamma} \quad ; \gamma = 1 \tag{6}$$

$$\theta = \frac{\sqrt{\varepsilon} - 3.47 + 6.22\eta - 3.82\eta^2}{7.01 + 6.89\eta - 7.83\eta^2} \tag{7}$$

From Fig. 1 it can be seen that the models of Topp et al. [8] and Malicki et al. [10] appear to be similar in terms of normalisation and also the experimental data of Topp et al. [8] and Roth et al. [9]. Equation (4a) can either follow the pattern of data. Thus it can be considered as a method for explaining the relationship between permittivity and volumetric water content in a normalisation approach.

To generate the formula for the permittivity and volumetric water content relationship that comes from normalisation method, it is necessary to determine the relationship between the volumetric water content and degree of saturation. The expression of porosity related to volume is shown in Eq. (8).

$$\eta = \frac{V_v}{V_t} \tag{8}$$

where V_v is the volume of the void. The degree of saturation can also be defined in relation to the volume as shown in Eq. (9).

$$\Theta = \frac{V_w}{V_v} \tag{9}$$

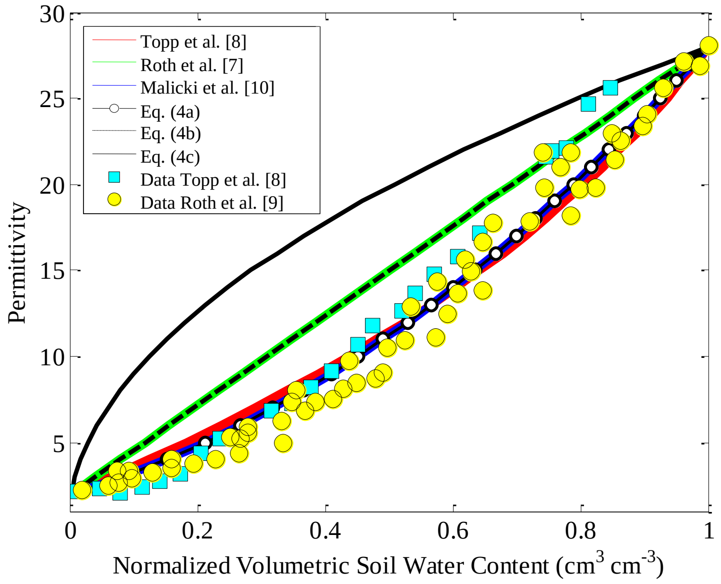

Fig. 1. Normalised volumetric soil water content.

By substituting Eqs. (4), (8) and (9) into Eq. (1), the following is then obtained:

$$\theta = \eta\left(\frac{\varepsilon - \varepsilon_{res}}{\varepsilon_{sat} - \varepsilon_{res}}\right)^{0.5} \tag{10}$$

The permittivity value is closely related to soil porosity. Arulanandan et al. [11] proposed an equation for the porosity and permittivity relationship, as shown below:

$$\varepsilon = 76.954\eta - 2.133 \tag{11}$$

In the online manual techniques reported by Singh [12], it is assumed that the volumetric soil water content value at saturation is proportional to 85% of the value of the porosity of the soil. This assumption is based on the fact that not all the pores in the soil can be filled with water, due to air trapped in the soil. At saturation, the value of permittivity of the soil is influenced by water and porosity. By using the assumption and Eq. (11), then the soil permittivity value at saturation can be determined as follows,

$$\varepsilon_{sat} = 65.410\eta - 2.133 \tag{12}$$

To determine the residual soil permittivity, the concept of simple mixture models is used. Assuming that in the residual state the contribution of the permittivity of water is very small and may be ignored, thus it can be written as:

$$\varepsilon_{res} = \varepsilon_a \frac{V_a}{V_t} + \varepsilon_s \frac{V_s}{V_t} \tag{13}$$

V_a/V_t is also known as the air-filled porosity, in which the value is the same as the porosity reduced by the volumetric water content at saturation. V_s/V_t is the volume fraction of the solid and is equal to one minus porosity. Therefore, Eq. (13) can be written as the following:

$$\varepsilon_{res} = \varepsilon_a (\eta - 0.85\eta) + \varepsilon_s (1-\eta) \tag{14}$$

By using the value of the permittivity of air is equal to 1 and permittivity of solid equal to 7, then the following results are obtained:

$$\varepsilon_{res} = 7 - 6.85\eta \tag{15}$$

By substituting Eqs. (12) and (15) into Eq. (10), a new equation is obtained that can explain the relationship between the volumetric water content and permittivity, as shown in Eq. (16):

$$\theta = \eta \left(\frac{\varepsilon - 7 + 6.85\eta}{72.26\eta - 9.133} \right)^{0.5} \tag{16}$$

Simplifying Eq. (16) with a porosity value equal to 0.53, which is taken from the average porosity of soil in Kaya [13], will result in an equation with a single parameter, which can be written as Eq. (17) as follows

$$\theta = 0.53 \left(\frac{\varepsilon - 3.369}{29.165} \right)^{0.5} \tag{17}$$

Secondary data are used to obtain the relationship between permittivity and volumetric soil water content in terms of normalisation. Data are obtained from previous studies with different methods of measurement, such as TDR [7-9, 14-17], capacitance probes [18], frequency domain [19] and different types of soil.

Several models of calibration have been used for comparison with the proposed model, such as Malicki et al. [10], Gardner et al. [20], Robinson et al. [15] and Topp et al. [8] for organic soil, and Roth et al. [9] which are shown as Eqs. (7), (18), (19), (20) and (21) respectively:

$$\theta = \frac{\sqrt{\varepsilon} + 1.208 - 2.454\rho_b}{9.93} \tag{18}$$

$$\theta = \eta \left(\frac{\sqrt{\varepsilon} - \sqrt{\varepsilon_{dry}}}{\sqrt{\varepsilon_{sat}} - \sqrt{\varepsilon_{dry}}} \right) \tag{19}$$

$$\varepsilon = 1.74 - 0.34\theta + 135\theta^2 - 55.3\theta^3 \tag{20}$$

$$\theta = \text{-}0.0233 + 0.0285\varepsilon - 0.000431\varepsilon^2 + 0.00000304\varepsilon^3 \tag{21}$$

3. Result and Discussion

Figure 2 shows the yield curve in Eq. (16) plotted along with secondary data and data with different porosities. From the figure, it is shown that all data is almost covered by the curve of porosity of 0.3 to 0.7.

Besides different results with the previous equation lies at very small permittivity values that do not result in soil moisture content value is negative. As the value of permittivity is very small, according to the proposed equation, the value of the volumetric soil water content is close to zero. On the condition of the volumetric soil water content being equal to zero, then the value of permittivity of the soil was entirely influenced by the solid and air. Porosity is a representation of the number fraction of air that would affect the value of permittivity. For the same volumetric soil water content condition, a greater porosity means more air, resulting in the values of permittivity becoming smaller, and vice versa.

Compared with the other calibration models of permittivity and volumetric soil water content, some significant differences can be seen as shown in Figs. 3, 4 and 5.

Figure 3 shows the comparison between the proposed model and Malicki et al. [10] (dot-dashed line), whose curves are still in the area of the secondary data, but it still does not match with the porosity of the secondary data. In Fig. 4, the curve of the Gardner et al. [20] model (dot-dashed line) are outside the area of secondary data for porosity (0.3-0.5), whereas in Fig. 5 the curve of the Robinson et al. [15] model just covers the area of secondary data for a volumetric soil water content range of 0-0.4. These three calibration models from previous studies provide negative results for permittivity values of less than 5.

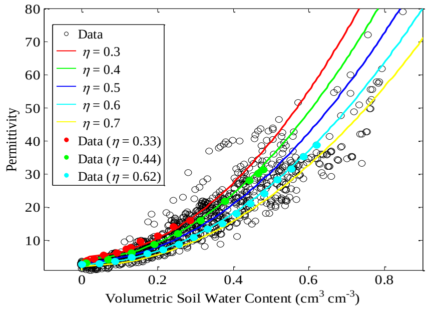

Fig. 2. Plot of θ and ε with Eq. (16) along with secondary data to changes in porosity.

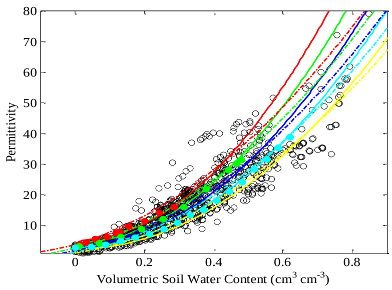

Fig. 3. Plot of θ and ε with Eq. (16) along with secondary data to changes in porosity and with Malicki et al. [10].

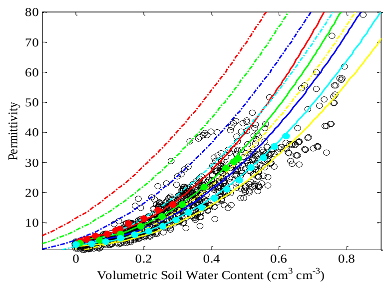

Fig. 4. Plot of θ and ε with Eq. (16) along with secondary data to changes in porosity and with Gardner et al. [20].

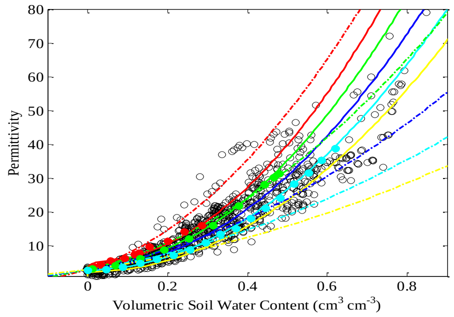

Fig. 5. Plot of θ and ε with Eq. (16) along with secondary data to changes in porosity and with Robinson et al. [15].

Equation (17) is plotted on a graph with other calibrations, namely Topp et al. [8] in Eq. (20) and Roth et al. [9] in Eq. (21), as shown in Fig. 6. The graph shows that the curve of Eq. (17) is quite good in explaining the relationship between the water content in the soil and the permittivity of the secondary data. The curve is also almost similar to the curves of both the other equations for the value of volumetric soil water content from 0-0.5.

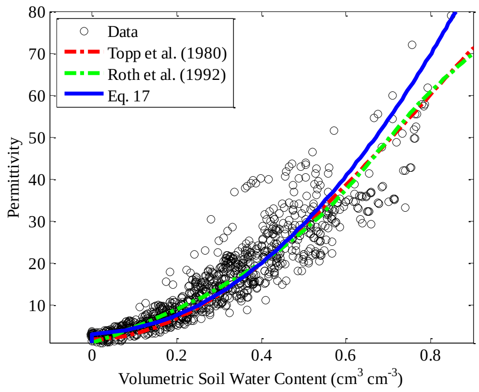

Fig. 6. Comparison of Eq. (17) with equations of Topp et al. [8]and Roth et al. [9] and the secondary data.

4. Conclusion

A normalisation approach has been conducted to obtain a calibration model between permittivity and volumetric soil water content. In this model, the relationship between the permittivity and volumetric soil water content is firstly specified in the form of a normalisation, where the value is between 0 and 1, and then the maximum and minimum values for permittivity are obtained from several assumptions. For the maximum value of permittivity or saturation, resulting from the relationship between permittivity and porosity, the saturation of the soil is proportional to 0.85 of the porosity. While the minimum value of permittivity or the residual results from the mixing model of permittivity, which is related to the porosity of the soil.

The proposed model gives a better result when compared with the other models on the secondary data. The differences in values of porosity in the data can also be explained by this model. Negative issues that arise in the volumetric soil water content when the value of permittivity is quite small can also be overcome by using this calibration method.

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