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REVIEW

Time Domain Reflectometry Calibration for Typical Upland Soils in Kyushu, Japan

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Abstract

Time Domain Reflectometry (TDR) has recently become popular as a method to measure soil water content. An empirical Topp's equation and some dielectric mixing functions are often used as calibration curves of TDR. This review describes the Topp's equation and dielectric mixing models. In addition, applicability of Topp's equation and some dielectric mixing models for the θ-ε relationships for typical upland soils (two types of Ando soils, Red-yellow soils, two types of Brown forest soils, and Toyoura sand) are discussed. Following are several remarks that are stressed on TDR: (1) The empirical Topp's equation underestimates soil water content for mineral soils of low bulk density. (2) Since dielectric mixing models described the effect of bulk density on the calibration curve, they could be more suitable than the Topp's equation for the experimented soils. (3) Judging from the fitness of the whole curve, the third-order polynomial regressions and α model were superior to the Maxwell-De Loor model, which has no parameter to be identified. (4) The Maxwell-De Loor model was found to be so flexible that it reasonably fitted with measured data for different types of soil.

Discipline: Agricultural engineering
Additional key words: dielectric permittivity, electromagnetic wave, mixing model, soil water content

Introduction

Soil water content is an important factor affecting plant growth. When soil water content is high but not excessive, transpiration and photosynthesis of plants are carried out more actively and a greater mass of nutrients is available to plants through dissolution, and thus plants can grow well. Soil water content also governs the air content and gas exchange in the soil, thus affecting the respiration of roots, the activity of microorganisms, and the chemical reaction in soil. Moreover, attention to soil water content is recently becoming more important in relation to both regional water balance and environmental problems.

Time domain reflectometry (TDR), an electromagnetic method, has recently become popular as a method to measure soil water content. The advantages of the TDR method over other methods for soil water content measurement are (1) calibration requirements are minimal (in many cases soil-specific calibration is unnecessary), (2) effects of temperature and hysteresis on the TDR measurement are small, and (3) the method is capable of providing continuous soil water measurements through automation and multiplexing. Therefore, the TDR method is suitable for field measurements as well as laboratory use. The TDR method has become increasingly popular in Japan, too.

For TDR measurement, the relationship between volumetric water content (θ) and effective permittivity of soil (ε) is needed. An empirical calibration curve obtained by Topp et al.[26] is often used for this purpose. Besides the empirical calibration curve, some dielectric mixing models have been proposed for describing the θ-ε relationships. In this review, we describe the empirical calibration curve and dielectric mixing models and discuss the applicability of Topp's equation and some dielectric mixing models for the θ-ε relationships for typical upland soils in Japan.

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Applicability of Topp's equation to θ-ε relationships for soils in Japan

1. Topp's equation

A calibration function relating the ε to θ is required for the TDR measurement. The most widely used calibration function is of Topp et al.[26]:

$$\varepsilon = 3.03 + 9.3\theta + 146\theta^2 - 76.7\theta^3 \quad (1)$$

Topp et al.[26] described that the equation can be applied to sandy loam, clay loam, and clay with a dry bulk density of 1.04–1.44 Mg m^{-3} and yield an accurate measurement of soil water content with a standard error of less than 1.3%.

Topp's equation has been confirmed by various calibration studies for silt loam[27], clay to very fine sandy loam[28], fine- and coarse-sand[30], and sand and sandy loam with varying gravel contents[8]. However, Topp's equation is not suitable for organic soils[14,24,26] and fine-textured soils[4]. In such field soils, an alternative calibration must be performed prior to actual TDR measurements.

Only limited information is available concerning the θ-ε relationships for soils in Japan and applicability of Topp's equation for them. The applicability of the equation has been confirmed for Sand (Toyoura sand)[15] and Regosols (Masa)[18]. However, it is not appropriate for Andisols[11–13,17,19,21]. Hatano et al.[13] compared water contents measured by the gravitational method and TDR for Gray-lowland soil, Brown forest soil and Gray-upland soil, and found that the Topp's equation was applicable as their calibration curve. However, they did not show the θ-ε relationships for these soils.

2. θ-ε relationships for upland soils in Kyushu, Japan, and Topp's equation

In the Kyushu province in Japan, the coverage of Andisols, Red-yellow soils, and Brown forest soils are 50.9, 25.2, and 14.2% respectively. Miyamoto and Chikushi[20] obtained the θ-ε relationships for six textured soils in Kyushu (two Andisols, Red-yellow soil, surface soil and subsoil of Brown forest soils, and Toyoura sand). Soil textures, organic matter content and soil physical properties of the soils are presented in Table 1 and Table 2.

Fig. 1 shows measured data of θ-ε relationships and calculated values by Topp's equation for each soil sample. The Topp's equation fitted well for the measured data of Toyoura sand (Fig. 1a) and topsoil of Brown forest soil (Fig. 1c). The topsoil of Brown forest soil had shrunk during the drying process; hence, the dry bulk density of the soil was changed from 1.35 to 1.47 Mg m^{-3}.

Table 1. Soil texture and organic matter content

Soils	Clay (wt. %)	Silt (wt. %)	Sand (wt. %)	Soil texture	Organic matter content (%)
Toyoura sand	0.3	0.4	99.3	S	0.0
Red-yellow soil	50.0	29.1	20.9	HC	11.5
Brown forest soil (Topsoil)	30.4	34.3	35.3	LiC	10.0
Brown forest soil (Subsoil)	61.8	31.1	7.1	HC	9.5
Andisol (Kumamoto)	39.1	35.9	25.0	LiC	30.0
Andisol (Miyazaki)	18.9	19.6	61.5	SCL	14.4

S: Sand, HC: Heavy clay, LiC: Light clay, SCL: Sandy clay loam.

Table 2. Physical properties of soils

Soils	Particle density (Mg m^{-3})	Dry bulk density (Mg m^{-3})	Air dryness (kg kg^{-1})	Porosity	Water content of air dried soil (m^3 m^{-3})
Toyoura sand	2.64	1.54*	0.000	0.42	0.000
Red-yellow soil	2.70	1.13	0.048	0.58	0.054
Brown forest soil (Topsoil)	2.64	1.47	0.035	0.44	0.051
Brown forest soil (Subsoil)	2.77	1.17	0.043	0.58	0.050
Andisol (Kumamoto)	2.44	0.73	0.120	0.70	0.088
Andisol (Miyazaki)	2.46	0.73	0.077	0.70	0.056

*: Value for Toyoura sand is measured by using disturbed soil sample.

Although the degree of shrinkage was relatively large as compared with Red-yellow soil and subsoil of Brown forest soil (0.01 Mg m^{-3}), the deviation from Topp's equation was small. This could be explained in terms of the applicable range of dry bulk density for Topp's equation[6].

The θ-ε relationships for other soils deviated significantly from the Topp's equation, and could not fit them even by moving the equation in parallel. Especially, the deviation from Topp's equation was most significant with the two Andisols (Fig. 1e, 1f). The θ-ε relationships for the two Andisols were around 0.10 m^3 m^{-3} lower than the Topp's equation at the same value of permittivity at the

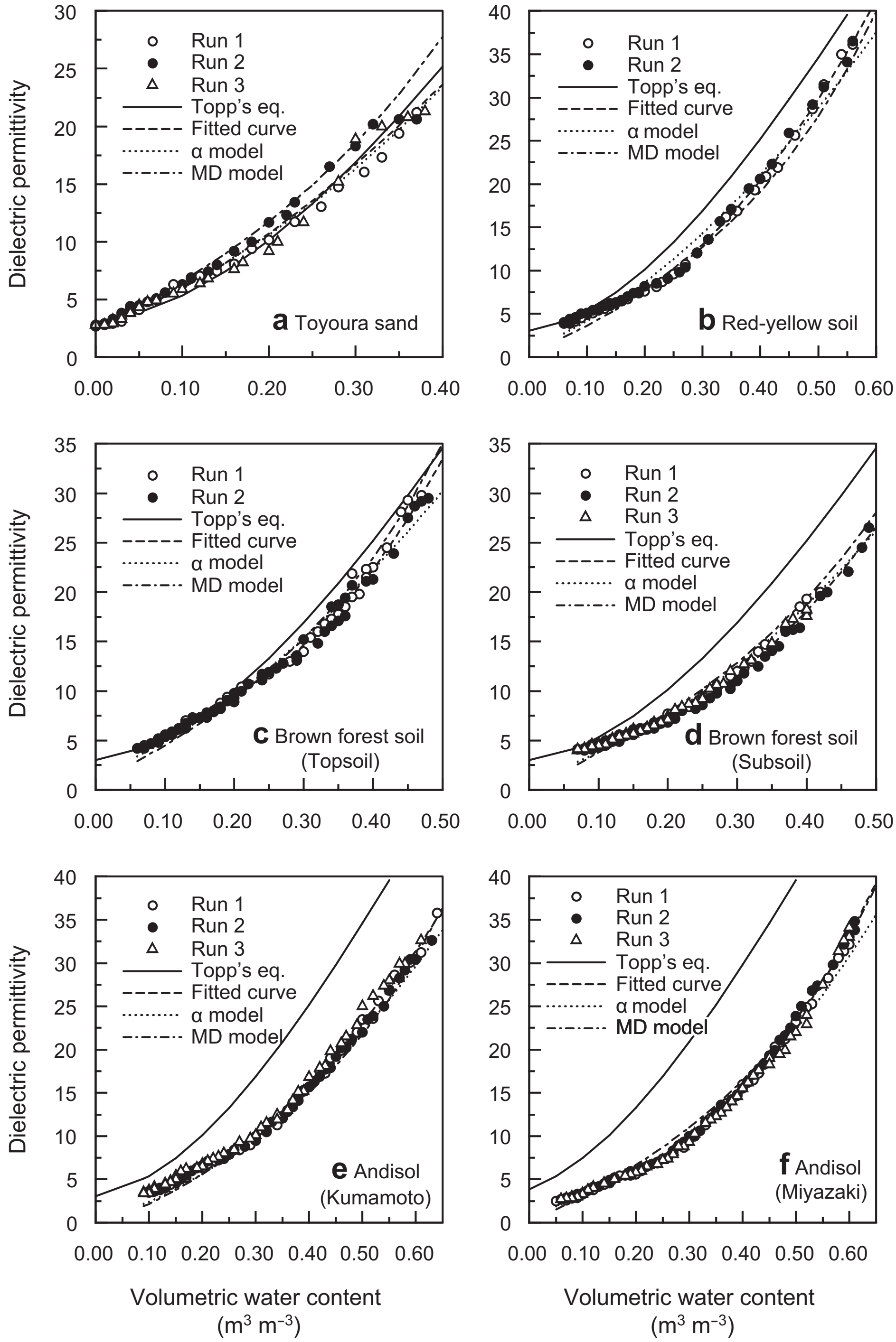

Fig. 1. Comparison of the relationship of volumetric water contents vs. effective permittivity among measured data, Topp's calibration function, fitted third polynomial function, α model, and Maxwell-De Loor model

Table 3. Parameters of calibration functions

Soils	$\varepsilon_{eff} = a + b\theta + c\theta^2 + d\theta^3$ ($\theta = e + f\varepsilon_{eff} + g\varepsilon_{eff}^2 + h\varepsilon_{eff}^3$)								
	a	b	c	d	R^2	e	f	g	h
Toyoura sand	2.76	23.6	89.5	–45.3	0.987	–0.0971	0.0404	–0.00141	0.0000249
Red-yellow soil	4.05	–3.81	115	–8.86	0.998	–0.1086	0.0508	–0.00173	0.0000235
Brown forest soil (Topsoil)	1.82	38.9	42.2	182.4	0.995	–0.0817	0.0386	–0.00102	0.0000116
Brown forest soil (Subsoil)	3.50	4.01	67.7	33.1	0.996	–0.1330	0.0621	–0.00263	0.0000449
Andisol (Kumamoto)	2.78	1.05	82.8	–8.48	0.997	–0.0402	0.0457	–0.00137	0.0000184
Andisol (Miyazaki)	1.82	11.6	31.7	60.1	0.998	–0.0460	0.0492	–0.00162	0.0000218

lower moisture range. Moreover, the difference from the equation became large at the higher moisture range. These results can be explained from the low dry bulk density (i.e. high porosity) and large amount of bound water related with the high organic matter content.

Dry bulk density affects the θ-ε relationships more than soil texture and particle size distribution. The θ-ε relationships for soils that have the same texture and similar dry bulk density were similar to each other (Red-yellow soil and subsoil of Brown forest soil). Comparison of the θ-ε relationships between two Andisols revealed that the relationships for the same soil type with the same dry bulk density were similar to each other even though they had different particle size distribution and organic matter content. Moreover, for the same volumetric water contents (Red-yellow soil and Andisol from Miyazaki), the lower the dry bulk density was, the lower the permittivity became. Jacobsen and Schjønning[16] found that the third-order polynomial calibration curve could be improved by adding a linear term of dry bulk density. Perdok et al.[22] determined the θ-ε relationships for three soils and found that the θ-ε relationships depended on dry bulk density.

Third-order polynomials have been often employed as empirical calibration curves (e.g. Roth et al.[24]). Miyamoto and Chikushi[20] also fitted the measured data by the individual calibration curves with third-order polynomials as listed in Table 3.

Applicability of dielectric mixing models for describing θ-ε relationships

1. Dielectric mixing model

The dielectric mixing models can estimate ε from the permittivities of the soil components. Therefore, the dielectric mixing model is suitable for evaluating the θ-ε relationships for some irregular soils, for example, with low dry bulk density, large amount of bound water, or relatively large permittivity of the solid phase. Moreover, the dielectric mixing model can be used for understanding the dependency of the effective permittivity on water content and soil physical properties.

Many of the dielectric mixing models have been proposed for describing the θ-ε relationships[2–4,7,9,10]. They have been examined by several authors[1,2,4,6,20,23,25,29]. Two typical dielectric mixing models have been often applied to describe the dielectric property for many types of soils; one is a theoretical model based on the Maxwell equation proposed by De Loor[5] (Maxwell-De Loor model), and another is a semi-empirical model proposed by Birchak et al.[3] (α model). In these models, the water phase in soil was treated as one phase. However, since water near the soil surface is restricted to its molecular movement and has a lower value of permittivity than that for free water, Dobson et al.[7] expanded these two models to the respective four-component system of free water, bound water, solid, and air.

For Maxwell-De Loor model (MD model):

$$\varepsilon = \frac{3\varepsilon_s + 2(\theta - \theta_{bw})(\varepsilon_{fw} - \varepsilon_s) + 2\theta_{bw}(\varepsilon_{bw} - \varepsilon_s) + 2(\phi - \theta)(\varepsilon_a - \varepsilon_s)}{3 + (\theta - \theta_{bw})\left(\frac{\varepsilon_s}{\varepsilon_{fw}} - 1\right) + \theta_{bw}\left(\frac{\varepsilon_s}{\varepsilon_{bw}} - 1\right) + (\phi - \theta)\left(\frac{\varepsilon_s}{\varepsilon_a} - 1\right)} \tag{2}$$

and for α model:

$$\varepsilon^\alpha = (1 - \phi)\varepsilon_s^\alpha + (\theta - \theta_{bw})\varepsilon_{fw}^\alpha + \theta_{bw}\varepsilon_{bw}^\alpha + (\phi - \theta)\varepsilon_a^\alpha \tag{3}$$

where α is a curve-fitting parameter, θ is volumetric water content, θ_{bw} is a volumetric water content of bound water, ϕ is porosity, and ε_s, ε_a, ε_{fw}, and ε_{bw} are the permittivities of soil solid, air, free water, and bound water respectively. Although organic matter in soils was not considered as one component of soil, the effects of both increasing bound water and decreasing soil bulk density by the organic matter can be included in these models.

2. Application of dielectric mixing models to θ-ε relationships for upland soils in Kyushu, Japan

When applying the four-component dielectric mixing models, we need to estimate the volume fraction of bound water and its relative permittivity. Dobson et al.[7] assumed that the volume fraction of bound water could be approximated to the volume of the monomolecular water layer covering the soil surfaces. Dirksen and Dasberg[6] applied this assumption to eleven soils and found a close correspondence between the estimated bound water content and the hygroscopic water content (air dryness). Moreover, they assumed that the permittivity of bound water was likely to be similar to that of ice.

To evaluate the parameters of the mixing models, Miyamoto and Chikushi[20] used the following permittivities. We assumed the volume fraction of bound water was the hygroscopic water content of the soil and its permittivity equal to that of ice (ε_{bw} = 3.2). The permittivity of free water of ε_{fw} = 80.4 at 20ºC was used. For the permittivity of the soil materials, as following Dirksen and Dasberg[6], we assumed ε_s = 5, which is an average of published values in the TDR frequency range[1,25,26]. The permittivity of air used was ε_a = 1.

Several researchers have used different α values for fitting their measured data; Roth et al.[25] used α = 0.46, Weitz et al.[29] obtained α = 0.47, Birchak et al.[3] and Alharthi and Lange[1] used α = 0.5, and Dobson et al.[7] found α = 0.65 fit their measured data best. These different α values depending on variety of soil were used for calibration experiments. The best-fitted α values for each soil sample were obtained by using a least square method[20].

The calculated results by MD model agreed well for all soils (Fig. 1). However, the calculated ε for Red-yellow soil and Brown forest soils were underestimated at the moisture range around air dryness. Contrary to these results, for Andisols the MD model could predict the θ-ε relationship better than that for Red-yellow soil and Brown forest soils. The results described above may be related with the facts as follows: (1) the different clay minerals play a role for adsorbing water molecules, (2) the same values of ε_s, and ε_{bw} are used for every soil, and (3) the dielectric mixing model is based on the assumption that multiple independent materials with different permittivity are distributed randomly.

The best-fitted values of α varied between 0.42 and 0.61 (Table 4). These values are similar to those reported by several researchers[1,3,7,25,29]. Since we obtained more measured data at a lower moisture range and weighted there, the calculated results by the α model were underestimated at the higher moisture range near saturation (Fig. 1).

Comparison between calibration curves

To evaluate the suitability of the Topp's equation, MD model, and α model, Miyamoto and Chikushi[20] calculated the root mean square error (RMSE) for fitting the water content obtained from gravimetric measurements (θ_g) and the corresponding water contents estimated using a particular calibration model (θ_{TDR}) as:

$$RMSE = \sqrt{\frac{\sum(\theta_g - \theta_{TDR})^2}{N}} \quad (4)$$

where N is the number of observations[12,16,29].

RMSE for calibration curves for each soil is summarized in Table 4. The RMSE of Topp's equation for Toyoura sand was the smallest among soils. Contrarily, the RMSEs for Andisols were larger than those for other soils. This result indicated that Topp's equation was not suitable for Andisols as a calibration curve. Weitz et al.[29] determined the θ-ε relationships for two volcanic soils and evaluated applicability of empirical calibration functions and dielectric mixing models. The RMSEs of the mixing models varied between 0.022 and 0.056 on the one hand, and the RMSEs of Topp's equation varied between 0.092 and 0.116 on the other hand.

Judging from the width of fitted range of soil water content, the third-order polynomial regression curve and α model were superior to the MD model. However, the

Table 4. RMSE (Root Mean Square Error) for Topp's equation, the fitted third polynominal, Maxwell-De Loor model, and α model

Soils	Topp's eq.	Fitted function	MD model	α model
Toyoura sand	0.0151	0.0110	0.0192	0.0131 (α = 0.47)*
Red-yellow soil	0.0466	0.0086	0.0266	0.0212 (α = 0.61)
Brown forest soil (Topsoil)	0.0244	0.0065	0.0157	0.0133 (α = 0.59)
Brown forest soil (Subsoil)	0.0628	0.0081	0.0193	0.0176 (α = 0.49)
Andisol (Kumamoto)	0.1026	0.0083	0.0245	0.0198 (α = 0.55)
Andisol (Miyazaki)	0.1014	0.0086	0.0178	0.0146 (α = 0.42)

*: The value in a parenthesis is best-fitted value of α.

MD model was found to be so flexible because it reasonably predicted measured values for different types of soil without fitting parameters.

Conclusions

The applicability of Topp's equation, the MD model, and the α model to the θ-ε relationships for six textured soils (two Andisols, Red-yellow soil, surface soil and subsoil of Brown forest soils, and Toyoura sand), which are typical upland soils in Kyushu Japan, was discussed in this review. The results are summarized as follows:

(1) Topp's equation is not suitable for soils with low dry bulk density even though the soils are non-volcanic soils.

(2) The effect of particle size distribution on the θ-ε relationships for Andisols is not significant in comparison with the effects of dry bulk density.

(3) The third-order polynomial regression curve was superior to both the MD model and the α model only when the θ-ε relationship for a soil had already been obtained.

(4) The MD model was found to be so flexible because it reasonably predicted measured values for different types of soil without fitting parameters.

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