Methods for prediction of soil dielectric properties: a review

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ABSTRACT

Electromagnetic sensors such as ground penetrating radar and electromagnetic induction sensors are among the most widely used methods for the detection of buried land mines and unexploded ordnance. However, the performance of these sensors depends on the dielectric properties of the soil, which in turn are related to soil properties such as texture, bulk density, and water content. To predict the performance of electromagnetic sensors it is common to estimate the soil dielectric properties using models. However, the wide variety of available models, each with its own characteristics, makes it difficult to select the appropriate one for each occasion. In this paper we present an overview of the available methods, ranging from phenomenological Cole-Cole and Debye models to volume-based dielectric mixing models, and (semi-) empirical pedotransfer functions.

Keywords: dielectric soil properties, phenomenological models, mixture models, (semi-)empirical models

1. INTRODUCTION

Buried land mines and unexploded ordnance (UXO) are present in a large number of countries around the world. They can be found at the locations of past military conflicts or at active and abandoned military training sites. The presence of land mines and UXO cause serious safety hazards, which require the clean up of contaminated land. Many of the geophysical methods for detection of buried landmines and UXO make use of electromagnetic signals. Dielectric medium properties are a critical parameter for most methods, because the dielectrics control the contrast between the object of study and the medium it is buried in. Additionally the dielectric medium properties control propagation, attenuation, and reflection of electromagnetic waves. The dielectric properties of a material are a function of among others: texture, bulk density, mineralogy, organic matter content, and frequency, but especially water content[1].

Previous work has shown the effect of spatial and temporal variability in the soil system. A significant part of the variability in landmine and UXO signatures can in fact be attributed to the temporal and spatial variability that is present in soils. Soil data from a wide range of environmental settings (temperate, tropical, and desert) show that soil water content varies widely and over distances of less than one meter[2-4]. This variability has important implications for sensors that are affected by the soil water content, as their performance may be variable over short distances. The performance of a sensor under specific soil conditions can be predicted using a thorough understanding of the physics of the soil-mine-sensor system.

To predict the performance of electromagnetic sensors it is common to use models that estimate the soil dielectric properties. Although a wide variety of models, each with its own characteristics, has been proposed no complete model is available that can describe the dielectric properties of a soil for all its variables[5, 6]. This makes it a challenge to select the best model for each occasion. The available methods can be grouped in (1) phenomenological (e.g., Cole-Cole and Debye), (2) volumetric, (3) empirical and semi-empirical (pedotransfer), and (4) effective medium models or approaches. The effective medium approach, or composite spheres model[7-10], is only accurate for known geometries and difficult to implement for heterogeneous and multiple-phase materials[11, 12]. We consider this approach irrelevant for the problems of UXO and landmine detection and it will be ignored in this paper.

We present a literature review of the available methods for prediction of dielectric properties of field soils. This review is an attempt to introduce the major groups of approaches. We discuss the most important exponents and publications of

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each approach. We will discuss the characteristics, some applications, and the advantages and disadvantages of each method. Finally, in the discussion and conclusion we will compare the different methods and give recommendations for improvements to the existing models.

2. THEORY

The interaction of electromagnetic energy with matter is affected by the characteristics of the material and by the frequency of the electromagnetic energy. Frequency dependent dielectric properties can be characterized in terms of losses of energy due to relaxation mechanisms that operate at different frequencies. The relaxations are caused by different forms of atomic- or molecular-scale resonance [13]. In a soil mixture the relaxation mechanisms may be attributed to the solid material and the pore water as well as to interfacial phenomena. Figure 1 summarizes some of the different types of relaxation mechanisms that play a role in wet soils. Many geophysical tools for detection of subsurface objects operate in frequency ranges between 0.1 and 10 GHz, which makes bound water relaxation the major resonance mechanism of interest.

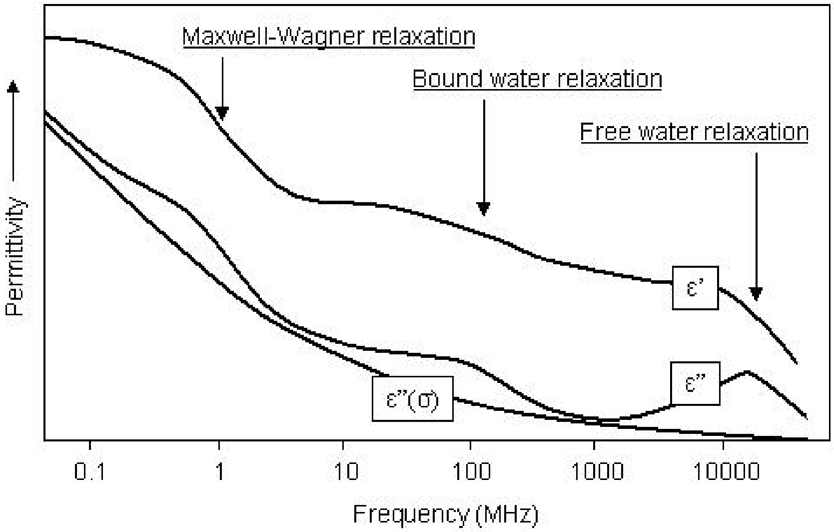

Fig. 1. Graph showing frequency-dependent dielectric properties and major relaxation phenomena of wet soils. ε' and ε" refer to the real and imaginary parts of the relative permittivity, respectively, while ε"(σ) represents the dc conductivity (from Hilhorst and Dirksen[14]).

Dielectric permittivity (ε*) is a complex function with real and imaginary components and is defined as $\varepsilon^* = \varepsilon' - j\varepsilon''$, where *j* is the square root of -1. The real part (ε') is often expressed as the relative permittivity (ε_r), which is the ratio of the electric-field storage capacity to that of free space[11]. The relative permittivity is a frequency dependent variable and decreases with increasing frequency[15]. The imaginary part (ε") of the dielectric permittivity is usually expressed in terms of dielectric losses, which include dispersive losses, as well as free-water relaxation and bound-water relaxation losses (Fig. 1).

At frequencies below 1 to 1.5 GHz ε* is only weakly frequency dependent[16] and dielectric losses are generally low[17]. However, at these low frequencies ε' and ε" are very sensitive to changes in soil water conductivity above about 10 mS/m[18, 19]. At frequencies below around 50 MHz ε* depends strongly on soil type[20, 21]. At frequencies above about 1 to 1.5 GHz the dielectric losses increase with increasing water content, even for low conductivity values[12].

Several studies document measurements of frequency dependent dielectric soil properties[12, 18, 19, 22-24] (Table 1). The results from these measurements show that is difficult to describe the relationship between textural characteristics and the frequency dependent complex dielectric properties of soils using one single model.

Table 1. Characteristics of some studies that document measurements of frequency dependent dielectric soil properties.

Name and reference	Frequency range (GHz)	Input[a]	# of [soils] & samples	Soil types
Wensink[18]	0.001-3	θ	11	Clay, Silt, Peat
Knoll[19]	0.0001, 0.001, 0.01	v_a, θ	11	artificial mixtures of Sand and Clay
Heimovaara[22]	0.001-0.15	θ	3	USDA[b]: SiL, LSa, SiClL
Curtis[23]	0.45-26.5	T_w, θ	[12] 30[c]	USDA[b]: Sa, SaL, Si, SiCl, SiClL, Cl
Nguyen[12]	1-0.75	θ	1	Sand

[a] θ:volumetric water content, v_a: volume air fraction in soil, T_w: soil water temperature.

[b] USDA texture classification[25].

[c] J.O. Curtis, personal communication, March 2005.

3. LITERATURE REVIEW

3.1. Phenomenological models

Phenomenological models such as Cole-Cole[26] and Debye[27] relate characteristic relaxation times to frequency dependent behavior of a material. These models allow for assessment of complex dielectric properties for specific frequencies. The Cole-Cole relaxation model describes the induced polarization effects as a function of frequency. The complex dielectric permittivity can be described as[12, 28]:

$$\varepsilon^*(f) = \left[\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\left(jf/f_{rel}\right)^{1-\beta}}\right] - \frac{j\sigma_{dc}}{2\pi f\varepsilon_0}. \tag*{[1]}$$

where ε_s and ε_∞ are the static value of the dielectric permittivity and the high-frequency limit of the real dielectric permittivity, respectively. For H_2O ε_s and ε_∞ equal 80 and 4.22, respectively, depending on temperature. ε_0 is the dielectric permittivity of free space ($8.854 \cdot 10^{-12}$ F/m)[22]. f_{rel} is the dielectric relaxation frequency of the material (17.1 GHz for water[22, 29]), σ_{dc} is the electrical conductivity and β is an empirical parameter to describe the spread in relaxation frequencies, which increases with the complexity of the mixture[26]. For distilled water, or other pure liquids with a single relaxation frequency, β is zero, resulting in the original Debye model[27]. For tap water and moist sandy soils β is 0.0125 and 0.3 according to Heimovaara[30] and Roth et al.[31], respectively. Some other values for β are reported in literature[34-36].

According to the Cole-Cole model the complex resistivity or impedance can be expressed as[32, 33]:

$$R^*(\omega) = R_0\left\{1 - m\left(1 - \frac{1}{\left(1+j\omega\tau\right)^c}\right)\right\}, \tag*{[2]}$$

where R_0 is the dc resistivity, m is a variable (0.1-1.0) depending on the mineral content, ω is the (radial) frequency, τ (range 10^{-4}-10^4) is the time constant, and c is a variable (0.2-0.6) depending on the grain size distribution. Roth et al. report a value of 8 for τ in moist sandy soils[31]. τ values for different materials have been reported in the literature[34-36].

As seen from the formulations above phenomenological models need recalibration for each specific material. Therefore, it is difficult to use these models to describe the dielectric differences between varying soil types.

3.2. Volumetric models

Volumetric models describe the dielectric properties of a soil based on the relative amounts of the different soil constituents and their individual dielectric characteristics. The basic input parameters to all models include solid matter, pore space, and volumetric water content. Depending on the model, input variables such as organic matter and bound water may provide additional accuracy for specific conditions. Usually, frequency dependence is not taken into account. The models have been calibrated, for example, by time-domain reflectometry. Over the years different volumetric mixing models have been proposed[20, 22, 37-42] that can be grouped in different types such as Arithmetic Average, Harmonic Average, Liechtenecker-Rother, and Time-Propagation[11]. The Complex Refractive Index (CRI) model or exponential model, which is based on the Liechtenecker-Rother model, is one of the most popular methods[6, 37]. The CRI model for a material with *n* components can be written as:

$$\varepsilon_m^{\alpha} = \sum_{i=1}^{n} v_i \varepsilon_i^{\alpha} \qquad [3]$$

where v_i is the volume fraction of the i^{th} soil constituent, and α is an empirical variable (0.5 according to some authors[e.g.,20, 37, 43]). The scaling factor α gives CRI and other volumetric mixing models a semi-empirical nature. The α parameter can theoretically vary from –1 to +1 but for multiphase mixtures such as soils values between 0.4 and 0.8 have been found[44]. Other values for α reported in the literature are 0.33[45, 46], 0.46 for three-phase systems[20] and 0.65 for four-phase systems including bound water[39]. Several attempts have been made to give a more physical basis to the scaling factor[e.g.,47]. It has been shown that the value of α also (inversely) correlates with the measurement frequency[48].

Another volumetric mixing model is the Maxwell-De Loor model[38], which assumes disc-shape inclusions with random distribution and orientation. This model has been used to describe dielectric properties of four-phase mixtures (ε_m) using[39, 42]:

$$\varepsilon_m = \varepsilon_h + \sum_{i=1}^{3} \frac{v_i}{3} (\varepsilon_i - \varepsilon_h) \sum_{j=1}^{3} \left(\frac{1}{1 + A_j \varepsilon_i / \varepsilon_b - 1} \right). \qquad [4]$$

Here, ε_h, ε_i, and ε_b are the dielectric permittivity of the host medium (solids), the permittivity of the inclusions, and the effective permittivity near boundaries, respectively, v_i represents the volume fraction of the inclusions, and A_j refers to the depolarization ellipsoid factors.

Recently, a new volumetric mixing equation based purely on the depolarization factors of different soil constituents has been introduced[6, 48]. This model has a strong theoretical basis and tries to overcome some problems that exist in other volumetric mixing models. In this approach the measured dielectric permittivity is related to the volume-weighted sum of the permittivities of the individual material constituents. A depolarization factor (*S*) is introduced to account for electric-field refractions at the material interfaces. In this mixing equation:

$$(\varepsilon - 1) = \sum_{i=1}^{n} (\varepsilon_i - 1) S_i v_i \qquad [5]$$

where v_i is the volume fraction of the i^{th} soil constituent, *S* is related to the electric field refraction in soil, which is in turn a function of the shape and surface roughness of the grains. Theoretically, the depolarization factor can be calculated for all materials but currently this is only possible for homogeneous materials with regular-shaped grains.

3.3. (Semi-) Empirical models

Empirical models are mathematical descriptions of the relationship between dielectric properties and other characteristics of a medium, especially volumetric water content and texture information. There is not necessarily a physical basis for the mathematical description. Therefore, an empirical model may only be valid for the data that were used to develop the relationship. Many empirical models have originated in the field of time-domain reflectometry (TDR), and were originally used to predict the soil water content from the velocity of electromagnetic signals along TDR probes in the soil.

The classic Topp-model[16] uses a third order polynomial to describe the relation between soil volumetric water content (θ) and bulk or apparent relative permittivity (K_a) for measurements taken below the relaxation frequency of water:

$$K_a = 3.03 + 9.3\theta + 146\theta^2 - 76.7\theta^3 \qquad [6]$$

The regression is an average of TDR measurements integrated over a frequency range of 1 MHz to 1 GHz for several soils and has proved very successful for a wide range of different soils and soil moisture conditions. Ledieu et al.[49] propose a linear relationship between soil water content and K_a, which can be used to expand the Topp-model for higher water contents. The model functions especially good for frequencies around 100 MHz[50]. At higher frequencies and moisture contents close to saturation (θ~0.4) the Topp-model over-predicts the bulk relative permittivity by up to 20%[50]. At very low water contents the Topp-model does not perform well, especially for soils with a large clay content[30, 51].

There exist various empirical models similar to equation [6] that are suitable for specific soil conditions. The bulk density has a profound effect on the relation between θ and K_a[20, 52, 53]. Soils high in organic matter usually have a lower bulk density. Conversion functions have been proposed to account for the bulk density and porosity variations between organic and mineral soils[54]. Dielectric measurements of samples high in organic matter content show that equation [6] may under-predict θ by about 30%. An alternative function has been proposed to account for this effect[55]. Clay content can have a significant effect on the relation between The presence of aligned ellipsoidal particles, for example in bedding planes of sedimentary deposits, also has an effect on the effective permittivity[56].

Brisco et al. present results for measurements with a field portable dielectric probe (PDP) at different frequencies ranging from 0.45 to 9.3 GHz[57]. The measurement variability is rather large and the number of soils studied is small. As a result, the third-order polynomial functions that are presented for each frequency may contain a significant error. At frequencies below around 50 MHz the dielectric permittivity depends strongly on soil type. Based on measurements of 6 soils at 1, 5, and 50 MHz it is shown that at the lower frequencies the soil type has a strong impact on both ε' and ε"[58]. Third-order polynomial functions for the data measured at 1 MHz and 50 MHz are given[58]. Also data are presented that show the effects of changes in volumetric water content and soil water temperature on the relationships between frequency (1-50 MHz) and ε^*.

Artificial Neural Networks (ANN's) provide an alternative means of determining the relationship between water content and bulk relative permittivity of soil empirically, either directly[59] or indirectly[60]. Using 10 samples (sand, loamy sand, sandy loam, sandy clay loam) from 5 different soils in Denmark Persson et al. demonstrate that ANN's can improve the accuracy of predicting this relationship[59]. ANN's do not produce a universal predictive model and need to be recalibrated for each new sample set.

Semi-empirical models are powerful and useful hybrids between empirical models and volumetric models. These models often use a volumetric mixing model as their base and have been calibrated for a specific set of soils. The models include information of physical background of dielectric behavior[39, 40, 48, 61]. They are sometimes able to describe frequency dependent behavior, but may only be valid for the data that were used to develop the relationship. The models by Dobson[39] and Peplinski[61] use input of the percentage of clay and sand in a soil, as well as the volumetric water content and bulk density to calculate the complex frequency dependent properties of field soils. The model by Hilhorst[48] uses Debye relaxation parameters, the soil matric pressure, which is related to textural characteristics[62], and a semi-empirical parameter (S, see equation [5]) to calculate the complex frequency dependent soil properties.

4. SUMMARY

The choice for which model to use depends on the desired level of detail. Table 2 presents a summary of available dielectric mixing methods. Most mixing and empirical models require few input parameters. Using basic information, available in soil and meterological databases, it is often possible to make good statements on the soil dielectric properties of a general area using these simple models[1]. Semi-empirical models such as those by Dobson et al.[39], Peplinski et al.[61], and Hilhorst[48] can provide additional information on for example frequency-dependent soil properties but require input variables not always available in databases. Additional field or laboratory measurements are necessary when information is needed on temporal or small-scale spatial variability in soil dielectric properties.

Both Dobson et al.[39] and Bohl and Roth[42] compare a number of mixing models for predicting the relationships between soil water content and dielectric soil properties. It is concluded that simple three- and four-phase CRI mixing models are adequate to describe mineral soils[42]. For organic soils (definition: http://www.soils.org/sssagloss/) only four-phase mixing models and the Maxwell-De Loor model provide good results.

5. CONCLUSION

We have presented a literature review of available methods for prediction of dielectric properties of field soils. The available methods have been grouped into phenomenological, volumetric, and (semi) empirical models and we have presented the major characteristics of the different groups. Relatively few approaches are as detailed yet easy to implement as the models by Dobson et al.[39] and Peplinski et al.[61]. Their models are based on measurements of a significant number of samples and include a physical base that allows for calculation of frequency dependent soil properties. The main flaw in their models is the poor overlap between both models around the zone of 1.3 GHz[63]. This is especially problematic because many electromagnetic sensors for the detection of buried objects operate in or near this frequency range. We suggest additional measurements in this frequency range would be very helpful to improve understanding of the frequency dependent soil characteristics.

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Table 2. Overview of dielectric mixing models.

		Input[b]			Output[b]	Calibrated for			
Name and reference	Type[a]	*f* range (GHz)	Texture	Other		*f* range (GHz)	# of soils	# of samples	soil types[c]
Debye[27]	1	∞	-	ε_s, ε_∞, ε_0, f_{rel}	ε', ε'', σ_{eff}	∞	-	-	-
Cole-Cole[26]	1	∞	-	ε_s, ε_∞, ε_0, f_{rel}, β	ε', ε'', σ_{eff}	∞	-	-	-
Birchack 3C[37]	2	-	v_a, v_s	θ, α, ε_i	K_a	4-6	0	2	Crushed Limestone, Bentonite Clay
Wang 4C[40]	2	?	v_a, v_s	v_{fw}, v_{bw}, ε_i	ε', ε''	1.4-5	?	?	
Dobson-De Loor[39]	2	1.4-18	v_a, v_s	v_{fw}, v_{bw}, ε_i	ε', ε''	1.4-18	5	5	USDA: SaL, L, SiL, SiL, SiCl
Roth 3C[20]	2	-	v_a, v_s	T_w, θ	K_a	∫ TDR range	10	13	USDA: SaL, ClL, L, SiL, SiCl, LSa, Peat
Bohl, 3C, 4C[42]	2	-	v_a, v_s	v_{fw}, v_{bw}, ε_i, α	K_a	∫ TDR range	17	34	USDA: SaL, Sa, ClL, L, SiL, SaClL, SiClL, SiCl, LSa, OS[d]
Bohl-De Loor[42]	2	-	v_a, v_s	v_{fw}, v_{bw}, ε_i, α	K_a	∫ TDR range	17	34	USDA: SaL, Sa, ClL, L, SiL, SaClL, SiClL, SiCl, LSa, OS
Hillhorst[6]	2	∞	v_i	v_i, S, ε_i	ε^*	-	-	-	
Topp classic[16]	3a	-	-	θ	K_a	∫ 0.001-1	2	4	USDA: SaL, ClL, Cl
Hallikainen[24]	3a	1.4-18 (9 incr.)	Cl, Sa	θ	ε', ε''	1.4-18	5	5	USDA: SaL, L, SiL, SiL, SiCl
Ledieu linear[49]	3a	-	-	θ	K_a	∫ TDR range	?	?	
Brisco PDP[57]	3a	0.45, 1.25, 5.3, 9.3	-	θ	K_a	0.45, 1.25, 5.3, 9.3	3	3	USDA: SaL, ClL, SiCl
Herkelrath Om[55]	3a	-	-	θ	K_a	∫ TDR range	1	5	OS
Roth Om[52]	3a	-	-	θ	K_a	∫ TDR range	9	18	USDA: Sa, SaL, LSa, SaClL, Cl, ClL, L, SiL, SiCl, OS
Campbell[58]	3a	0.001, 0.05	-	θ	K_a	0.001-0.05	6	6	Sand, Silt, Clay
Malicki BD[54]	3a	-	-	θ, ρ_b	K_a	∫ TDR range	18	34	USDA: Sa, SaL, SaClL, Cl, ClL, L, SiL, SiClL, SiCl, OS
Curtis[50]	3a	0.1, 0.5, 1	-	θ	K_a	0.1-1	50-75	200-250[e]	
Persson ANN[59]	3a	-	Cl, Si, Sa	θ, ρ_b, Om	K_a	∫ TDR range	5	10	USDA: Sa, LSa, SaL, SaClL
Dobson semi-emp[39]	3b	1.4-18	Cl, Sa	θ, ρ	ε', ε'', σ_{eff}	1.4-18	5	5	USDA: SaL, L, SiL, SiCl
Peplinski semi-emp[61]	3b	0.3-1.3	Cl, Sa	θ, ρ_b, ρ_s	ε', ε'', σ_{eff}	0.3-1.3	4	4	artificial mixtures of Sand, Silt, Clay
Hilhorst semi-emp[48]	3b	0.001-100	v_a, v_s	ε_s, ε_∞, v_{fw}, f_{rel}, p_m, S_i	ε', ε''	0.02, FD sensor and ∫ 0.01-1	7	11	USDA: SiL, SaL, Cl, SiClL, ClL, SiCl + pure Sand (1) and Clay (3)

[a] Model types refer to (1) phenomenological, (2) volumetric, (3a) empirical, and (3b) semi-empirical.

[b] Symbols mean Cl: clay %, Sa: sand %, Si: silt %, Om: organic matter %, K_a: apparent relative permittivity, ρ_b: dry bulk density, ρ_s: bulk density of solids, θ: volumetric water content, T_w: temperature of soil water, v_a: volume air fraction in soil, v_{bw}: volume bound water fraction in soil, v_{fw}: volume free water fraction in soil, v_s: volume solid fraction in soil, α: empirical variable, β: spread in relaxation frequencies, ε_i: dielectric permittivity of ith soil component, ε': real part of dielectric permittivity, ε'': imaginary part of dielectric permittivity, ε^*: complex dielectric permittivity, ε_s: static dielectric permittivity, ε_∞: dielectric permittivity at infinite frequency, σ_{eff}: effective dielectric conductivity, p_m: matric pressure, S_i: depolarization factor of ith soil component.

[c] USDA texture classification[25], Sa: sand, SaL: Sandy Loam, SaClL: Sandy Clay Loam, Cl: Clay, ClL: Clay Loam, L: Loam, SiCl: Silty Clay, SiClL: Silty Clay Loam, SiL: Silt Loam.

[d] OS: organic soil.

[e] J.O. Curtis, personal communication, March 2005.

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