

A Pore Water Conductivity Sensor

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ABSTRACT

The electrical permittivity and conductivity of the bulk soil are a function of the permittivity and conductivity of the pore water. For soil water contents higher than 0.10 both functions are equal, facilitating in situ conductivity measurements of the pore water. A novel method is described, based on simultaneous measurements of permittivity and conductivity of the bulk soil from which the conductivity of the pore water can be calculated. A prototype of a pore water conductivity sensor based on this method is presented. Validation results show that the method can be used for a broad range of soils and is valid for water contents between 0.10 and saturation and for the conductivity of the pore water up to 0.3 S m⁻¹.

ONE METHOD of determining the conductivity of the pore water of soil, σ_p , is by extracting a sample of water from the soil matrix. This is a labor-intensive task and not well suited for automation. Additionally, it is not certain that all ions are collected in the extracted sample. Another way is to translate the electrical conductivity of the bulk soil, σ_b , to σ_p using methods, models, and estimates such as those described by Rhoades et al. (1990) or Mualem and Friedman (1991). The weakness of these methods is that they are empirical relationships.

The electrical permittivity of the bulk soil, ϵ_b , is a function of both the soil water content, θ , and the permittivity of the pore water, ϵ_p (e.g., Nyfors and Vainikainen, 1989). Soil water content, θ , is a quantity defined as the volume fraction of water in the soil. Similarly, σ_b is a function of both θ and σ_p .

Malicki et al. (1994) found a high degree of linear correlation between σ_b and ϵ_b values measured using time domain reflectometry for a broad range of soil types. They found an attractive method to calculate σ_p from simultaneous measurements of σ_b and ϵ_b . However, Malicki's method is still an empirical one. The aim of this work was to approach the problem from a slightly different angle to derive a more fundamental relationship between σ_b and σ_p .

THEORY AND METHODS

Bulk Soil Conductivity vs. Pore Water Conductivity

The relative electrical permittivity of a dielectric material, ϵ , is a complex quantity expressing the ability to polarize the material in an electric field (E -field) and is defined as

$$\epsilon = \epsilon' - j\epsilon'' \quad [1]$$

with $j = \sqrt{-1}$. In this paper the dielectric can be either water, solids, or air, or a mixture of them. In the following,

the superscript ' refers to the real part of ϵ and the superscript '' refers to the imaginary part of ϵ . For a static E -field the real part of the permittivity, ϵ' , is usually referred to as dielectric constant. The imaginary part of the permittivity, ϵ'' , represents the total energy absorption or energy loss. The energy losses include dielectric loss, ϵ_d , and loss by ionic conduction

$$\epsilon'' = \epsilon_d'' + \frac{\sigma_i}{\omega\epsilon_0} \quad [2]$$

where σ_i is the specific ionic conductivity of the material, and ω the radian frequency (rad s⁻¹). The frequency (Hz) of the applied E -field is $f = \omega/2\pi$. The permittivity for free space is $\epsilon_0 = 8.854 \times 10^{-12}$ F m⁻¹.

Let us consider the water that can be extracted from the pores of the soil matrix. The permittivity and conductivity of the pore water will be denoted by subscript p . The imaginary part of the complex permittivity of the pore water is ϵ_p'' . In soil science it is not customary to use ϵ_p'' . It is more practical to use the conductivity of the pore water, σ_p , which can be defined as

$$\sigma_p = \omega\epsilon_0\epsilon_p'' = \omega\epsilon_0\left(\epsilon_{dp}'' + \frac{\sigma_{ip}}{\omega\epsilon_0}\right) \quad [3]$$

where σ_{ip} represents the ionic conductivity of the extracted pore water. Dielectric losses are frequency dependent and have a maximum at the relaxation frequency. The relaxation frequency of water is 17 GHz at 20°C (Kaatze and Uhlendorf, 1981). The operating frequency for most dielectric or conductivity sensors is $\ll 1$ GHz. At frequencies low with respect to the relaxation frequency of water, ϵ_{dp}'' is negligible and Eq. [3] can be reduced to

$$\sigma_p \approx \sigma_{ip} \quad [4]$$

Frequently σ_p is referred to as the electrical conductivity (EC) of the pore water. Note that EC refers to the conductivity of the pore water and not to that of the bulk soil. Ionic conduction is a function of temperature. In the case of a NaCl-water mixture, the conductivity increases by 2.25% °C⁻¹. Often the measured σ_p or EC is given corrected for temperature dependence to a temperature of 20°C. This temperature correction depends on the composition of the solution and will not be used here. The complex permittivity of the pore water, ϵ_p , is equal to that of pure water. The real part of the complex permittivity of the pore water $\epsilon_p' = 80.3$ at 20°C with a temperature coefficient of about -0.37°C^{-1} (Kaatze and Uhlendorf, 1981). By analogy with Eq. [1] we can write the following approximation for ϵ_p

$$\epsilon_p \approx \epsilon_p' - j\frac{\sigma_p}{\omega\epsilon_0} \quad [5]$$

The permittivity and conductivity of the bulk soil will be denoted by subscript b . The complex permittivity of the bulk soil, ϵ_b , is proportional to both ϵ_p and a function of θ , $g(\theta)$. This $g(\theta)$ function includes soil type and frequency dependency. In the following we assume that ϵ_b and σ_b are measured for the same frequency and soil type. For dry soil, there is no water to facilitate ionic conduction; that is, the conductivity of the

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bulk soil $\sigma_b \approx 0$. However, dry soil material is still polarizable. Hence the permittivity for dry soil $\epsilon'_{\sigma_b=0} \neq 0$; $\epsilon'_{\sigma_b=0}$ appears as an offset to ϵ_b . Now it is reasonable to postulate the following form for the complex permittivity of the bulk soil

$$\epsilon_b = \epsilon_{\sigma_b=0} + \epsilon_p g(\theta) \quad [6]$$

Note that $\epsilon'_{\sigma_b=0}$ is a complex value and includes dielectric and ionic loss. However, since $\sigma_b \approx 0$ for dry soil, we may approximate $\epsilon'_{\sigma_b=0}$ by its real part $\epsilon'_{\sigma_b=0}$. Note also that $\epsilon'_{\sigma_b=0}$ is the extrapolated intercept with the y axis from the linear part of the ϵ'_b vs. σ_b plot. With this and Eq. [5] substituted in Eq. [6], ϵ_b can be written as

$$\epsilon_b = \epsilon'_{\sigma_b=0} + \epsilon'_p g(\theta) - j \frac{\sigma_p}{\omega \epsilon_0} g(\theta) \quad [7]$$

An electric model for a dielectric, like soil, between two electrodes is a lossy capacitor. The admittance, Y , of this capacitor is a complex quantity that is proportional to ϵ_b of the bulk soil. Y is the reciprocal of the impedance Z . For soil Y can be defined by

$$Y = j\omega \epsilon_0 \epsilon_b \kappa \quad [8]$$

where κ is a geometry factor that is determined by the distance between the electrodes and their areas in contact with the soil. Note that contact problems of the electrodes with the soil will be reflected in κ . The equivalent circuit for such a lossy capacitor is a loss-free capacitor, C , with a conductor, G , in parallel. C represents the energy storage capability of the soil and is related to ϵ'_b . G represents the energy loss and is related to σ_b . Y may be written in terms of C and G as

$$Y = G + j\omega C \quad [9]$$

From Eq. [8] and [9], and with Eq. [1] to [7] in mind, the real and imaginary parts of Y can be found

$$G = \sigma_p G(\theta) \kappa \quad [10]$$

and

$$\omega C = \omega \epsilon_0 [\epsilon'_{\sigma_b=0} + \epsilon'_p g(\theta)] \kappa \quad [11]$$

or in terms of the measurable bulk quantities σ_b (dividing Eq. [10] by κ) and ϵ'_b (dividing Eq. [11] by $\omega \epsilon_0 \kappa$)

$$\sigma_b = \sigma_p g(\theta) \quad [12]$$

and

$$\epsilon'_b = \epsilon'_{\sigma_b=0} + \epsilon'_p g(\theta) \quad [13]$$

From Eq. [12] and [13] the ionic conductivity of the pore water can be written as

$$\sigma_p = \frac{\epsilon'_p \sigma_b}{(\epsilon'_b - \epsilon'_{\sigma_b=0})} \quad [14]$$

The model of Eq. [14] describes the relationship between σ_p of the pore water (the water that can be extracted from the soil) and the values ϵ'_b and σ_b as measured in the bulk soil using a dielectric sensor. The offset $\epsilon'_{\sigma_b=0}$ can be calculated from the ϵ'_b and σ_b values measured at two arbitrary free water content values.

The relationships between the bulk soil parameters ϵ'_b and σ_b and the corresponding pore water parameters ϵ'_p and σ_p is different when the water present is bound to the soil matrix rather than free water. The model of Eq. [14] cannot be used for the conduction due to ions moving through the lattice of ionic crystals in a dry or almost dry soil. Therefore, the model is only valid for the free water in the matrix. Thus $\epsilon'_{\sigma_b=0}$ is not the value for ϵ'_b if $\theta = 0$. For sand, the free water content corresponds with $\theta > 0.01$, but for clay it can be $\theta > 0.12$ (Dirksen and Dasberg, 1993). As a rule of thumb, the model applies for most normal soils and other substrates for growing, like rockwool, if $\theta > 0.10$.

The Dielectric Sensor

For both ϵ'_b and σ_b equally (see Eq. [12] and [13]), only $g(\theta)$ will be affected to a major extent by the frequency, by the shape of the electrodes, by the contact between electrodes

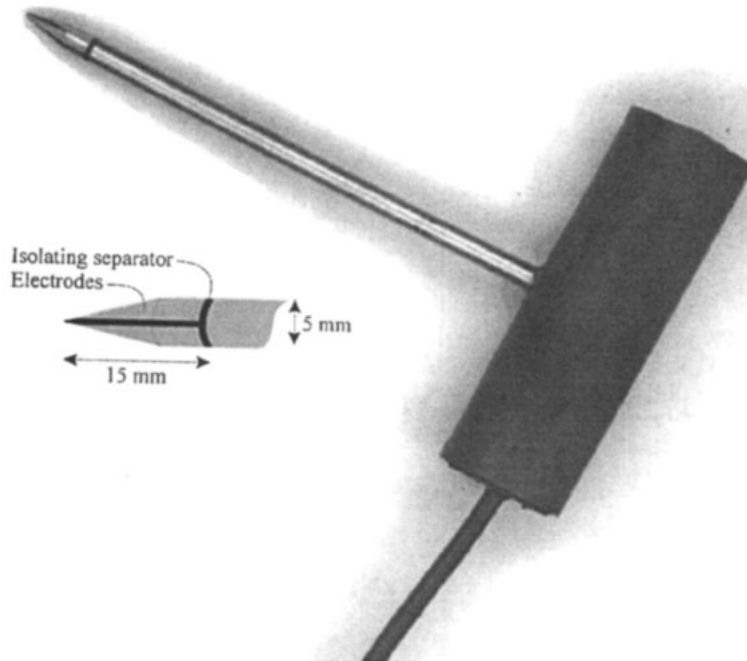


Fig. 1. A prototype of a sensor for the measurement of the conductivity of the pore water in the soil matrix. A temperature sensor is located near the sensor tip. The measuring frequency of the sensor is 30 MHz. The drawing shows more details of the sensor tip.

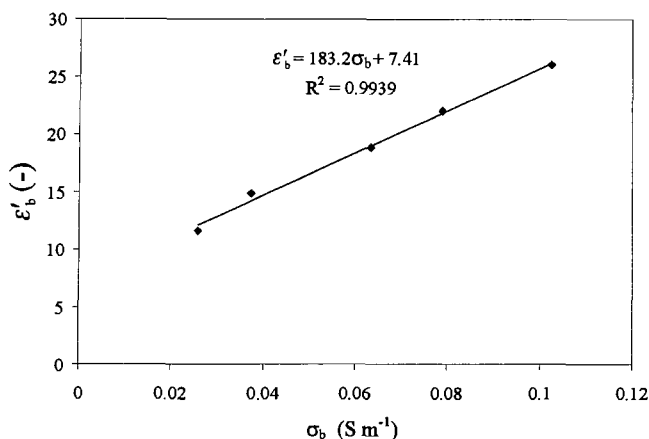


Fig. 2. The linear relationship between the real part of the permittivity, ϵ'_b , as a function of the conductivity of the bulk, σ_b , for glass beads. The conductivity of the applied water was 0.4 S m^{-1} .

and soil, and by the soil composition. Due to the ratiometric form of Eq. [14] with respect to ϵ'_b and σ_b , $g(\theta)$ will be eliminated. Therefore, contact problems have only a minor effect on the conductivity measurement of the pore water. This allows development of a small sensor tip for easy insertion in the soil. In Fig. 1, a prototype of a pore water conductivity sensor as developed by IMAG in Wageningen, the Netherlands, is shown. For a detailed description of the sensor electronics the reader is referred to Hilhorst et al. (1993) and Hilhorst (1998). The "T"-shaped sensor is commercially available from Delta-T Devices Ltd. (Cambridge, UK).

The sensor is built around an application-specific integrated circuit (ASIC) developed for dielectric sensors. It contains all analogue and digital electronics to measure ϵ'_b and σ_b . The measuring frequency is 30 MHz, which was more or less arbitrarily chosen. The ASIC measures 4 by 4.5 mm. Therefore all the electronics can be conveniently placed in the cylinder at the top of the sensor rod. The sensor rod is 10 cm long and 5 mm in diameter. The rod ends in a sharp point to facilitate insertion of the electrodes into the soil. The sensor tip is ≈ 15 mm long and split into two metal electrodes separated from each other by a thin sheet of isolating material. A temperature sensor is located close to the sensor tip to facilitate temperature measurements. The ASIC is embedded in a cylinder of hard polyurethane molding. The flexible polyurethane output cable contains the RS232 signal wires and power supply wires. This cable is connected to a PSION-Workabout that runs the software for further signal processing and contains the model of Eq. [14].

Validation of the Theory

Relationship Between Bulk Conductivity and Permittivity

First we will demonstrate the validity of the assumption that ϵ'_b changes linearly with σ_b if θ is varied. Four samples of wet glass beads of 0.2 mm at arbitrary θ were prepared by slowly extracting solution from an initially saturated sample. Since σ_p is not allowed to change with θ , drying by evaporation was avoided. The measurements of ϵ'_b and σ_b , and also the measurement of σ_p (in the water left on top of the samples), were performed using the sensor of Fig. 1. This sensor measures ϵ'_b and σ_b , performs the calculations, and returns only σ_p . For this experiment a software facility was built in to export also the ϵ'_b and σ_b . The measurement of σ_p was checked using a laboratory four-electrode conductivity meter at 1 kHz. Water content was determined by the gravimetric method. The experiment started with clean glass beads, and σ_p was measured before the solution was applied.

The result for the relationship between ϵ'_b and σ_b is shown in Fig. 2. From this data it followed that for glass beads $\epsilon'_{\sigma_b=0} = 7.4$. The σ of the applied solution was 0.4 S m^{-1} . With $\epsilon'_{\sigma_b=0} = 7.4$ in Eq. [14] we found for the conductivity of the pore water of all glass bead samples $\sigma_p = 0.4 \text{ S m}^{-1}$ within $\pm 0.1 \text{ S m}^{-1}$.

Model Evaluation

The model of Eq. [14] was evaluated for five different soils, glass beads of 0.2-mm diam. and a slab of rockwool. The soils were samples from the Dirksen and Dasberg (1993) experiment. Their compositions are listed in Table 1. The salinity of the soil samples was left as it appeared. The salinity of the rockwool slab and the glass beads were adjusted to $\sigma_p = 0.3 \text{ S m}^{-1}$ and $\sigma_p = 0.1 \text{ S m}^{-1}$, respectively, using water–NaCl solutions. Sufficient water was left on top of the saturated samples to measure σ_p of the soil solution. The measurements of ϵ'_b and σ_b , and also the measurement of σ_p (in the water left on top of the samples), were performed using the sensor of Fig. 1. This sensor measures ϵ'_b and σ_b , performs the calculations, and returns only σ_p . The measurement of σ_p was checked using a laboratory four-electrode conductivity meter at 1 kHz.

Each material was dried in 10 steps by slowly extracting solution from an initially saturated and thoroughly mixed sample. In this way 10 water contents between $\theta = 0.10$ and saturation were created. The change in θ was measured using a balance. Since the salinity of the pore water is not allowed to change with θ , drying by evaporation was avoided. The experiment was carried out at a temperature of 20°C . The measured σ_p values are listed in the eighth column of Table

Table 1. Soil composition and validation results.

Soil	Clay	Silt	Sand	Organic matter	Offset† $\epsilon'_{\sigma_b=0}$ (-)	Conductivity pore water, σ_p		
						Extract‡	Calculated§	
							Average	Standard deviation
			%					
Glass beads¶	—	—	—	—	7.6	0.10	0.09	0.01
Rockwool	—	—	—	—	4.1	0.30	0.31	0.01
Groesbeek	10	70	20	0.95	2.7	0.25	0.20	0.01
Wichmond	14	31	55	4.3	1.9	0.10	0.11	0.005
Ferralsol-A	63	26	11	0	4.4	0.08	0.05	0.006
Munnikenland	40	56	3	5	5.8	0.31	0.29	0.02
Attapulgit	100	0	0	0	3.1	0.13	0.13	0.01

† Value found for the permittivity $\epsilon'_{\sigma_b=0}$ at which the bulk conductivity $\sigma_b=0$.

‡ Measured ionic conductivity of a pore water extract σ_p as determined using a laboratory 4-electrode conductivity meter at 1 kHz.

§ Average values with their standard deviations calculated according to Eq. [14] for σ_p at 10 θ values between 0.10 and saturation.

¶ Diameter of the glass beads is 0.2 mm.

1. The average values with their standard deviations for σ_p , at the 10 θ steps, calculated according to Eq. [14], are listed in the last two columns. The seventh column lists the measured σ_p of a pore water extract. Comparison of the σ_p values measured in the soil solution and the σ_p values calculated from ϵ'_b and σ_b justifies the model of Eq. [14]. The values found for $\epsilon'_{\sigma_b=0}$ are listed in the sixth column.

DISCUSSION AND CONCLUSIONS

The relationship between simultaneously measured values of the real part of the permittivity, ϵ'_b , and the electrical conductivity of the bulk soil, σ_b , measured at the same frequency, is to a major extent linear. ϵ'_b and σ_b are equally affected by the shape of the electrodes, by the contact between electrodes and soil, and by the soil composition. In general this applies for any soil where the water content $\theta > 0.10$. In addition at low water contents, thus at low ϵ'_b values, the method becomes sensitive to the term $\epsilon'_b - \epsilon'_{\sigma_b=0}$ in Eq. [14].

The intercept with the y axis, $\epsilon'_{\sigma_b=0}$, of the linear part of the ϵ'_b vs. σ_p plot is not the value one would expect for $\sigma_b = 0$. In case of the glass beads of Fig. 2, $\epsilon'_{\sigma_b=0} = 7.4$ at $\sigma_p = 0.4$ and $\epsilon'_{\sigma_b=0} = 7.6$ at $\sigma_p = 0.1$, but for dry glass beads we measured $\epsilon'_b = 3.7$. Thus, there should be a bending of the ϵ'_b vs. σ_p curve near the y axis. This bending was not observed in this research. Therefore, further research on $\epsilon'_{\sigma_b=0}$ as a function of temperature and σ_p for different materials is desired.

Due to the linear relationship between ϵ'_b and σ_b , the ionic conductivity of the pore water in the soil, σ_p , can be found from a simultaneous measurement of ϵ'_b and σ_b independently of θ . Contact problems have only minor effect on σ_p measurements. To facilitate calibration $\epsilon'_{\sigma_b=0} = 4.1$ can be used as an average. In this case, calibration of the sensor for σ_p is not required if $\theta > 0.1$.

The presented sensor has a measurement limit at a bulk conductivity of 3 mS cm^{-1} , but this is not the limit of the method. For high salt concentrations or for bound water ϵ'_p may deviate from that of free water. However, as long as the actual ϵ'_p of the pore water is known Eq. [14] can still be used.

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