

Measurement of relative permittivity in sandy soils using TDR, capacitance and theta probes: comparison, including the effects of bulk soil electrical conductivity

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Abstract

Measurement of the apparent dielectric permittivity of soils (dielectric constant) is becoming a popular way of estimating soil volumetric water content. This paper focuses on the measurement of apparent permittivity in four sandy soils using; time domain reflectometry (TDR), a surface capacitance insertion probe (SCIP) and a Theta probe. Measurement of the apparent permittivity using the SCIP and Theta probe are compared with the apparent permittivity measured using the TDR.

Calibration of such instrumentation has remained relatively empirical following the engineering approximation presented by Topp et al. (Topp, G.C., Davies, J.L., Anan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Res. Research* 16, 574–582.). The refractive index model proposed by Whalley (Whalley, W.R., 1993. Considerations on the use of time domain reflectometry (TDR) for measuring soil water content. *J. Soil Sci.* 44(1), 1–9.) based on that of Birchak et al. (Birchak, J.R., Gardner, C.Z.G., Hipp, J.E., Victor, J.M., 1974. High dielectric constant microwave probes for sensing soil moisture. *Proc. IEEE* 62(1), 93–98.) is investigated as a means of gaining some physical understanding of the relative contributions of the different dielectric components in soils. Predictions made by the model are tested against results using multiple linear regression. The predictions agree well with the observed measurements. Inter-electrode conductivity is found to contribute significantly to the apparent permittivity measured using the SCIP and to a lesser extent the TDR but not the Theta probe. Inclusion of inter-electrode conductivity in regression analysis improved results. The Theta probe was found to overestimate the apparent permittivity of the soil by ~ 1.5 when compared with TDR results. It is suggested that this may be the result of compaction of the soil close to the electrodes, coupled with a strong bias in the sensitivity of the probe to the region very close to the central electrode. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Soil water content; Capacitance probe; Soil relative permittivity; Time domain reflectometry; Theta probe; Surface capacitance insertion probe

1. Introduction

Measurement of the apparent permittivity of a soil provides an elegant method of estimating its water

content. A variety of sensors are now commercially available which utilise this relationship to estimate soil volumetric water content. In order that results presented in the literature are consistent it is important to compare what each device measures and its measurement limitations. The advantages of such sensors over the widely used neutron probe method are that they can be automated, used close to the soil

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surface and contain no radioactive source. They are of use in hydrological research and in commercial applications such as scheduling irrigation in agriculture and horticulture and anywhere else where it is important to know the water content of a porous material.

The complex permittivity (ϵ^*) of a material is a measure of the extent to which the charge distribution within the material is polarised in an external electric field. It has a real part (ϵ') referred to in this paper as the relative permittivity (ϵ_r) describing energy storage and an imaginary part (ϵ'') describing losses which are mostly due to ionic conduction:

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (1)$$

where j is $\sqrt{-1}$ and ϵ'' is $\sigma/\omega\epsilon_0$, the dc conductivity (σ) divided by the product of the angular frequency (ω) and electric constant (ϵ_0).

Polar molecules such as water are permanently polarised and orient themselves with the applied field. In becoming orientated with the field, the molecules absorb energy from it, which is released when the field is removed and the molecules return to their random orientation. In nature, the most common polar liquid is water, which has a relative permittivity of ~ 80 , in comparison to 1 for air and ~ 5 for quartz (Carmichael, 1982), the major constituent of most sandy soils. The amount of water in a porous material, therefore, strongly influences the apparent permittivity of the mixture. Hence an estimate of the volumetric water content can be achieved from measurements of apparent permittivity using a suitable calibration.

Accurate measurement of soil relative permittivity (ϵ_r) is fundamental to this process. In practice, as demonstrated in this paper, different dielectric measurement techniques produce slightly different apparent permittivity values. The three methods used in the paper are: time domain reflectometry (TDR) which is the best established dielectric technique (Topp et al., 1980; Dirksen and Dasberg, 1993; Heimovaara, 1993; Whalley, 1993; Malicki et al., 1996; Wyseure et al., 1997); the surface capacitance insertion probe (SCIP), which is both cheaper and more adaptable than TDR (Dean, 1994; Gardner et al., 1998; Robinson et al., 1998) and the recently introduced Theta probe (Model ML-01, Delta-T

devices, Burwell, Cambridge), which is a low cost, fixed frequency, impedance sensor (Miller and Gaskin, 1995; Gaskin and Miller, 1996).

All measurements made using these instruments are to a greater or lesser extent contributed to by the electrical conductivity of the medium. Therefore, in this paper the permittivity measured by an instrument is termed apparent permittivity with the symbol K used to denote this measurement; ϵ_r is reserved for the theoretical relative permittivity. The terms K_a , K_{SCIP} , K_c and K_{TP} are used to denote an apparent permittivity measured by the TDR, SCIP, corrected for soil electrical conductivity and the Theta probe respectively. The values of K are not the same and differ according to the way in which the bulk soil electrical conductivity affects measurements, this is discussed in more detail in Section 2.

Sandy mineral soils ($>65\%$ sand, particle size >0.06 mm) present a relatively simple three phase system (solid, liquid and gas), in which the effects of organic matter, clays and soil surface area on the relative permittivity of the soil water can normally be neglected. Topp et al. (1980) presented an empirical calibration between soil apparent permittivity measured by the TDR (K_a) and the volumetric water content of mineral soils. This serves as a good benchmark for comparison of calibrations and has been shown to be applicable to sandy soils (Nadler et al., 1991; Roth et al., 1992). However, the empirical approach provides little understanding of the soil factors controlling the dielectric properties of the soil.

1.1. Soil dielectric mixing models

Semi-physical models have been presented by a number of authors seeking to understand the dielectric properties of soils. One approach is to assume that the relative permittivity of the soil is a function of the different dielectric components and their relative quantities and can be expressed by a mixing equation of the form:

$$\epsilon_r^\alpha = \sum_i V_i \epsilon_i^\alpha \quad (2)$$

where V_i is the volume fraction and ϵ_i is the relative permittivity of the i th soil component and α is an exponent. Models of this form have been presented by a number of authors with empirical exponents

Table 1

Slope and intercept values for regressions using sands and mineral soils, plotting $\sqrt{\varepsilon_r}$ vs. volumetric water content using TDR

Data source:	Slope	Intercept	Material
Zegelin et al. (1989)	8.55	1.55	Bungendore fine sand
Whalley (1993)	8.28	1.10	Redhill sand
Drungil et al. (1989)	8.03	1.61	Sand
Drungil et al. (1989)	8.03	1.62	Sandy loam
Topp et al. (1980)	8.98	1.88	Empirical curve for mineral soils
Gregory et al. (1995)	7.26	1.45	4 sandy soils

(Birchak et al., 1974; Dobson et al., 1985; Roth et al., 1990). The determined exponent is considered by the authors to reflect, in some way, the geometry of the system, in much the same way as the depolarisation factors used in the theoretical models discussed in Sihvola (1997). For the case where the exponent is 0.5 it becomes the refractive index model as used by Whalley (1993) and Heimovaara et al. (1994) with TDR. This relationship is based on that presented by Maxwell (1873) showing that the refractive index (η) of a homogeneous and isotropic material is $\eta = \sqrt{\varepsilon_r}$; in this work the sands are assumed to be such a material. In his review, de Loor (1990) suggests that $\alpha = 0.5$ holds for measurements made at relatively high frequencies and so the use of refractive index should be reserved for measurements made using microwave remote sensing or TDR. This does not however, preclude the plotting of $\sqrt{\varepsilon_r}$ as a function of water content for data collected using lower frequency sensors.

The model used in this work is based on that presented by Whalley (1993) where $\sqrt{\varepsilon_r}$ can be considered equivalent to refractive index for measurements made using the TDR; for convenience all results are discussed in terms of $\sqrt{\varepsilon_r}$, the mixing formula is presented as Eq. (3):

$$\sqrt{\varepsilon_r} = \theta(\sqrt{\varepsilon_w} - 1) + \frac{\rho_b}{\rho_s}(\sqrt{\varepsilon_s} - 1) + 1 \quad (3)$$

where θ is volumetric water content, ε_w the relative permittivity of water and ε_s the relative permittivity of the solid, ρ_s is the density of the solid (g cm^{-3}), and ρ_b is the dry bulk density of the mixture (g cm^{-3}).

For soil of constant ρ_b , the relationship between $\sqrt{\varepsilon_r}$ and θ is therefore linear; the slope of the relationship is related to the water content of the soil by $\sqrt{\varepsilon_w} - 1$, and the intercept is a function of the relative

permittivity of the dry mixture. For a soil at a temperature of 20°C ($\varepsilon_w = 80.2$) a slope of 7.96 would be predicted. Similarly, (assuming $\rho_s = 2.65 \text{ g cm}^{-3}$) for a soil with a bulk density of 1.7 g cm^{-3} , an intercept of 1.60 would be predicted for an ε_s of 4, 1.75 for an ε_s of 5. For a given value of ε_s the change of $\sqrt{\varepsilon_r}$ with respect to bulk density can therefore be calculated. For ε_s values of 4 and 5 the factors of $0.38 \rho_b$ and $0.47 \rho_b$, respectively, the constant increasing as the relative permittivity of the solid rises. This approach is particularly suited to sandy soils containing mostly quartz as the relative permittivity of quartz is well documented with a value of about 5 (Carmichael, 1982). The approach becomes more difficult when soils containing mixtures of minerals with different permittivities are involved. However, in work examining a number of light and medium textured soils Robinson (1998) found a value of five to adequately describe the mineral fraction.

Experimental values of the slope and intercept of this relationship (Eq. (3)) have been presented by a number of authors (using TDR) for sandy and mineral soils (Table 1). Most of these values lie close to the values predicted by the model, although, with one exception, the slopes are slightly greater than those expected. This might be either due to the experimental error or as will be demonstrated in this work the effects of the solution electrical conductivity increasing the value of the apparent permittivity at higher water contents (Eq. (9)).

2. Methods and materials

2.1. Measurement of soil relative permittivity

Permittivity measurements were made using each

of the three instruments in samples of four sandy soils at known water content and dry bulk density. The TDR and SCIP instruments that were used, were designed to operate with detachable pairs of parallel, stainless steel electrodes which were inserted into the soil during measurements (Robinson et al., 1998). This meant that both TDR and SCIP measurements could be made using the same electrodes in the sample, without disturbing the soil between measurements.

2.2. Time domain reflectometry

A Tektronix (1502C) TDR system was used throughout the experiments. A 1 m length of coaxial cable was used to connect the TDR to a pair of waveguide connectors which were, in turn, attached to the stainless steel electrodes inserted into the soil. The pairs of stainless steel electrodes were 6 mm in diameter and 100 mm in length with a 25 mm centre spacing (Robinson et al., 1998). The TDR was used to measure both apparent relative permittivity (K_a) and inter-electrode conductivity using software developed by Heimovaara (1993). Each waveform was downloaded to a PC and interpreted using this software. The inter-electrode conductivity measured in this way is equivalent to the measurement at about 20 kHz (Heimovaara, 1994). The sensor measurements were calibrated for conductivity (σ) in solutions of potassium chloride. The cell constant of 0.125 was determined from measurements against a conductivity bridge (Robinson et al., 1998).

2.3. Surface capacitance insertion probe

The SCIP gives an instantaneous measurement of frequency which is a function of the electrode capacitance; from this, an apparent soil permittivity (K_{SCIP}) is obtained. The instrument used the same two parallel stainless steel electrodes as the TDR, described above.

One of the most attractive features of capacitance probes is their simplicity of concept and use when compared with the TDR. The capacitance of a pair of electrodes is a function of the relative permittivity of the material in which they are embedded and their geometric configuration:

$$C = \varepsilon_r g \varepsilon_0 \quad (4)$$

where $C(F)$ is the capacitance, ε_r is relative

permittivity, g is a geometric constant and ε_0 is the electric constant (8.854 pF m^{-1}). The principle of operation of the SCIP is to include the capacitor in the tuned circuit of an oscillator and to measure the frequency of oscillation, F (Hz) (Dean et al., 1987):

$$F = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

where the circuit inductance and capacitance are $L(H)$ and $C(F)$, respectively. With 100 mm electrodes, the oscillation frequency drops from about 150 MHz in air (relative permittivity 1) to about 70 MHz in water (relative permittivity ~ 80).

Most dielectrics are not perfect insulators, especially soils, which contain an electrically conducting ionic solution. This has an impact on the measurement of relative permittivity using this instrument. A model, based on circuit analysis, which accounts for the response of the probe in an ionic solution, was presented by Dean (1994). Robinson et al. (1998) showed that an improved version agreed well with measurements for 50 and 100 mm long electrodes. The apparent permittivity, neglecting inter-electrode conductance, is given by:

$$K_{SCIP} = \frac{\left(\frac{C_3}{\omega^2 LC_3 - 1}\right) - C_A}{g \varepsilon_0} \quad (6)$$

where C_A is $C_1 + C_2$ and C_1 is the electrode capacitance (between ~ 1 and 100 pF for 100 mm electrodes), C_2 is a stray parallel capacitance (in the order of 1 pF) and C_3 is the circuit board capacitance (15 pF); L is the instrument inductance and ω is the angular frequency ($2\pi F$). When conductance across the electrodes (G) is taken into account, the corrected apparent permittivity, K_c , is (Robinson et al., 1998):

$$K_c = \frac{\left(\frac{\omega C_3 + \sqrt{\omega^2 C_3^2 - 4(\omega^2 LC_3 - 1)G^2}}{2\omega(\omega^2 LC_3 - 1)}\right) - C_A}{g \varepsilon_0} \quad (7)$$

The apparent permittivity derived by both Eqs. (6) and (7) was tested to determine if Eq. (7) improved the measurement of relative permittivity in soil.

Table 2
Location and description of sandy soils used in the data acquisition

Soil	Horizon	Northern Irish soil survey/soil survey of England and Wales	Nature of soil	Location grid reference
(1) Portrush a	C	Shallow brown earth	Sand dune	24 878,405
(2) Portrush b	B	Shallow brown earth	Dune slack	24 877,401
(3) Antrim Hills	B _s	Peaty podsol	Moorland	34 160,275
(4) Herringswell	A _p	Redlodge series	Agriculture	TL 698,713

2.4. Theta probe

The Theta probe is a compact, buriable dielectric sensor (Gaskin and Miller, 1996). The instrument measures impedance at a fixed oscillation frequency of 100 MHz. The technique compares a section of fixed transmission line with a set of stainless steel electrodes whose characteristic impedance varies with the water content of the soil in which they are embedded (Gaskin and Miller, 1996). The probe has four, 60 mm electrodes, a central electrode surrounded by three equidistant outer electrodes. The electrodes are 3 mm in diameter with a radial spacing of 15 mm. The voltage output can be converted to apparent permittivity (K_{TP}) using a calibration established with known dielectrics. Calibration of the theta probe was performed in the laboratory using eight dielectric fluids (Robinson, 1998) whose relative permittivities were: air, 1; white paraffin, 1.9; propan-2-ol, 20.1; ethanol, 24.3; methanol, 32.6; glycol, 37.7, and water, 80.2.

2.5. The soil materials

Large disturbed samples (> 5 kg) were collected

Table 3
Physical and chemical properties of the soils

	Soil 1	Soil 2	Soil 3	Soil 4
USDA textural classification	Sand	Sand	Sandy loam	Sand
Sand (%)	98.9	96.1	65.4	93.5
Slit (%)	0.0	2.4	32.7	4.2
Clay (%)	0.7	0.4	1.1	0.3
Organic matter (%)	0.36	1.07	1.03	2.06
pH (1:2.5)	8.45	6.82	4.82	6.55
Solution electrical conductivity 1:5 ($S m^{-1}$)	0.0033	0.0022	0.0013	0.0295
Surface area ($m^2 g^{-1}$)	0.9	0.4	5.2	0.7
Mineralogy	Quartz	Quartz	Quartz (> 5% iron oxide/Kaolinite)	Quartz

from sandy soils at three field sites in Northern Ireland and one in England (see Table 2 for details). The upper 40 mm of soil was removed initially to avoid most of the organic matter. The physical and chemical properties of the soils are presented in Table 3. Conventional procedures were used to determine soil particle size, organic matter content, mineralogy, pH, solution electrical conductivity and surface area (full details in Robinson, 1998), on air dried subsamples of each soil. All the soils contain mostly sand sized particles with little clay or organic matter. The soil solution conductivity was low in soils 1, 2 and 3 but much higher in soil 4 due to its agricultural usage and the application of fertiliser. All the soils had low surface area and the mineralogy was predominantly quartz; soil 3 had some iron hydroxide staining.

2.6. Repacked soil samples

The soil samples were initially prepared by sieving through a 5 mm mesh to help homogenise them and to remove any large stones and root material. The soils were air dried for six weeks in the laboratory. Subsamples were removed for physical and chemical

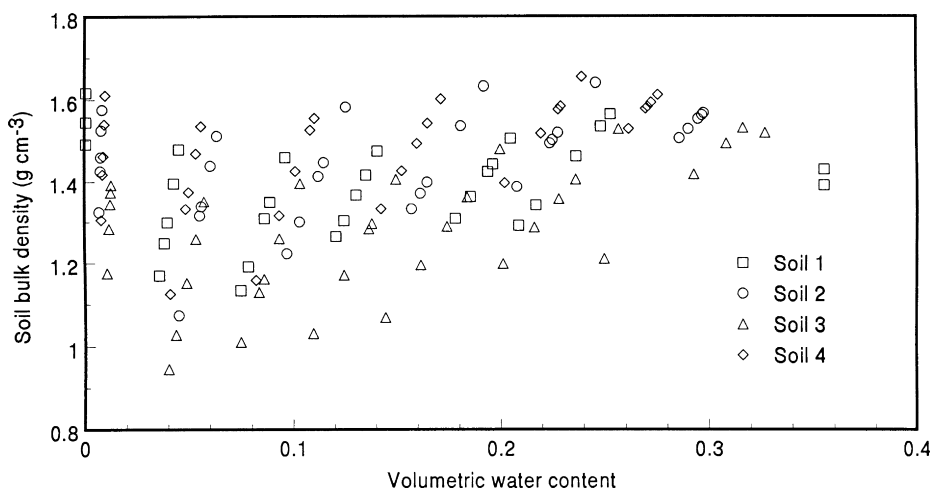


Fig. 1. Soil bulk density plotted for the corresponding water contents for the repacked soil cores.

analysis. The use of repacked soil samples for permittivity measurement followed the approach of Gardner et al. (1998). Similar methods have been adopted by other workers (e.g. Malicki et al., 1996) as repacking of soil allows measurements to be performed over a wide range of water content and dry bulk density.

A plastic core, 0.103 m in diameter, capped at one end, was packed with air dried soil to a height of 0.14 m to give a prepared sample of volume 1167 cm³. This was weighed on a balance accurate to 0.1 g. A pair of the stainless steel electrodes was fully inserted into the centre of the sample and measurements were taken using the TDR and then the SCIP. The electrodes were carefully removed and the theta probe was inserted into an undisturbed part of the core. After this measurement, the sample in its core was re-weighed and then a temperature probe inserted into the soil to measure soil temperature. A 10 g subsample of soil was removed and oven dried so that the gravimetric water content could be obtained.

The soil was then removed from the core and mixed with the remainder of the soil. The core was then repacked with soil to a slightly greater mass (higher bulk density) than done previously. TDR, SCIP, Theta probe and temperature measurements were made using the same procedure. This was repeated for repacked soil at five bulk densities but with the same gravimetric water content. Volumetric water content and bulk density were calculated from the gravimetric water content and the wet mass of the

repacked mixture contained in the known volume of the core following the same procedure as Gardner et al. (1998).

To obtain measurements over a range of water content, the above procedure was repeated with progressively wetter soil. After the air dried soil measurements had been made, between 80 and 100 g of de-ionised water were added to the soil using an atomiser spray gun whilst continually mixing. After thorough mixing, the soil was repacked into the core and samples again taken for oven drying. This process was repeated until a range from air dry to saturation was achieved.

2.7. Statistical analysis

2.7.1. Multiple linear regression analysis

This was performed using \sqrt{K} as the dependent variable. The regression analysis used volumetric water content (m³ m⁻³) as the main independent variable with dry bulk density (g cm⁻³) and inter-electrode conductivity (S m⁻¹) as the other variables. Multiple linear regression analysis assumes the variables to be independent, soil water content and bulk soil electrical conductivity are not. However, in this work the analysis is used to demonstrate an effect of conductivity and not provide reliable correction factors. In order to show this effect all the data sets included soils with a minimal bulk soil electrical

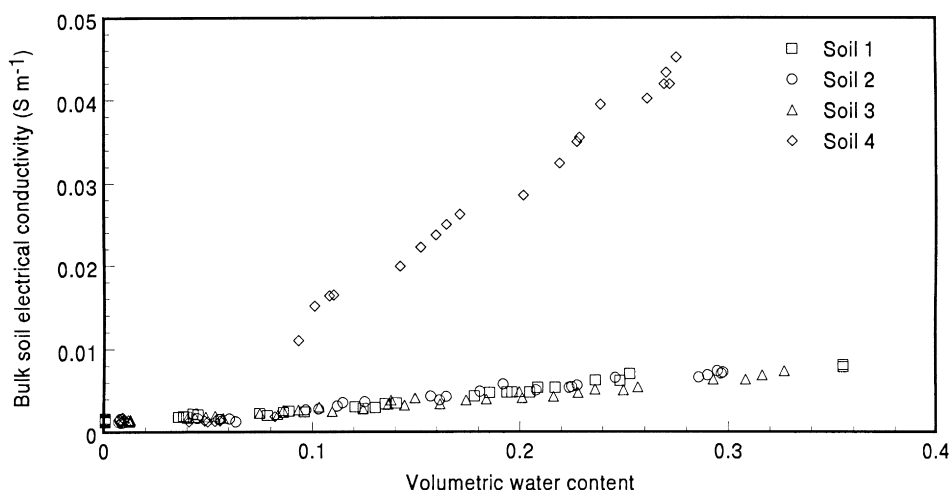


Fig. 2. Inter-electrode conductivity plotted as a function of water content for the four sandy soils.

conductivity and soils with greater bulk soil electrical conductivity.

The introduction of any additional variable into a regression will improve the model fit. To counter this effect, and to distinguish additional significant variables the adjusted R^2 (Weisberg, 1985; Jacobsen and Schjonning, 1993) was used for comparing models with differing numbers of variables:

$$\text{adjusted } R^2 = 1 - \left(\left(\frac{n-1}{n-p} \right) \times (1 - R^2) \right) \quad (8)$$

where n is the number of observations used to fit the model and p is the number of variables contained within the model.

3. Results and discussion

3.1. Dry bulk density and bulk soil electrical conductivity

The soil dry bulk density and bulk soil electrical conductivity (measured using the TDR) data from the repacked cores are presented in Figs. 1 and 2, respectively. The bulk density values ranged from < 1.0 to $> 1.6 \text{ g cm}^{-3}$; they were smallest for soil 3 which contained more silt. The bulk soil electrical conductivity increased with water content but even close to saturation was low ($< 0.01 \text{ S m}^{-1}$) in soils 1, 2 and 3. At $\theta < 0.08$, the bulk soil electrical conductivity of

soil 4 was similar to the other soils but then increased with increasing θ , to nearly 0.05 S m^{-1} at a water content of 0.3. This much higher bulk soil electrical conductivity was consistent with its higher soil solution conductivity (Table 3).

3.2. Measurement of soil relative permittivity using the TDR, SCIP and Theta probe

The apparent permittivity measurements made as a function of water content using each of the instruments are presented in Fig. 3. The line on each of the graphs represents a slope of $\sqrt{\epsilon_w} - 1$. Fig. 3(a) shows that the data collected using the TDR were linear and highly clustered.

Fig. 3(b) and (c), shows the data collected using the SCIP. The apparent permittivity values shown in Fig. 3(b) were calculated using Eq. 6 (K_{SCIP}), which does not include a conductance term. Soil 4, which had the highest solution electrical conductivity had consistently higher values of apparent permittivity than the other three soils. The use of Eq. (7) to calculate the corrected apparent permittivity (K_c) by including the inter-electrode conductance brought the apparent permittivity values for soil 4 to values similar to the other soils (Fig. 3(c)). Use of Eq. (6) results in considerable overestimation of the relative permittivity even for low bulk soil electrical conductivity.

The soils data for the Theta probe, corresponding to the measurements made with the TDR and SCIP, are

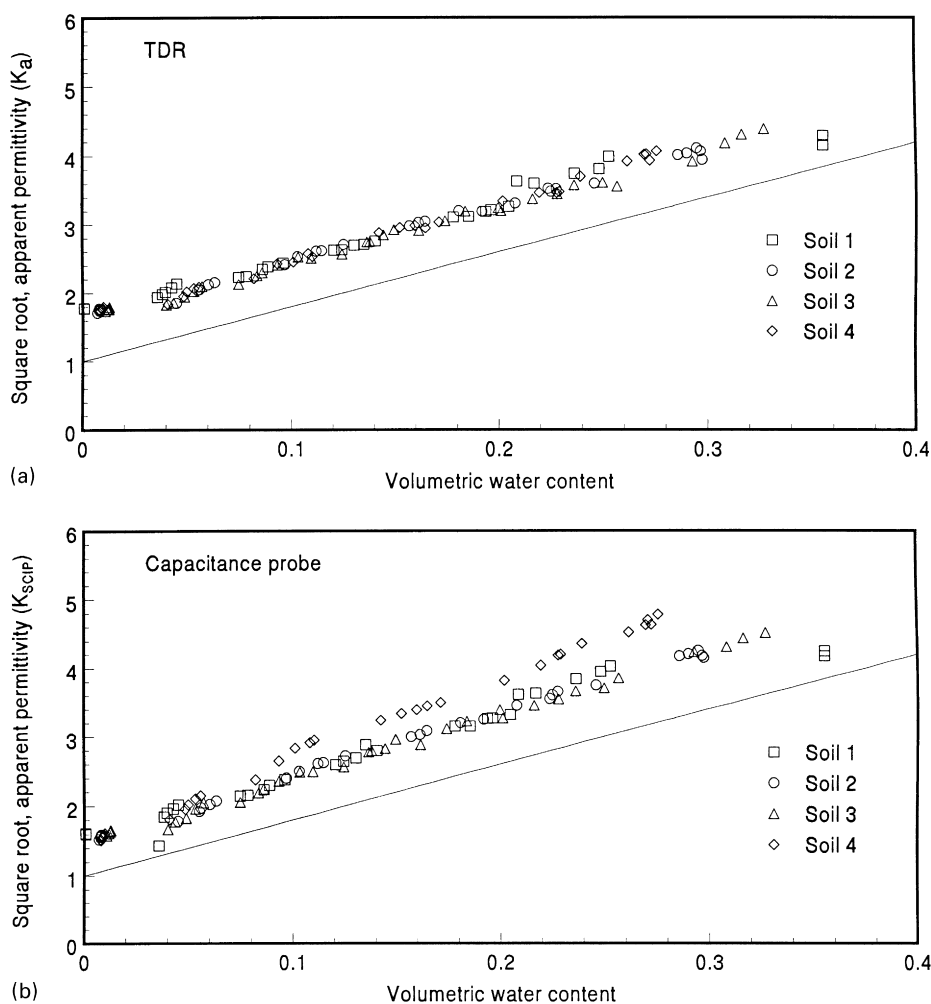


Fig. 3. (a) square root of the soil apparent permittivity (K_a) measured using the TDR, plotted as a function of water content; (b) square root of the soil apparent permittivity (K_{SCIP}) measured using the surface capacitance probe (Eq. (6)), plotted as a function of water content; (c) square root of the soil apparent permittivity corrected for bulk soil electrical conductivity (K_c) measured using the surface capacitance probe (Eq. (7)), plotted as a function of water content; and (d) square root of the soil apparent permittivity (K_{TP}) measured using the Theta probe, plotted as a function of water content.

presented in Fig. 3(d) and are slightly less clustered than the TDR data; this is discussed in more detail in the section comparing the three methods.

3.3. Multiple linear regression analysis

The results of the multiple linear regression analysis are presented in Table 4. The TDR coefficient for water content of 7.91 agrees remarkably well with that predicted by the model. The values of 8.5 for the SCIP

and 8.7 for the Theta probe diverge from the values predicted by the model. In the case of the SCIP electrical conductivity is still seen to have some effect even when using Eq. (7) suggesting that the modelling of the probe response has to be improved. The reason why the Theta probe should overestimate is unclear and forms part of the discussion later on.

The analysis clearly confirms the importance of bulk density as a significant factor in the measurement of soil relative permittivity as has been demonstrated

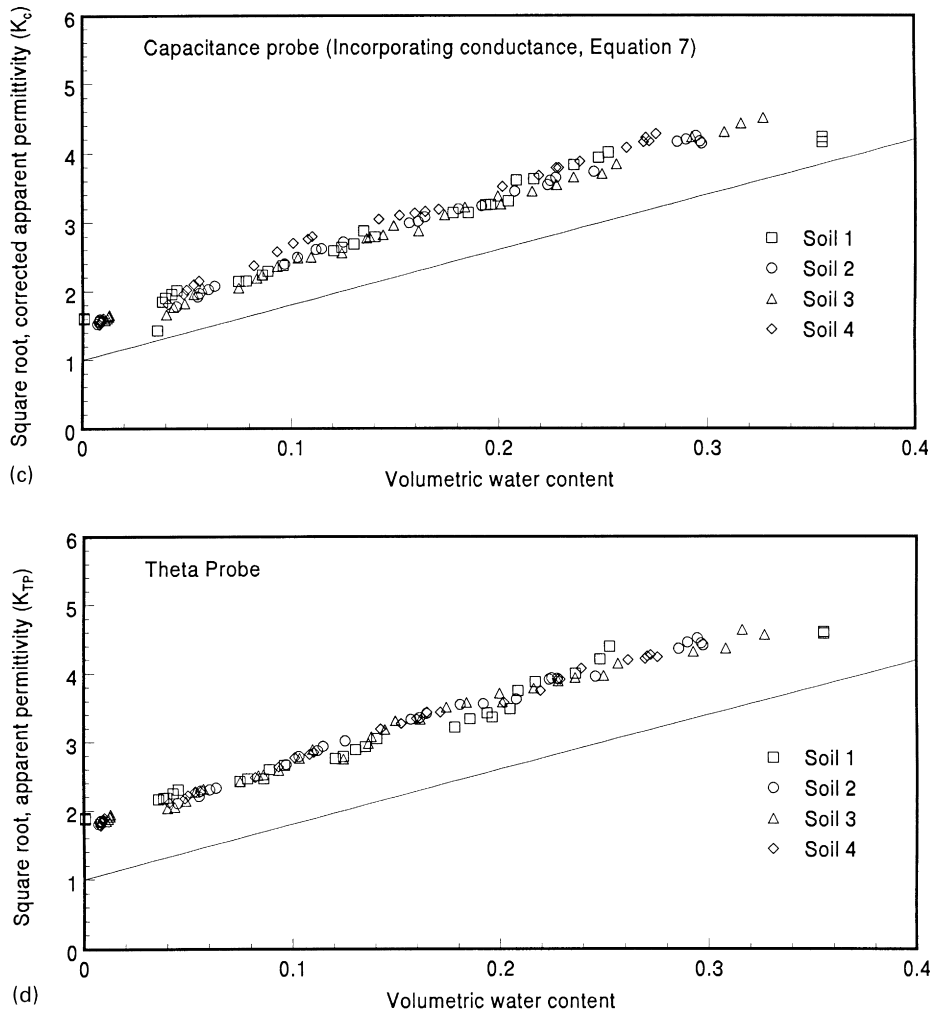


Fig. 3. (Continued).

by others (Whalley, 1993; Jacobsen and Schjonning 1993).

Whalley (1993) suggested that one of the reasons that water content coefficients might be higher than the model predicts (Eq. (3)) was that the imaginary part of the apparent permittivity contributed to the measurement of relative permittivity. The transmission line equation used to describe the apparent permittivity measured by TDR (White et al., 1994) is presented below:

$$K_a = \varepsilon' \left(\frac{1 + \sqrt{1 + \tan^2(\varepsilon''/\varepsilon')}}{2} \right) \quad (9)$$

where ε'' is $\sigma/\omega\varepsilon_0$, the conductivity (σ) divided by the product of the angular frequency (ω) and electric constant (ε_0) and dielectric relaxation phenomena. This equation cannot be directly applied to determine the relative permittivity from the apparent permittivity, the reason being that the frequency used to determine the contribution of the imaginary part is unknown. Both Wyseure et al. (1997) and Robinson (1998) demonstrated that the bulk soil electrical conductivity contributes to the measurement of ε_r using the TDR. The value of K_a was found to increase with increasing electrical conductivity which Eq. (9) predicts. It is important to try to account for this effect,

Wyseure et al. (1997) therefore, adopted a pragmatic, empirical approach and found that for soils with a bulk soil electrical conductivity of $< 0.25 \text{ S m}^{-1}$ the apparent relative permittivity increased linearly according to:

$$K_a = \varepsilon_r + 14.32\sigma \quad (10)$$

where the value of σ is in S m^{-1} .

The correction factor presented in Eq. (10) means that the output of the regression analysis for bulk soil electrical conductivity can be compared. As already pointed out water content and bulk soil electrical conductivity are not independent. However, by incorporating soils with negligible conductivity and significant conductivity the multiple regression should give a reasonable estimate of the contribution of each of the variables. Eq. (10) can be used to test this in the case of the bulk soil electrical conductivity. The results presented in Table 4 with bold typeface include bulk soil electrical conductivity in the regression analysis for the three instruments.

Bulk soil electrical conductivity was found to be significant in the measurement of apparent permittivity made using the TDR and the SCIP but not the Theta probe. The coefficients determined by the regression analysis can be used to demonstrate the relative impact bulk soil electrical conductivity has on the determination of soil relative permittivity. The bulk soil electrical conductivity coefficients for the TDR and SCIP are given in Eqs. (11) and (12), respectively:

$$\sqrt{K_a} = \sqrt{\varepsilon_r} + 1.72\sigma \quad (11)$$

$$\sqrt{K_c} = \sqrt{\varepsilon_r} + 6.28\sigma \quad (12)$$

What is clear from these qualitative coefficients is that the effect on the TDR is small and that the effect on the capacitance probe is some 3.5 times greater. In order to test the validity of the coefficients the results were compared with the correction factor (Eq. (10)) proposed by Wyseure et al. (1997). As a means of comparison Eqs. (11) and (12) were used to predict K as a function of σ applied using Eq. (3) with the soil bulk density fixed to 1.7 g cm^{-3} and the water content to values representing field capacity (0.15) and saturation (0.36). The results are compared graphically in Fig. 4 with the adjustment according to Eq. (10)

presented by Wyseure et al. (1997) for TDR. This clearly demonstrates close agreement between the TDR coefficient determined by the regression analysis and the results presented by Wyseure et al. (1997). This suggests that Eqs. (11) and (12) give an approximate correction required when using these instruments. The correction for TDR in the usual range of bulk soil electrical conductivity for sandy soils becomes increasingly important as conductivity increases between 0.0 and 0.25 S m^{-1} . We therefore conclude that for estimating water content in sandy soils, bulk soil electrical conductivity should only be discounted below values of 0.05 S m^{-1} . Below this value K_a can be considered equivalent to ε_r in the case of the TDR, but when using the capacitance probe a correction is required to obtain values of ε_r .

To obtain the best results when modelling the soil relative permittivity this small but significant effect should be taken into account before testing a physical model such as the one presented by Whalley (1993) or at least considered in any discussion of results:

$$\begin{aligned} \sqrt{\varepsilon_r} &= \sqrt{K} - \sigma(\text{coeff}) \\ &= \theta(\sqrt{\varepsilon_w} - 1) + \frac{\rho_b}{\rho_s}(\sqrt{\varepsilon_s} - 1) + 1 \end{aligned} \quad (13)$$

where σ is the bulk soil electrical conductivity (S m^{-1}) and (coeff) is the correction coefficient, the values of which are given in Table 4 for the TDR and SCIP.

The effect of conductivity on the Theta probe was not found to be significant. However, Robinson (1998) demonstrated empirically using ionic solutions that the Theta probe is affected by conductivity in this range and that the value of K_{TP} decreases as electrical conductivity increases. This is opposite to the effect on both the TDR and SCIP which both give higher apparent permittivities as the electrical conductivity of the medium increases.

3.4. Comparison of the three methods

The work of both Wyseure et al. (1997) and the multiple linear regression analysis presented in this work (Table 4) demonstrate that for the range of bulk soil electrical conductivity encountered in these

Table 4

Results of multiple linear regression using the sandy soils data collected from repacked soil cores (126 samples). Numbers highlighted in bold include inter-electrode conductivity in the analysis, value in brackets is the respective p value (significance level)

Instrument	Constant	Water content coefficient	Bulk density coefficient	Bulk soil electrical conductivity coefficient	Adj. R^2
TDR	1.278	7.981	0.286	–	0.990
Capacitance probe (Eq. (6))	0.666	9.312	0.640	–	0.958
Capacitance probe (Eq. (7))	0.990	8.982	0.401	–	0.984
Theta probe	1.531	8.835	0.207	–	0.988
TDR + σ	1.322	7.910 (> 0.001)	0.253 (> 0.001)	1.72 (0.040)	0.990
Capacitance probe (Eq. (6)) + σ	1.150	8.522 (> 0.001)	0.270 (> 0.001)	19.20 (> 0.001)	0.989
Capacitance probe (Eq. (7)) + σ	1.148	8.724 (> 0.001)	0.280 (> 0.001)	6.28 (> 0.001)	0.988
Theta probe + σ	1.567	8.777 (> 0.001)	0.179 (> 0.001)	1.43 (0.158)	0.988

four sandy soils K_a can be considered equivalent to ε_r . The apparent permittivity measurements made by the SCIP (corrected for conductance using Eq. (7)) and Theta probe were plotted for comparison against those measured using the TDR (Fig. 5). The SCIP data corresponded closely with the TDR data. However, the Theta probe data are clearly offset from the TDR data. The mean values of apparent permittivity were: 7.66, for the TDR; 7.71, for the SCIP and 9.16, for the Theta probe. The difference between the mean apparent permittivity value for the TDR and SCIP is small but the difference between the TDR and Theta probe is almost 1.5. This offset cannot be accounted for by the influence of the bulk soil electrical conductivity;

Robinson (1998) demonstrated that this would decrease the value of K_{TP} compared with K_a . Water content estimated using the Theta probe measurements and a standard calibration, such as that of Topp et al. (1980), is likely to result in a consistent overestimation of the actual water content of approximately 4%.

One explanation for this result could be that the electrode configuration of the Theta probe limits the penetration of the electric field into the dielectric (Whalley, 1993; Knight 1992). Knight (1992) suggested a design rule for electrodes based on the energy distribution in the sample and the ratio of the electrode diameter to spacing. The design rule

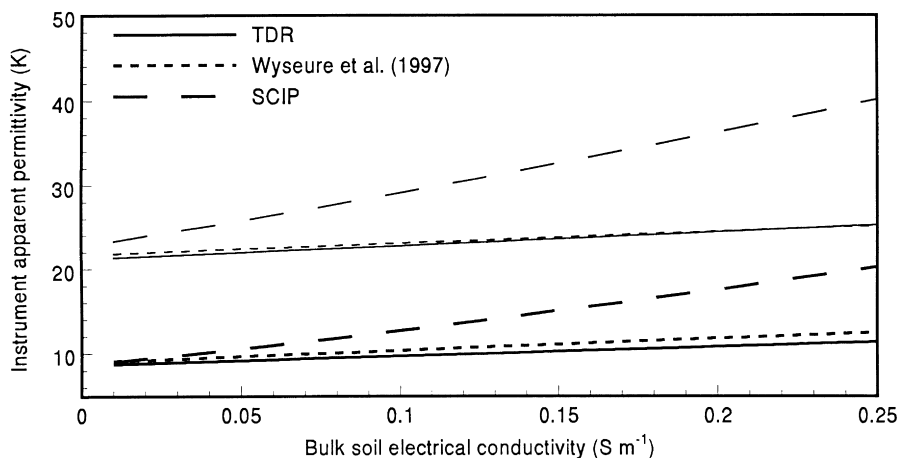


Fig. 4. Comparison of effect of bulk soil electrical conductivity on the measurement of apparent relative permittivity using the SCIP and TDR. Upper lines represent a water content of 0.36, lower lines represent a water content of 0.15.

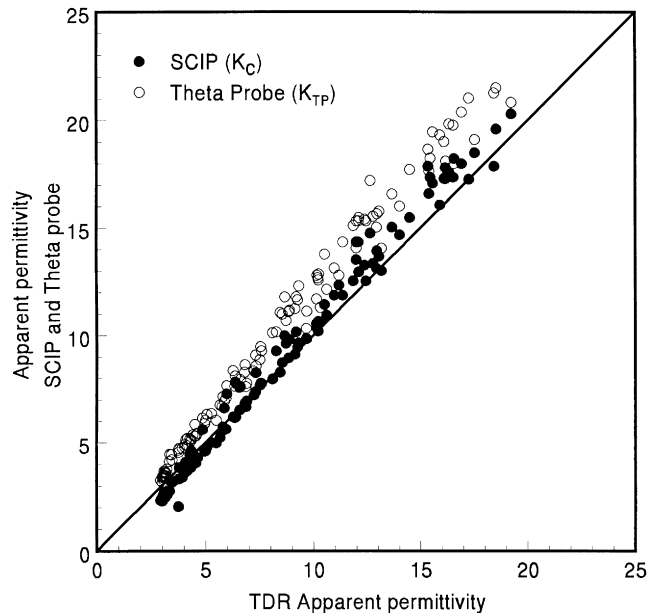


Fig. 5. Comparison of the apparent permittivity measured with the SCIP (Eq. (7)) and the Theta probe compared with the TDR values.

suggests that for a reasonable energy spread a diameter to spacing ratio of no less than 0.1 should be obtained. The value for the Theta probe is on this threshold whilst the value for the TDR/SCIP electrodes of 0.24 is much better. The value of 0.1 means that much of the Theta probe energy will be confined to the area immediately surrounding the inner electrode, whereas the value of 0.24 for the other instruments means that the energy will spread further into the dielectric so be less susceptible to compaction.

Analysis following that of Knight (1994) demonstrates that the field is very concentrated around the central electrode (Fig. 6). Compaction caused by the insertion of the electrodes into the dielectric will increase the bulk density and the water content at the electrode/dielectric interface and may bias the measurement of apparent permittivity; essentially confining it to the zone immediately around the central conductor. This would mean that the water content estimated is valid for this compressed soil but not necessarily representative of the sample as a whole. This argument is borne out by the data (Fig. 3(d)) which show an increased spread as water content rises. This effect will be less significant for static sensors that are used to estimate changes in water

content rather than measure absolute values. A more thorough investigation of the sampling volume of this instrument such as the one presented by Petersen et al. (1995) for TDR would prove a useful contribution to the measurement of apparent permittivity using this technique. This overestimation of relative permittivity may well be the reason that bulk soil electrical conductivity appears to be insignificant in the multiple linear regression analysis, the packing effect completely swamping any conductivity effect.

4. Conclusions

The measurement of soil permittivity using the TDR, surface capacitance insertion probe and the Theta probe was examined. The TDR and SCIP measurements of apparent permittivity in the sands corresponded to a high degree. The Theta probe values of apparent permittivity were found to be on average ~ 1.5 higher than the corresponding TDR and SCIP results. It is hypothesised that this may be due to soil compaction around the electrodes and the relatively small sampling volume of the Theta probe. Further work is required to characterise the sampling volume of the instrument and confirm this hypothesis.

1+3 wire probe configuration

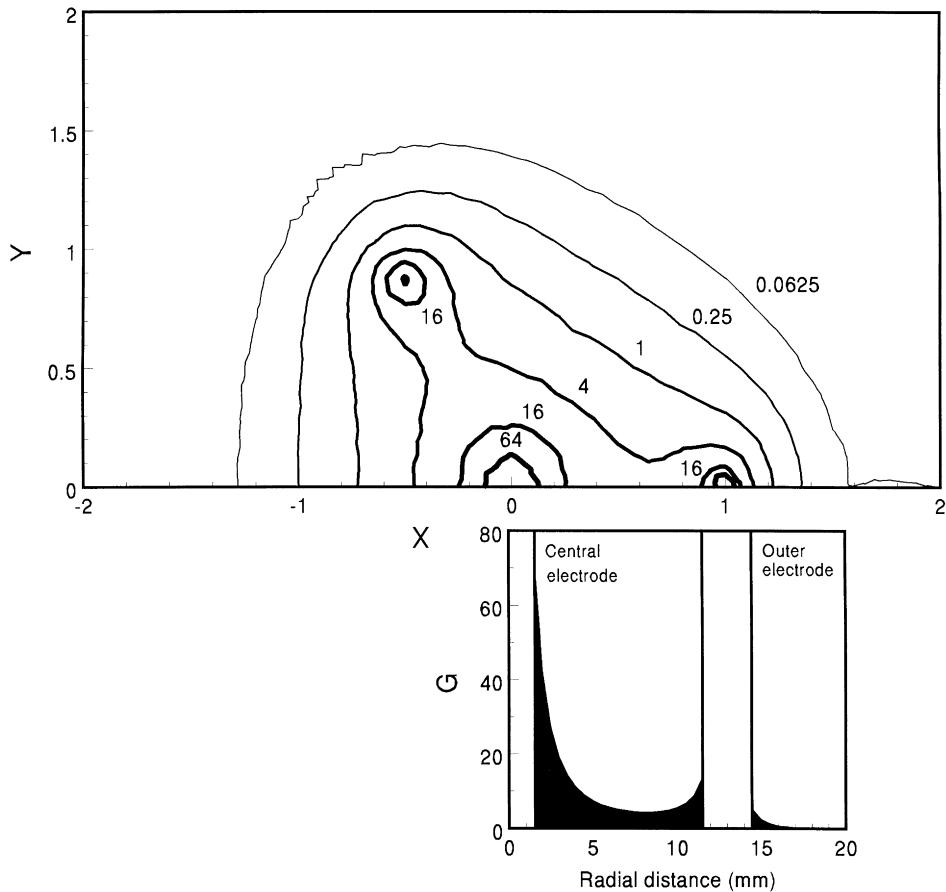


Fig. 6. Two dimensional relative spatial sensitivity function plotted for the Theta probe electrode configuration (After Knight, 1994). Upper diagram, plan view, the lower diagram is the corresponding side elevation.

Multiple linear regression showed that bulk soil electrical conductivity was significant in the measurement of apparent permittivity made using the TDR and SCIP. The EC coefficient determined for TDR was found to be supported by the correction factor proposed by Wyseure et al. (1997). We conclude that the effect of bulk soil electrical conductivity in sandy soil should only be neglected when the value is $< 0.05 \text{ S m}^{-1}$, then K_a can be considered equivalent to ϵ_r for the purposes of estimating soil water content. For accurate modelling the effect should either be accounted for or at least its relevance discussed in terms of the measurements made. In the case of the

SCIP it was found that in order to obtain an accurate measurement of ϵ_r from K_c a correction factor has to be applied as the influence on the SCIP was ~ 3.5 times greater.

The use of a linear model based on refractive index for TDR or $\sqrt{\epsilon_r}$ for the lower frequency devices was found to give estimates that corresponded to a high degree with measurement. Predictions by the model were found to agree with coefficients determined by multiple linear regression. The results suggest that this mixing approach can successfully be applied to measurements made in sandy soils which are mostly quartz.

References

- Birchak, J.R., Gardner, C.Z.G., Hipp, J.E., Victor, J.M., 1974. High dielectric constant microwave probes for sensing soil moisture. *Proc. IEEE* 62 (1), 93–98.
- Carmichael, R.S., 1982. *Handbook of physical properties of rocks*, CRC Press Inc, Boca Raton, Florida, USA.
- Dean, T.J., 1994. The IH capacitance probe for measurement of soil water content. IH Report No. 125. Institute of Hydrology, Wallingford, Oxon, UK.
- Dean, T.J., Bell, J.P., Baty, A.B.J., 1987. Soil moisture measurement by an improved capacitance technique. I. Sensor design and performance. *J. Hydrol.* 93, 67–78.
- de Loor, G.P., 1990. The dielectric properties of wet soils. BCRS Report No. 90–13 Proj. No. AO-2.1. The Netherlands Remote Sensing Board, BCRS Delft, The Netherlands.
- Dirksen, C., Dasberg, S., 1993. Improved calibration of time domain reflectometry soil water content measurements. *Soil Sci. Soc. Am. J.* 57, 660–667.
- Dobson, M.C., Ulaby, F.T., Hallikainen, M.T., El-Rayes, M.A., 1985. Microwave dielectric behaviour of wet soil. Part II. Dielectric mixing models. *IEEE Trans Geosci. Remote Sensing* 23 (1), 35–46.
- Drungil, C.E.C., Abt, K., Gish, T.J., 1989. Soil moisture determination in gravelly soils with time domain reflectometry. *Trans. ASAE* 32 (1), 177–180.
- Gaskin, G.J., Miller, J.D., 1996. Measurement of soil water content using a simplified impedance measuring technique. *J. Agric. Engng Res.* 63, 160–163.
- Gardner, C.M.K., Dean, T.J., Cooper, J.D., 1998. Soil water content measurement with a high-frequency capacitance sensor. *J. Agric. Engng Res.* 71, 395–403.
- Gregory, P.J., Poss, R., Eastham, J., Micin, S., 1995. Use of time domain reflectometry (TDR) to measure the water content of sandy soils. *Aust. J. Soil Res.* 33, 265–276.
- Heimovaara, T.J., 1993. Time domain reflectometry in soil science: theoretical backgrounds, measurements and models, PhD Thesis, Universiteit van Amsterdam, Netherlands.
- Heimovaara, T.J., 1994. Frequency domain analysis of time domain reflectometry waveforms. 1. Measurement of the complex dielectric permittivity of soils. *Water Res. Research* 30 (2), 189–199.
- Heimovaara, T.J., Bouten, W., Verstraten, J.M., 1994. Frequency domain analysis of time domain reflectometry waveforms. 2. A four component complex dielectric mixing model for soils. *Water Res. Research* 30 (2), 201–209.
- Jacobsen, O.H., Schjonning, P., 1993. A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. *J. Hydrol.* 151, 147–158.
- Knight, J.H., 1992. Sensitivity of time domain reflectometry measurements to lateral variations in soil water content. *Water Res. Research* 28, 2345–2352.
- Knight, J.H., 1994. Sampling volume of TDR probes used for water content monitoring: theoretical investigation. TDR Applications in soil science, Danish Institute for Plant and Soil Science, Foulum, Denmark.
- Malicki, M.A., Plagge, R., Roth, C.H., 1996. Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. *Eur. J. Soil Sci.* 47, 357–366.
- Maxwell, J.C., 1873. *Treatise on electricity and magnetism*, Oxford University Press, London.
- Miller, J.D., G.J. Gaskin, 1995. The development and application of the Theta probe soil water sensor. MLURI Technical Note, MLURI, Craigiebuckler, Aberdeen, UK.
- Nadler, A., Dasberg, S., Lapid, I., 1991. Time domain reflectometry measurements of water content and electrical conductivity of layered soil columns. *Soil Sci. Soc. Am. J.* 55, 938–943.
- Petersen, L.W., Thomsen, A., Moldrup, P., Jacobsen, O.H., Rolston, D.E., 1995. High resolution time domain reflectometry: sensitivity dependency on probe design. *Soil Sci.* 159 (3), 149–154.
- Robinson, D.A., 1998. Soil water content estimates based on the measurement of soil relative permittivity: use of capacitance, time domain reflectometry and impedance sensors, PhD Thesis, University of Ulster, Coleraine, Co. Londonderry, Northern Ireland.
- Robinson, D.A., Gardner, C.M.K., Evans, J., Cooper, J.D., Hodnett, M.G., Bell, J.P., 1998. The dielectric calibration of capacitance probes for soil hydrology using an oscillation frequency response model. *Hydrol. Earth Sys. Sci.* 2, 83–92.
- Roth, C.H., Malicki, M.A., Plagge, R., 1992. Empirical evaluation of the relationship between soil dielectric constant and volumetric water content and the basis for calibrating soil moisture measurements by TDR. *J. Soil Sci.* 43, 1–13.
- Roth, K., Schulin, R., Fluhler, H., Attinger, W., 1990. Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. *Water Res. Research* 26 (10), 2267–2273.
- Sihvola, A., 1997. A review of dielectric mixing models, Report 248, Helsinki University of Technology, Department of the electrical and communications engineering.
- Topp, G.C., Davies, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Res. Research* 16, 574–582.
- Weisberg, S., 1985. *Applied linear regression*, 2. Wiley, New York, pp. 324.
- Whalley, W.R., 1993. Considerations on the use of time domain reflectometry (TDR) for measuring soil water content. *J. Soil Sci.* 44 (1), 1–9.
- White, I., Knight, J.H., Zegelin, S.J., Topp, G.C., 1994. Comments on Considerations on the use of time domain reflectometry (TDR) for measuring soil water content. *Eur. J. Soil Sci.* 45 (4), 503–508.
- Wyseure, G.C.L., Mojid, M.A., Malik, M.A., 1997. Measurement of volumetric water content by TDR in saline soils. *Eur. J. Soil Sci.* 48, 347–354.
- Zegelin, S.J., White, I., Jenkins, D.R., 1989. Improved field probes for soil water content and electrical conductivity measurement using Time Domain Reflectometry. *Water Res. Research* 25 (11), 2367–2376.