

# Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR

C. H. ROTH, M. A. MALICKI\* & R. PLAGGE

*Institute of Ecology, Technical University of Berlin, Berlin, Germany and*

*\*Polish Academy of Sciences, Institute of Agrophysics, ul. Doswiadczalna 4,  
20-236 Lublin, Poland*

## SUMMARY

The paper is addressed to soil scientists who use Time-Domain Reflectometry (TDR) technology to measure soil moisture. The practical aspects of the measurement calibration are discussed, and an empirical approach to establishing the existence of a universal calibration function is presented.

Samples of 11 mineral soil horizons and seven organic soil horizons with different chemical and physical properties (including magnetic properties) were selected with the aim of determining their dielectric constant–volumetric water content relationship as calibration functions for TDR soil moisture measurements. These samples were supplemented by other, soil-like, capillary-porous reference materials (montmorillonite, glass beads, washed sand and a sand from a C horizon).

The study showed that a unique calibration function for mineral soils and another distinct calibration function for organic soils can be established.

## INTRODUCTION

In the past decade, several studies have indicated the possibility of using time-domain reflectometry (TDR) as a non-destructive method of soil moisture measurement (Topp *et al.*, 1980; Dasberg & Dalton, 1985; Topp & Davis, 1985; Yanuka *et al.*, 1988; Malicki & Skierucha, 1989).

From the scarce data on the calibration functions for TDR soil moisture measurements (i.e. relationship of volumetric water content,  $\theta$ , vs. dielectric constant of the soil,  $K$ ), it appears that the moisture readings are not significantly affected by soil temperature or salinity, and that different soils need not be individually calibrated if they are derived from mineral parent material (Topp *et al.*, 1980; Malicki & Skierucha, 1989). Furthermore, relationships of  $\theta$  vs.  $K$  for mineral soils do not vary substantially between soils of different texture or structure. Therefore, it may be possible to use a single calibration function that is common for all soils.

It has been reported elsewhere that organic soils may have different dielectric properties compared to mineral soils (Topp *et al.*, 1980). This suggests that the presence of organic matter might affect the calibration function for mineral soils. However, there are no reported data on this possible complication.

Some ferric soils, particularly Ferralsols derived from basalt, which are very common in southern Brazil and other basaltic regions in the tropics, exhibit magnetic properties (susceptibility to a static magnetic field) due to the presence of maghemite and magnetite (Mullins, 1977). The background theory of soil moisture determinations using TDR assumes dielectric loss of soil to

be equal to zero, and magnetic permeability to be equal to unity (Davis & Chudobiak, 1975), which implies that soil approximates to a perfect dielectric and has no magnetic properties. The velocity of the pulse propagation is inversely proportional to both the square root of the medium's (soil) dielectric constant and the square root of its magnetic permeability. Therefore the calibration function of a soil that shows susceptibility to an extraneous magnetic field might differ from the one that is valid for non-magnetic soils, leading to an overestimation of readings of soil moisture. To date, no data in support of this hypothesis have been reported.

**Table 1.** Verification of the measurements of dielectric constant at 20°C

Medium	$K$ (measured)	$K$ (tabulated)
Benzene	$2.36 \pm 1.15$	2.29
Acetone	$21.1 \pm 0.85$	21.4
Glycol	$35.4 \pm 3.52$	38.7
Water	$80.9 \pm 2.52$	80.1

In many studies of soil-water dynamics, capillary-porous materials such as glass beads or different types of sand have been widely used as reference materials in experiments with artificially packed soil columns (Topp & Miller, 1966; Poulouvassilis & Tzimas, 1975; Gillham *et al.*, 1976). In future, such experiments might increasingly employ TDR to monitor water transport. However, no data concerning the moisture-dielectric constant relationships of such materials are available.

More detailed information about these aspects is required in order to evaluate the range of applicability of TDR for soil moisture determination. It also needs to be established whether a unique calibration function exists for mineral soils as well as for organic soils. Furthermore, little is known about the error made when using a bulk calibration function instead of calibration functions pertaining to single soil types or horizons.

Therefore, an empirical approach was undertaken to examine the following problems: (i) whether unique calibration functions of mineral soils and organic soils exist, and to what degree capillary-porous reference materials and also soils that exhibit magnetic properties differ from these functions; and (ii) how great is the loss in accuracy of the TDR soil moisture readings when bulk calibration functions are used instead of calibration functions obtained for each individual soil type or horizon.

## MATERIALS AND METHODS

### *Materials tested*

Mineral and organic soil samples with various textures, organic matter contents, total content of Fe and particle densities, were selected. The soil types, profile locations and depths of horizon from which the samples were taken are shown in Tables 2a and 3a.

Samples of mineral soils were air dried before sieving, and analyses were performed on the fraction with equivalent grain sizes below 2 mm. Standard procedures were used to determine relevant physical and chemical properties for both mineral and organic samples (Page *et al.*, 1982; Klute, 1986). The results are given in Tables 2b and 3b. To obtain the gravimetric water content, the mineral soils were oven dried at 105°C and the organic soils were first dried at 40°C and then again at 105°C, to check possible losses due to volatilization of readily decomposable organic compounds. No significant effect of oven temperature was observed in this study.

**Table 2a.** Mineral soils studied—site and soil type

Sample number	Locality	Soil type (FAO)	Horizon	Depth (cm)
1	Paraná, Brazil	Haplic ferralsol	Ah	0–10
2	Paraná, Brazil	Haplic ferralsol	Bws	120–140
3	Germany	Haplic luvisol	Bt	90–120
4	Germany	Haplic podzol	Bhs	30–45
5	Elba, Italy	Chromic luvisol	Ah	0–20
6	Elba, Italy	Chromic luvisol	Bt	150–180
7	Elba, Italy	Luvic calcisol	Ah	0–20
8	Elba, Italy	Luvic calcisol	Btk	80–100
9	Lublin, Poland	Haplic chernozem	Ap	0–20

**Table 2b.** Mineral soils studied—chemical and physical properties

Sample number	Organic matter (%C)	pH in CaCl <sub>2</sub>	Fe <sub>total</sub> (%)	Porosity (cm <sup>3</sup> cm <sup>-3</sup> )	Texture			Particle density (g cm <sup>-3</sup> )	Bulk density (g cm <sup>-3</sup> )
					Clay <sup>a</sup> (%)	Silt <sup>b</sup> (%)	Sand <sup>c</sup> (%)		
1	1.12	3.7	1.9	0.450	12	6	82	2.62	1.44
2	0.35	4.0	2.8	0.419	18	8	72	2.67	1.55
3	0.19	7.2	2.3	0.447	23	75	2	2.53	1.43
4	1.93	3.5	1.2	0.449	2	10	88	2.54	1.40
5	1.00	4.4	3.6	0.449	23	31	46	2.63	1.46
6	0.21	5.1	4.4	0.414	34	31	35	2.65	1.54
7	1.17	5.2	3.4	0.428	24	26	50	2.57	1.47
8	0.63	6.9	4.4	0.482	46	28	26	2.53	1.31
9	3.36	6.3	ND <sup>d</sup>	0.448	46	52	2	2.28	1.26

<sup>a</sup> < 2 µm; <sup>b</sup> 2–63 µm; <sup>c</sup> 63–2000 µm; <sup>d</sup> ND = not determined.

**Table 2c.** Mineral soils studied—parameters of calibration functions,  $\theta(K) = a + bK + cK^2 + dK^3$ 

Sample number	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>R</i> <sup>2</sup>	SD
Bulk	−0.0728	0.0448	−0.00195	0.0000361	0.9845	0.0150
1	−0.0658	0.0400	−0.00170	0.0000322	0.9962	0.0072
2	−0.0972	0.0485	−0.00242	0.0000522	0.9961	0.0082
3	−0.0391	0.0379	−0.00148	0.0000256	0.9925	0.0071
4	−0.1200	0.0571	−0.00286	0.0000551	0.9962	0.0081
5	−0.0769	0.0474	−0.00232	0.0000496	0.9964	0.0074
6	−0.0672	0.0448	−0.00205	0.0000419	0.9960	0.0077
7	−0.0771	0.0499	−0.00253	0.0000556	0.9948	0.0089
8	−0.0584	0.0468	−0.00220	0.0000411	0.9933	0.0112
9	−0.0472	0.0384	−0.00136	0.0000214	0.9970	0.0073

**Table 3a.** Organic soils and materials studied—site and soil type

Sample number	Locality	Soil type (FAO)	Horizon	Depth (cm)
10	Berlin	Fibric histosol	H <sub>1</sub>	0–20
11	Berlin	Fibric histosol	H <sub>2</sub>	50–70
12	Berlin	Cambic arenosol	O <sub>1</sub>	8–6
13	Berlin	Cambic arenosol	O <sub>2</sub>	6–5
14	Berlin	Cambic arenosol	O <sub>3</sub>	5–3
15	Berlin	Cambic arenosol	O <sub>4</sub>	3–0
16	Berlin	Cambic arenosol	Ah	0–10

**Table 3b.** Organic soils and materials studied—chemical and physical properties

Sample number	Organic matter (%C)	pH in CaCl <sub>2</sub>	Porosity (cm <sup>3</sup> cm <sup>-3</sup> )	Particle density (g cm <sup>-3</sup> )	Bulk density (g cm <sup>-3</sup> )
10	54.8	5.2	0.786	1.21	0.26
11	48.7	5.2	0.581	1.38	0.58
12	44.0	ND <sup>a</sup>	0.678	0.75	0.24
13	41.8	ND	0.715	0.70	0.20
14	38.9	3.4	0.660	1.06	0.36
15	32.2	3.3	0.753	1.50	0.37
16	10.5	3.4	0.527	1.63	0.77

<sup>a</sup>not determined.**Table 3c.** Organic soils and materials studied—parameters of calibration functions,  $\theta(K) = a + bK + cK^2 + dK^3$ 

Sample number	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>R</i> <sup>2</sup>	SD
Bulk	−0.0233	0.0285	−0.000431	0.00000304	0.9712	0.0355
10	−0.0159	0.0316	−0.000504	0.00000329	0.9941	0.0195
11	−0.0354	0.0504	−0.001747	0.00002359	0.9948	0.0122
12	−0.000269	0.0383	−0.001270	0.00002170	0.9780	0.0286
13	−0.0388	0.0400	−0.001325	0.00002260	0.9984	0.0098
14	−0.00515	0.0404	−0.001510	0.00002493	0.9976	0.0099
15	−0.00299	0.0359	−0.000994	0.00001336	0.9947	0.0160
16	−0.0394	0.0492	−0.002108	0.00003591	0.9975	0.0080

**Table 4a.** Magnetic soils studied—site, soil type and magnetic permeability

Sample number	Locality	Soil type (FAO)	Horizon	Depth (cm)	$\mu^a$ at 30 MHz
17	Paraná, Brazil	Rhodic ferralsol	Ah	0–10	1.01
18	Paraná, Brazil	Rhodic ferralsol	Bws	140–160	1.04

<sup>a</sup>Magnetic permeability.

**Table 4b.** Magnetic soils studied—chemical and physical properties

Sample number	Organic matter (% C)	pH in CaCl <sub>2</sub>	Fe <sub>total</sub> (%)	Porosity (cm <sup>3</sup> cm <sup>-3</sup> )	Texture			Particle density (g cm <sup>-3</sup> )	Bulk density (g cm <sup>-3</sup> )
					Clay <sup>a</sup> (%)	Silt <sup>b</sup> (%)	Sand <sup>c</sup> (%)		
17	2.86	4.5	18.4	0.601	80	16	4	2.88	1.15
18	0.74	3.9	18.5	0.611	81	16	3	2.88	1.12

<sup>a</sup> < 2  $\mu$ m; <sup>b</sup> 2–63  $\mu$ m; <sup>c</sup> 63–2000  $\mu$ m.

**Table 4c.** Magnetic soils studied—parameters of calibration functions,  $\theta(K) = a + bK + cK^2 + dK^3$ 

Sample number	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>R</i> <sup>2</sup>	SD
Bulk	−0.0981	0.0529	−0.00198	0.0000273	0.9747	0.0310
17	−0.162	0.0751	−0.00368	0.0000604	0.9883	0.0206
18	−0.147	0.0666	−0.00279	0.0000394	0.9876	0.0231

The mineral soil samples were tested for the presence of magnetism using a magnet. Two samples that exhibited magnetic susceptibility were identified (Table 4a). Chemical and physical properties, determined as above, are listed in Table 4b. The magnetic permeability of these samples was determined according to a procedure described below (see Appendix).

The mineral and organic soil samples were complemented by a set of capillary-porous reference materials: montmorillonite, glass beads, washed sand from a river bed, and a sand from the C horizon of a forest soil. These materials were characterized chemically and physically (Tables 5a and 5b).

#### *Determination of dielectric constant*

The TDR meter used and the measurement procedure are described elsewhere (Malicki & Skierucha, 1989; Malicki *et al.*, 1992). The TDR probes are the same miniprobe as those used by Malicki *et al.* (1992) in their laboratory studies.

In summary, the system consists of a pulse generator operating with a 250 ps rise-time needle pulse, a voltage recording circuitry, a coaxial feeder cable, a TDR miniprobe and a personal

**Table 5a.** Capillary-porous reference materials studied—site and/or material

Sample number	Locality	Material
19	Berlin	C material (arenosol)
20	Berlin	Washed sand
21	—	Glass beads (100 $\mu\text{m}$ )
22	Poland	Montmorillonite

**Table 5b.** Capillary-porous reference materials studied—chemical and physical properties

Sample number	Organic matter (%C)	Porosity ( $\text{cm}^3 \text{cm}^{-3}$ )	Texture			Particle density ( $\text{g cm}^{-3}$ )	Bulk density ( $\text{g cm}^{-3}$ )
			Clay <sup>a</sup> (%)	Silt <sup>b</sup> (%)	Sand <sup>c</sup> (%)		
19	0.18	0.370	0	2	98	2.65	1.67
20	0.00	0.351	0	1	99	2.65	1.72
21	0.00	0.411	0	0	100	2.87	1.69
22	0.83	0.535	63	36	1	2.69	1.25

<sup>a</sup> < 2  $\mu\text{m}$ ; <sup>b</sup> 2–63  $\mu\text{m}$ ; <sup>c</sup> 63–2000  $\mu\text{m}$ .

**Table 5c.** Capillary-porous reference materials studied—parameters of calibration functions,  $\theta(K) = a + bK + cK^2 + dK^3$ 

Sample number	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>R</i> <sup>2</sup>	SD
Bulk	−0.0927	0.0460	−0.00199	0.0000298	0.9725	0.0154
19	−0.134	0.0627	−0.00354	0.0000706	0.9894	0.0093
20	−0.191	0.0837	−0.00542	0.0001193	0.9938	0.0082
21	−0.197	0.0806	−0.00581	0.0001540	0.9970	0.0042
22	−0.041	0.0364	−0.00142	0.0000197	0.9895	0.0076

computer for controlling measurements and calculating results. The miniprobe consists of two parallel needles 0.5 mm in diameter, separated by a distance of 5 mm and of length 54 mm. The absolute error of the TDR system mentioned, as applied for the dielectric constant measurements, is illustrated in Table 1 by reference to measurements made on several organic liquids with known dielectric constants.

Soil samples were moistened in 10 to 12 steps to cover the range from air dryness to saturation. For each moisture step, the wetted soil was placed in a glass vessel of volume *c.* 100  $\text{cm}^3$ , compacted and then weighed. The dielectric constant was then determined (in five replicates) by inserting the TDR miniprobe vertically into the vessel. Finally, the vessel, of known volume, was emptied, and

the moisture of the sample was determined gravimetrically. Volumetric water content and bulk density were calculated using the gravimetric moisture content, the mass and the volume of the vessel containing soil.

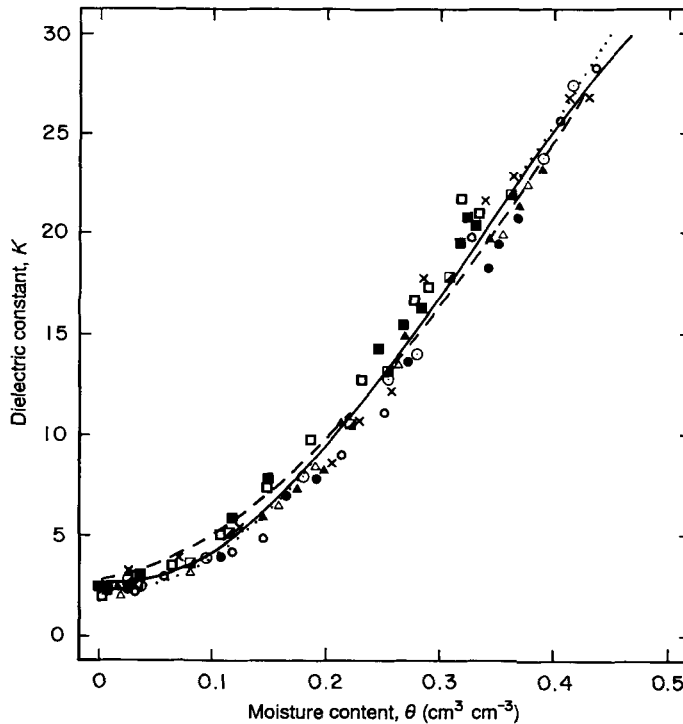
The  $K$  vs.  $\theta$  relationship for each individual sample was found by fitting third-degree polynomials. In addition, bulk curves were established for sets of data selected for soils and materials of the same origin. Although other functions could be used for fitting, third-degree polynomials were chosen and inverse functions ( $\theta = \theta(K)$ ) computed to make the results readily comparable with those curves obtained and reported previously by other investigators.

#### Determination of magnetic permeability

The magnetic permeability of soils was calculated from changes in the inductance of a coil buried first in an air-dry reference soil (having magnetic permittivity equal to 1) and then again in the air-dry soil under consideration, as illustrated in Fig. 1 in the Appendix. A detailed description of the measurement and calculation procedures can also be found in the Appendix.

## RESULTS AND DISCUSSION

The parameters of the individual calibration curves of  $\theta = \theta(K)$  are listed in Tables 2c, 3c, 4c and 5c, including the coefficients of determination and the standard deviations for each function.



**Fig. 1.** The dielectric constant,  $K$ , of the mineral soils studied (refer to Tables 2a and 2b) in relation to volumetric soil moisture content,  $\theta$ . The solid line shows the fitted polynomial:

$$K(\theta) = 2.87 - 11.1\theta + 276\theta^2 - 272\theta^3 \quad (R^2 = 0.985, SD = 0.94).$$

(■ □)=haplic ferralsol, (▲ △)=haplic luvisol, (▲ △)=chromic luvisol, (● ○)=luvic calcisol, (○)=chernozem, (×)=podzol, (---)=Topp *et al.* (1980), (·····)=Malicki & Skierucha (1989).

The scatter of the readings was normally distributed, so that standard deviation was taken as a measure of the absolute error of measurement. When comparing standard deviations of the bulk calibration functions with those of the individual curves, it was found that in all cases the bulk calibration curves showed a two- to threefold greater error of readings. Curve fit as expressed by the coefficient of determination was also better for the individual calibration functions.

The bulk of mineral soils tested (Fig. 1) closely followed the bulk calibration functions described elsewhere (Topp *et al.*, 1980; Malicki & Skierucha, 1989). Soils of quite different origin, with different chemical and physical properties (Tables 2a and 2b), show  $K(\theta)$  relationships close enough to be substituted by a single function, unique for all of them, for the price of an error of measurement that is up to twofold greater when compared to individual functions (standard deviations of 0.0150 and 0.0071–0.0112, respectively).

The dielectric constants of organic soil samples and materials measured at each selected moisture level were lower when compared to the mineral soils. The respective  $K(\theta)$  relationship (Fig. 2) deviated significantly from the function found for mineral soils. The data are in quite close agreement with the results observed by Topp *et al.* (1980) for an organic soil. Apparently, bulk density plays an important role. However, a detailed discussion of the nature of these effects is beyond the scope of this paper.

The calibration function for the two samples showing magnetic properties deviated from that pertaining to organic soils, and was also found to differ slightly from the function for mineral soils. The  $K(\theta)$  relationship (Fig. 3) indicated an initially smaller slope up to a moisture content of about

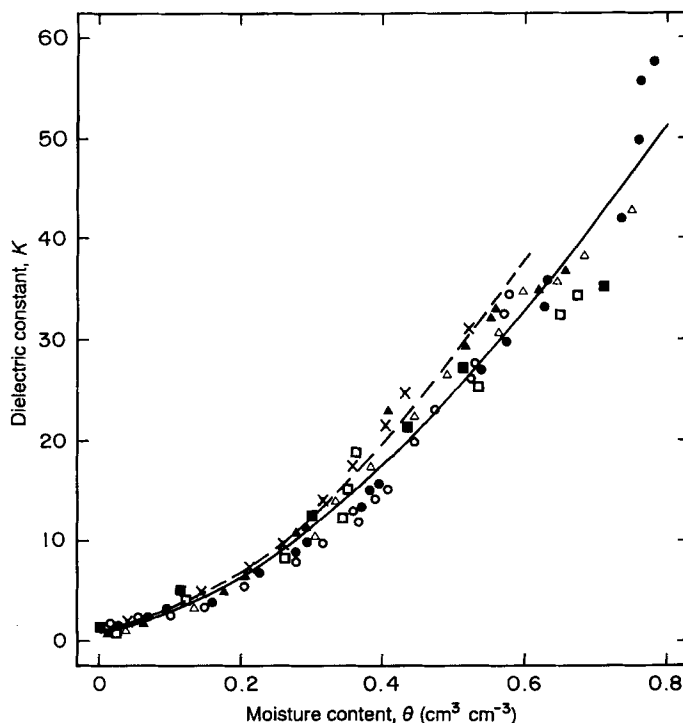
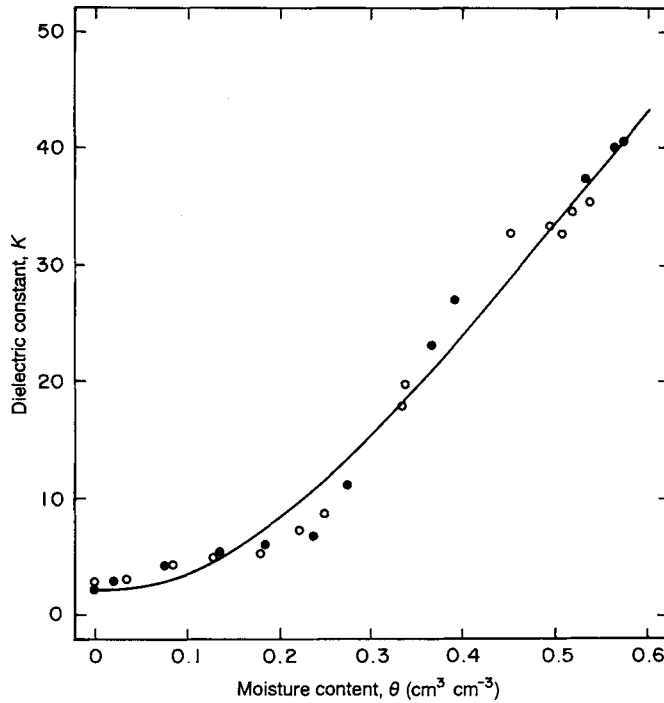


Fig. 2. Dielectric constant,  $K$ , of the organic soils and materials studied (refer to Tables 3a and 3b) in relation to volumetric soil moisture content,  $\theta$ . The solid line shows the fitted polynomial:

$$K(\theta) = 0.97 - 10.9\theta + 87.4\theta^2 - 28.0\theta^3 \quad (R^2 = 0.967, \text{SD} = 2.52).$$

(●) = peat weakly decomposed, (○) = peat well decomposed. Cambic arenosol: (□) = undecomposed oak leaves, (◻) =  $O_2$ ; (■) =  $O_2$ ; (▲) =  $O_3$ ; (△) =  $O_4$ ; (×) = Ah. (---) = Topp *et al.* (1980).





**Fig. 3.** Dielectric constant,  $K$ , of the soils with magnetic properties studied (refer to Tables 4a and 4b) in relation to volumetric soil moisture content,  $\theta$ . The solid line shows the fitted polynomial:

$$K(\theta) = 3.92 - 41.6\theta + 374\theta^2 - 322\theta^3 \quad (R^2 = 0.987, \text{SD} = 1.59).$$

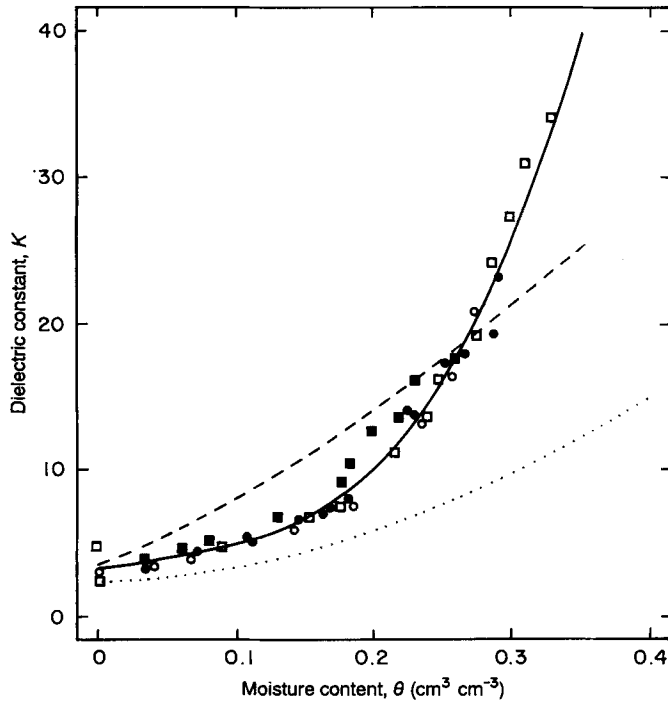
Rhodic ferralsol: (●) = Ah, (○) = Bws.

0.20, after which the function started to converge with the calibration function for the normal mineral soils.

These two samples differ greatly from the others in their clay content, particle density, total Fe content and bulk density (Tables 4a and 4b), but it was initially thought that their magnetic properties might affect the  $K(\theta)$  relationships. Because induced magnetism needs time to develop, its intensity depends either on the frequency of the exciting field or on the rise-time of the exciting pulse. It can be seen that magnetic permeabilities of the samples (Table 4a) appeared to be insignificant at a period of less than 33 000 ps (which corresponds to a frequency of more than 30 MHz). Because the employed pulse rise-time (250 ps) is significantly smaller, it seems justifiable to conclude that the process of magnetic polarization of these soils cannot succeed in time to follow changes in the magnetic field of the exciting TDR pulse.

Finally,  $K(\theta)$  curves for the four reference materials studied were also grouped into one bulk calibration function (Fig. 4), showing higher dielectric constants at a given moisture content compared to the calibration curves of the other samples. All four materials have in common the absence, or a very low content, of organic matter, but differ in specific surface area as well as in grain size and particle density. A similar  $K(\theta)$  relationship, deviating from other mineral soils, was also observed by Malicki & Skierucha (1989) for a sandy soil with no organic matter. It is important to point out the significant divergence of this calibration function, because such materials are frequently used as substitutes for soils in investigations on solute transport in soil columns, due to facilitated reproducibility resulting from the simple composition of these materials.

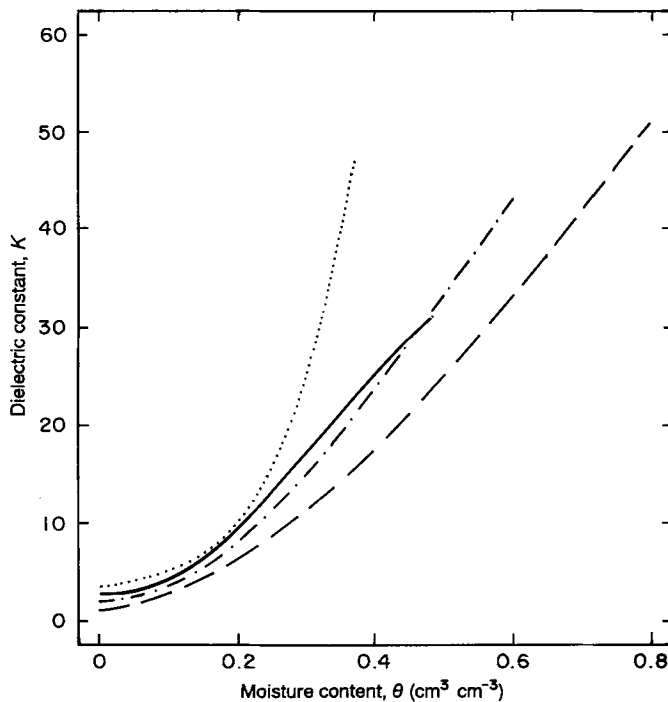
For easier comparison, all four bulk calibration curves are summarized in Fig. 5. The respective function parameters are listed in the headings of Figs 1–4.



**Fig. 4.** Dielectric constant,  $K$ , of the capillary-porous reference materials studied (refer to Tables 5a and 5b) related to volumetric soil moisture content,  $\theta$ . The solid line shows the fitted polynomial:

$$K(\theta) = 2.57 - 38.5\theta + 263\theta^2 - 1310\theta^3 \quad (R^2 = 0.981, SD = 1.07).$$

(●) = C material (arenosol), (○) = washed sand, (■) = glass beads (100  $\mu\text{m}$ ), (□) = montmorillonite. Topp *et al.* (1980): glass beads (30  $\mu\text{m}$  and 100  $\mu\text{m}$ ) = (---), vermiculite = (····).



**Fig. 5.** Comparative plot of the dielectric constant–volumetric water content relationship for all investigated soils. Refer to preceding figures for respective polynomials. (—) = mineral soils, (---) = organic soils and materials, (- - -) = magnetic soils, (····) = other capillary-porous media.

## CONCLUSIONS

In practical terms of usefulness of TDR moisture measurements, two unique calibration functions appear to be valid—one which is common for mineral soils, and another common for organic soils. This makes calibration of the TDR soil moisture measurements for each specific soil at each particular site unnecessary, if an absolute error in  $\theta$  of  $0.015 \text{ cm}^3 \text{ cm}^{-3}$  for mineral soils and  $0.035 \text{ cm}^3 \text{ cm}^{-3}$  for organic soils is acceptable. However, should demands on accuracy in specific cases be higher, individual calibrations may prove necessary.

The presence of magnetic susceptibility in soil does not appear to have an effect on the TDR soil moisture calibration function, as the magnetic domains of such soils cannot succeed in time to follow changes in the magnetic field of the exciting TDR pulse.

Capillary porous materials that are often used in laboratory studies of water transport processes might require individual calibration, as they exhibit different calibration functions when compared to mineral soils.

## ACKNOWLEDGEMENTS

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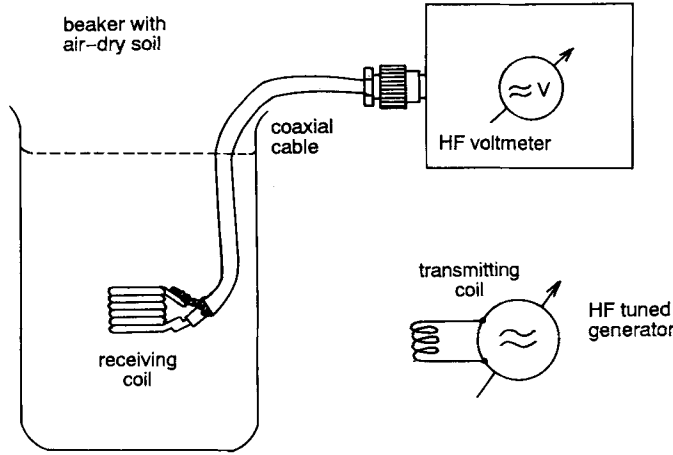
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## APPENDIX

*Determination of magnetic permeability of soils*

Figure 6 illustrates a system for the determination of the magnetic permeability of the investigated soil materials. A coil is buried in an air-dry soil kept in a beaker and then compacted. The coil is



**Fig. 6.** System for the determination of magnetic permeability of soil materials, as used in this study. The inductance of the coil and the capacitance of the section of a coaxial cable (as well as stray capacitances of the system) constitute a parallel resonant circuit with a resonant frequency that is dependent on the magnetic permeability of the medium in which the coil is buried. The receiving coil (with an inductance of about  $0.43 \mu\text{H}$ ) is 7 mm in inner diameter, and is wound with no spaces with 9 turns of enamelled copper wire (diameter 1 mm). The section of the coaxial cable is 40 cm long and has an electrical capacitance of about 40 pF. The resonant frequency of the receiving circuit in air-dry soil is about 30 MHz. The transmitting coil has an inductance of about  $2 \mu\text{H}$ .

connected to a high-frequency voltmeter input by a section of coaxial cable. This coil, together with the coaxial cable, constitutes a parallel resonant circuit with a resonant frequency of about 30 MHz, and is able to receive electromagnetic signals from the surrounding environment. This resonant circuit, in combination with the HF voltmeter, constitutes a receiver of electromagnetic signals.

A high-frequency tuned generator supplies another coil. The generator together with the coil constitutes a transmitter. The latter is located about 1 m away from the beaker containing the soil sample. Energy from the electromagnetic wave radiated by the transmitter is most effectively received by the receiver if the resonant frequency of the receiving circuit is the same as that of the transmitter. When the receiving coil is buried in a material of magnetic permeability greater than 1, the resonant frequency of the circuit decreases. The new resonant frequency can be found by tuning the generator until the HF voltmeter indicates a maximum voltage.

The resonant frequency,  $f$ , of the receiving circuit is expressed as:

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

where  $L$  is the inductance of the coil and  $C$  is the total capacitance of the resonant circuit (including capacitance of the coaxial cable, self capacitance of the coil as well as input capacitance of the HF voltmeter), from which the inductance of the coil can be found as:

$$L = \frac{1}{4\pi^2 f^2 C} \quad (2)$$

The inductance of a coil can also be expressed in terms of the magnetic permeability of the material in which it is buried, as:

$$L = L_0 \mu \quad (3)$$

where  $\mu$  is the relative magnetic permeability of the material and  $L_0$  is the inductance of the coil in a vacuum.

Let a soil material that is not attracted by a magnet (i.e having  $\mu = 1$ ) be a reference. Then:

$$L/L_{\text{ref}} = L_0\mu/L_0\mu_{\text{ref}} = \mu/\mu_{\text{ref}} \quad (4)$$

where  $L_{\text{ref}}$  is the inductance of the coil buried in the reference soil material and  $\mu_{\text{ref}}$  is its magnetic permeability. Substituting Equation (2) into the left side of Equation (4) leads to:

$$(f_{\text{ref}}/f)^2 = \mu/\mu_{\text{ref}} \quad (5)$$

where  $f_{\text{ref}}$  is the resonant frequency of the circuit with the coil buried in the reference soil material. Because  $\mu_{\text{ref}} = 1$ , Equation (5) simplifies to:

$$\mu = (f_{\text{ref}}/f)^2 \quad (6)$$

where  $\mu$  is the relative magnetic permeability of the soil under investigation.

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