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SOIL MOISTURE MEASUREMENT BY SOIL IMPEDANCE MEASURING METER: LABORATORY CALIBRATION AND FIELD EVALUATION

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Soil impedance measuring meter is relatively a new device and utilises the principle of measuring the dielectric constant of the soil, and hence water content by soil electrical impedance method at 100 MHz. The probe is supplied with a general calibration by the manufacturer and very little has been published on the materials-specific calibration. Hence, the output (mV) of the probe was calibrated versus volumetric water content (θ_v) of silty clay loam soils, loamy very fine sand soil and chalky material. For $\theta_v < 0.6$ m^3m^{-3}, a third order polynomial relationship between θ_v and the probe's output was found suitable (r^2=0.99) for calibration. A good correlation was found between moisture content measured by this new probe and that with neutron probe under field condition, for silty clay loam soil (r=0.96) and for chalky material (r=0.97).

The probe is comparatively small and easy to install but its effective sampling volume is limited (42.4 cm^2). Therefore, it is most suitable for homogeneous soils and pot experiments. The sensitivity of the probe is greatly influenced by conditions close to the central rod and a 0.5 mm annular gap between this rod and the surrounding material resulted in 42% reduction in output.

Key words: Soil moisture, Theta probe, Calibration, Dielectric constant, Effective sampling volume.

Introduction

An accurate estimate of soil water content and water fluxes is required in soil and hydrological studies. There are several techniques for measuring soil water content including, gravimetric (Gardner 1986) detection of thermalised neutrons (Bell 1969; Greacen 1981) measurement of the electrical resistance (Gardner 1986) measurement of the dielectric constant (k) of the soil (Fellner-Feldegg 1969; Topp *et al* 1980) and measurement of the soil electrical impedance.

Techniques based on the measurement of the dielectric constant of the soil with capacitance probes (Bell *et al* 1987; Dean *et al* 1987) time domain reflectometry (Topp *et al* 1980; Derksen and Dasberg 1993; Jacobsen and Schjonning 1993) or impedance measuring meter are based on fact that soil water content strongly influences the dielectric properties of the soils (Hallikainen *et al* 1985). The dielectric constant of free water ($k_{water} \sim$ □ 80) at 20°C is significantly greater than that of air ($k_{air} \sim 1$) and soil material ($k_{soil} \sim 4$) (Zegelin *et al* 1992).

The impedance measuring meter, Theta probe (trade name) consists of a 100 MHz sinusoidal oscillator, a fixed impedance section of coaxial line and a stainless steel wire sensing probe which behaves as an additional section of transmission line with an impedance dependent on the dielectric constant of the surrounding probe wires. This device has been jointly developed by the Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, UK and Delta-T Devices, Burwell, Cambridge, UK.

Theta probe measures the soil impedance by propagating an oscillator signal (100 MHz) along the transmission line into the soil probe. The transmission line's impedence changes as the impedance of the soil changes. The impedance of soil has two components; the apparent dielectric constant and the ionic conductivity. The signal frequency has been chosen to minimise the effect of ionic conductivity, so that changes in the transmission line impedance are dependent almost solely on the soil's apparent dielectric constant. These changes cause a voltage standing wave to be produced, which augments or reduces the measurement prongs. The ratio between the oscillator voltage and the reflected by the rods, the voltage standing wave ratio, is used to measure the apparent dielectric constant of the soil.

Theta probe is a recent addition to the range of soil moisture measuring devices and supplied with a general calibration by the manufacturer and very little material specific has been published. This study was designed to calibrate the device output (mV) against the volumetric water content of soil and chalk materials as well as known dielectric constant and to determine the effective sampling volume and possible effects of a gap between the transmission lines and the surrounding materials.

Materials and Methods

Output of the Theta probe was calibrated for the water content of the silty clay loam which is very fine sand soil and chalky materials. Samples were air-dried, ground and passed through a 2 mm sieve and divided into several sub-samples. The sub-samples were moistened from air dry to 0.5 m^3m^{-3}, in steps of about 0.1 m^3m^{-3}, by spreading them on a plastic sheet. Pre-determined amount of water was sprayed and mixed thoroughly to obtain a homogeneous mixture. The moistened samples were then stored in sealed polyethylene bags at 4°C for two days and were mixed well twice a day to achieve a uniform distribution of water in the samples. After two days, the samples were packed into PVC cylinders, 100 mm in diameter and 150 mm in length, to about 1.3 Mg m^{-3} bulk density in nine replicates. Another set of soil and chalk water suspensions with water content ranging from 0.6 to 0.9 m^3m^{-3} with an increment of 0.1 m^3m^{-3} were also prepared to calibrate the device at higher water contents. Water contents of the samples were measured by Theta probe at a frequency of 100 MHz. Before inserting the extended transmission lines (rods) of the probes into the packed samples to measure the water content, four holes slightly smaller in diameter than the rods and spaced identically to the rods were drilled to avoid any compaction effect. Measurements were made about 3 h after insertion of rods to eliminate the effects of gradients of water around the rods. The suspension samples were shaken well before reading. After shaking, the extended transmission lines of the probe were inserted into the suspended samples and read the stabilised output.

Although different moisture contents were developed by adding a known quantity of water to a known volume of soil/chalk, water contents of the moistened samples were also measured gravimetrically immediately after the probe measurements and this water content was used in all further calculations after converting them into volumetric water content (m^3m^{-3}).

The prob's outputs (mV) were also calibrated for dielectric constant using different binary solutions of known dielectric constant (Table 1) (Washburn 1929).

Effective sampling volume of the instrument was measured by packing air-dried and moistened (0.3 m^3m^{-3}) ground samples in 50, 75 and 100 mm in diameter PVC cylinders, each 150 mm long, in nine replicates. The rods of the probe were inserted (using the same technique described previously) along the axis of each cylinder and output voltage was recorded.

The sensitivity of the probes was examined by inserting the extended transmission lines in water with and without introducing annular gaps around the central and outer rods. The gaps were introduced using electrical insulating tape with an increment of 0.12 mm, ranging from 0 10 1.2 mm. After putting each layer of insulation tape around the respective rod (central or outer), the probe was immersed in water for the measurements to be made.

Table 1

Binary solutions and their dielectric constant values

Binary solutions	Chemical-water ratio (w w^{-1})	Dielectric constant
Toluene	1-0	2.39
Chloroform	1-0	5.00
Acetone	1-0	20.70
Ethyl alcohol	1-0	26.50
Ethyl alcohol	0.9-0.1	29.80
Ethyl alcohol	0.8-0.2	34.10
Ethyl alcohol	0.7-0.3	38.10
Methyl alcohol	0.8-0.2	43.10
Methyl alcohol	0.6-0.4	52.40
Methyl alcohol	0.4-0.6	61.40
Methyl alcohol	0.2-0.8	69.60
Methyl alcohol	0.1-0.9	77.60
Water	0.0-1	82.60

For field evaluation, the probes were installed at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 m below the ground level in duplicate. Six neutron probe access tubes were also installed and soil water content was measured using an IH II neutron probe at the same depths at which the theta probes were installed. The published calibration graph (Bell 1976) was used to convert the neutron count rate to soil volumetric water content.

Results and Discussion

Calibration. The gravimetric method is a standard method for calibration of all other techniques for measurement of soil moisture. The gravimetric measurement of water expresses the weight or volume of water expelled by oven-drying at 105°C, per unit weight or volume of the soil. In the Theta probe, the output signal responds to the dielectric properties of the medium around the transmission line and water content strongly influences the dielectric properties of the soil (Hallikainen *et al* 1985). Water in unsaturated soil is held within a range of pore sizes and shapes by surface tension forces as well as thin films on particle surfaces (particularly of clay minerals) by chemical bonding. The water molecules which are free to relax as their dipoles respond to field reversals mainly affect the dielectric properties of the soil.

Fig 1 shows the relationship obtained between the probe output (mV) and volumetric water content (θ_v) for the soil and chalk. At water contents <0.3 m^3m^{-3}, both curves show a simple linear relationship between θ_v and mV, whereas at water contents between 0.3 and 0.6 m^3m^{-3}, the relationships are more curved, and >0.6 m^3m^{-3}, the relationships are exponential.

As the sampled soils and chalk profiles have maximum water holding capacity ≤ 0.6 m^3m^{-3} (Burnham 1990) empirical relationships between mV and θ_v □< $m^3m^{-3}$for soils and chalk were derived by fitting a third order polynomial equation. The equation; for silty clay loam soil, the relation was

$$\theta_v=-8.83+0.0807*(mV)-8E\text{-}05*(mV)^2+6.95E\text{-}08(mV)^3 \quad .....(1)$$

for loamy very fins sand soil, the relation was

$$\theta_v=-10.3+0.077*(mV)-7E\text{-}05*(mV)^2+6.0E\text{-}08(mV)^3 \quad .....(2)$$

and for chalk, the relation was

$$\theta_v=-10.3+0.0771*(mV)-7.1E\text{-}05*(mV)^2+6.35E\text{-}08(mV)^3 \quad .....(3)$$

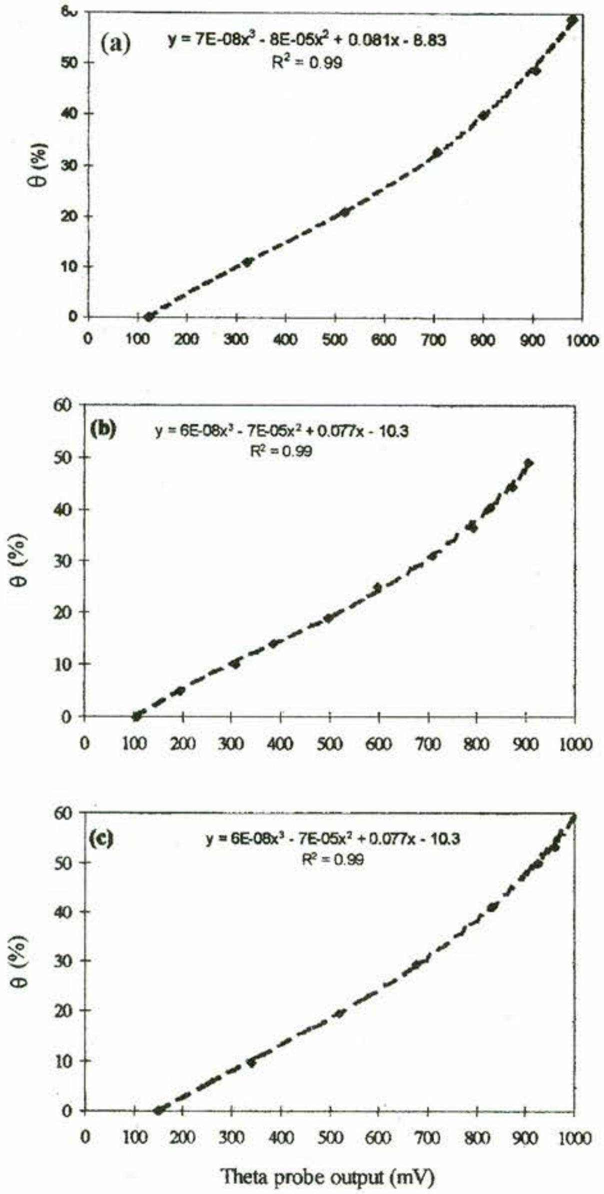

Fig 1. Calibration curves for theta probe output (mV) verses measured volumetric water content; (a) silty clay loam soil, (b) loamy very fine sand soil and (c) chalk material.

These curves can be used as empirical calibrations for determination of water content from mV with standard error of estimate of 0.72 for silty clay loam soils, 0.53 for loamy very fine sand and 0.59 for chalk.

As mentioned earlier, the impedance of the transmission line changes as the impedance of the material surrounding the transmission line changes. Although the impedance of the surrounding material depends upon its dielectric properties, it is difficult to know the dielectric constant of the material from the outpout signal of the probe because its output is in mV. Therefore the probe was also calibrated using binary solutions of known dielectric constants. The calibration curves for known dielectric constant against output voltage, is plotted as Fig 2. The suggested experimental relationship between dielectric constants of the solutions and the probe output (mV) is

$$k_a=15.24-0.232*(mV)+0.00113*(mV)^2-1.647E\text{-}06(mV)^3+7.707E\text{-}10(mV)^4 \quad .....(4)$$

Effective sampling volume and sensitivity of the probe. The results show that the increase in volume of soil around the outer rods did not affect the output of the probe (Table 2). There were no differences in the outputs of the probe when installed in dry and wet samples of different volumes (294.5, 662.7 and 1178.1 cm^3) of chalk, silty clay loam and loamy very fine sand. This suggests that the probe samples very small soil volume (42 cm^3) and measured the water content of the soil and chalk materials only that were within the orbit of the outer rods. Zegelin *et al* (1992) clearly demonstrated that the electric field distribution around the insertion rods of a probe depends on the geometry of the probe. In this study a coaxial four-wire probe was used. In coaxial three or multi-wire probes, most of the energy (and hence most of the measurement sensitivity) is concentrated around the central

Table 2

The effect of sample volume on the output of the probe (mV)

Material	Moisture (cm^3 cm^{-3})	Volume of sample (cm^3) 294.5†	 662.7‡ (mV)	 1178.1§
Upper chalk	Air dry	144 (2.4)	140 (1.8)	142 (3.2)
	0.30	675 (3.3)	687 (4.1)	678 (3.7)
Silty clay loam	Air dry	121 (2.5)	126 (3.6)	119 (2.9)
	0.30	711 (4.6)	704 (5.7)	709 (6.0)
loamy very fine sand	Air dry	103 (2.8)	101 (3.2)	106 (2.7)
	0.30	706 (5.2)	713 (6.4)	701 (5.8)

† Sample diameter 5 and length 15 cm, ‡ Sample diameter 7.5 and length 15 cm, § Sample diameter 10.0 and length 15 cm, Figures in parentheses are values of standard deviation.

Table 3
The effect of introducing annular gap around the rods on the output of the probe (rods were immersed in water)

Annular gap around			Probe output	S.E
Central rod (mm)	Side rod 1 (mm)	Side rod 2 (mm)	(mV)	
0	0	0	1134	1.00
0.12	0	0	1016	1.15
0.24	0	0	866	289
0.36	0	0	752	4.62
0.48	0	0	653	2.31
0.60	0	0	593	2.60
0.72	0	0	537	2.00
0.84	0	0	492	1.73
0.96	0	0	463	1.45
1.08	0	0	435	1.76
1.20	0	0	410	3.00
1.20	0.12	0	410	2.05
0	0.12	0	1133	1.53
0	0.24	0	1134	1.15
0	0.24	0.12	1132	1.45
0	0.24	024	1133	2.08

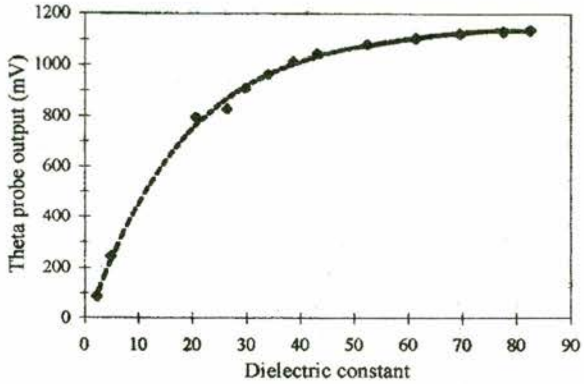

Fig 2. Theta probe output (mV) responses to pure liquids of known dielectric constant.

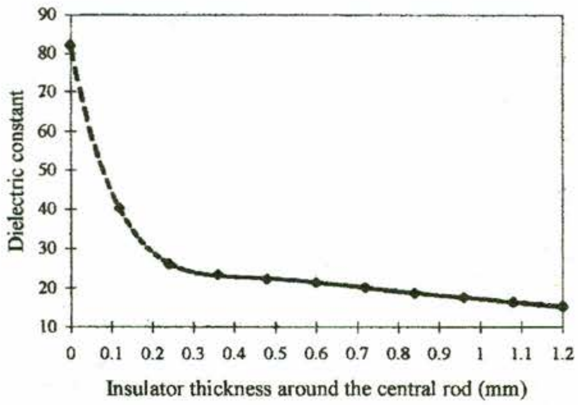

Fig 3. Sphere of influence of central rod of the theta probe with respect to dielectric constant.

insertion rod and falls off rapidly with distance from the central rod (Knight 1992).

The sensitivity of the probe is another critical answerable issue. So, the sensitivity of the probe was examined. A large reduction in output of the probe was observed when the surrounding rods were insulated (Table 3). These results are consistant with the previous observations of Knight (1992) and Whalley (1993) in which they found highest sensitivity in the immediate vicinity of the central insertion rod of TDR.

Fig 3 and 4 show decrease in k and θ_v with the annular thickness of the insulator around the central rod. The decrease in k and θ_v were precipitous as insulation thickness was increased from 0 to 0.48 mm and after that the decrease was almost linear with further increase in the annular thickness of insulator. The results obtained by Annan (1977), Zegelin *et al* (1992) and Whalley (1993) in similar studies confirm the above observations. Annan (1977) and Whalley (1993) tested the sensitivity of a three-wire probe by immersing the transmission lines in water and introducing annular gaps using electrical insulation around the central wire only. They found tremendous loss of sensitivity resulting from annular gaps. Similarly, Zegelin *et al* (1992) used wax and ethanol to examine the sensitivity of a coaxial probe and reported a similar trend in the reduction of k as the annular thickness of wax around the central conductor increased.

Field Evaluation. Under field conditions, water content measured by the Theta probe was compared with the neutron probe (Fig 5). The results show a good correlation between these two techniques (r = 0.94 for soil and r = 0.95 for chalk) and confirm the performance of the Theta probe.

A possible explanation for the deviation from the 1:1 ratio at low and high water content in silty clay loam soil are: at low water content, the theta probe gave lower water content than that measured by the neutron probe because of contact of the

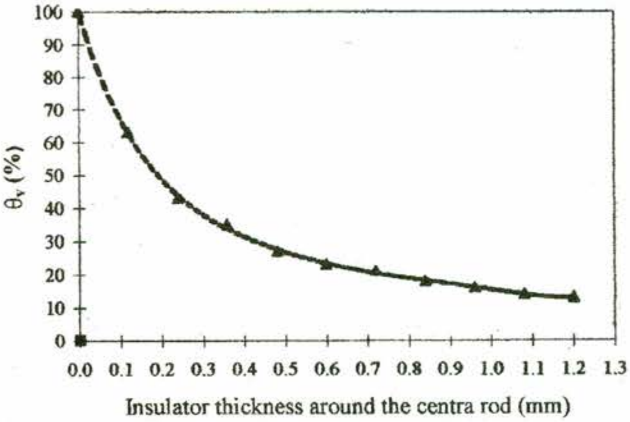

Fig 4. Sphere of influence of central rod of the theta probe with respect to water content.

rods with surrounding material. A fine gap could be anticipated along axis of the rods on drying that cause under-estimation. Contrarily, at higher water content, possibly there was thin film of free water around the rods (in the possible anticipated fine gap) and the probe overestimated the water content. The chalk matrix was nearly saturated during installation of Theta probe and the chalk close to the rods might have been compressed in spite of all the care that was taken to avoid compaction. The sensitivity of the Theta probe is greatly affected by the conditions close to the central rod so that any irregularity around the central rod could significantly affect the output.

Conclusion

Although, the Theta probe has a limited effective sampling volume for moisture measurements, it is a good device for qualitative water measurements. The probe can also be used successfully to monitor the periodical changes in water content at different depths of a profile, from which first arrival time or break through at any given depth can be computed. However, quantitative measurements of the water content of a profile for drainage fluxes might be improved by increasing effective sampling volume.

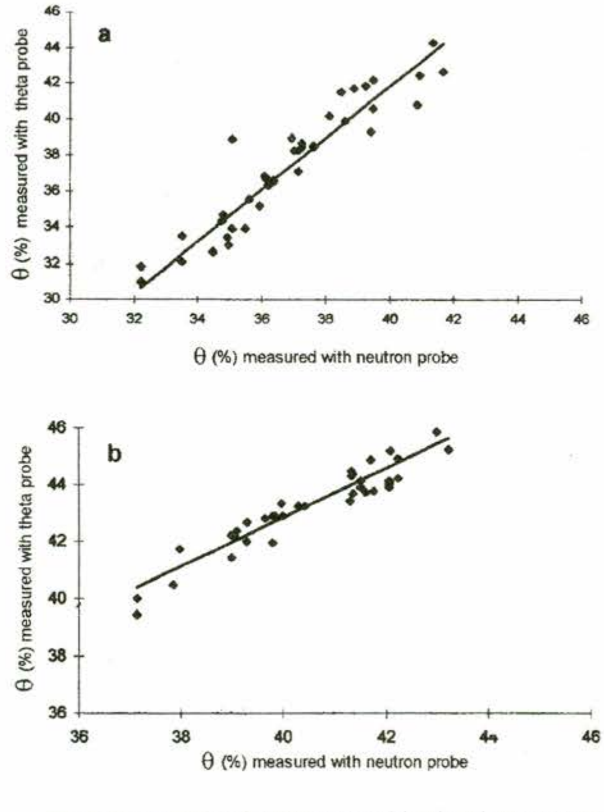

Fig 5. Comparative θ (%) measured in situe by neutron probe and theta probe; (a) soil and (b) chalk.

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