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by T.H.W. Baker and L.E. Goodrich

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Measurement of soil water content using the combined time-domain reflectometry – thermal conductivity probe

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A two-pronged metal probe measures the thermal conductivity and apparent dielectric constant of soils in the laboratory and in the field. One prong acts as a transient line heat source probe in measuring thermal conductivity. The apparent dielectric constant of the soil is determined by the time-domain reflectometry (TDR) technique, using both prongs as a parallel transmission line. Volumetric water content is determined from the apparent dielectric constant, making use of an empirical relation valid for most soils. For volumetric water contents above about 8%, the apparent dielectric constant shows a strong dependence on water content and relatively small changes can be measured; sensitivity increases with water content. For volumetric water contents less than 8%, a soil-dependent empirical relation between water content and thermal conductivity has been developed that is most sensitive at lower water contents. The combined probe provides a means of monitoring the water content of soils over a wide range of values, in the field and in the laboratory.

Key words: soil water content, time-domain reflectometry, thermal conductivity.

Une sonde à double pointe mesure la conduction thermique et la constante diélectrique apparente des sols en le laboratoire et sur le terrain. Une pointe agit comme une source de ligne de chaleur transitoire pour mesurer la conductivité thermique. La constante diélectrique apparente du sol reste déterminée par une technique de réflectométrie en fonction du temps (TDR), utilisant les deux pointes comme ligne de transmission. La teneur en eau volumétrique est déterminée en partant de la constante diélectrique apparente, au moyen d'une relation empirique valable pour la plupart des sols. Pour les teneurs en eau volumétriques supérieures à environ 8%, la constante diélectrique apparente dépend fortement de la teneur en eau, et des changements relativement faibles peuvent être mesurés; la sensibilité augmente avec la teneur en eau. Pour les teneurs en eau volumétriques inférieures à 8%, une relation empirique fonction du sol a été développée entre la teneur en eau et la conductivité thermique; cette relation est très sensible aux teneurs en eau plus faibles. La sonde fournit un moyen de mesurer de façon continuelle les teneurs en eau des sols s'étendant sur une large gamme en laboratoire ou sur le terrain.

Mots clés : teneur en eau des sols, réflectométrie fonction du temps, conductivité thermique.

[Traduit par la revue]

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Introduction

The ability to measure the water (moisture) content of soils *in situ* is essential in all soil-related disciplines. It is critical in the planning, design, construction, operation, and management of any system where soil is a major component. Two excellent reviews of the commonly used techniques to measure soil water content have already been prepared by McKim *et al.* (1980) and Schmugge *et al.* (1980). They present the advantages and disadvantages of each method, including cost factors.

The combined probe was first introduced in a previous paper (Baker and Goodrich 1984) showing some preliminary results in utilizing the probe as a field monitoring device to measure ground temperature, volumetric water content, and thermal conductivity, and to determine whether the pore water around the probe is frozen. This technical note begins by describing the probe and its operation, but focuses on the measurement of soil water content, utilizing both electromagnetic and thermal properties of the soil to improve the precision of the measurement through the whole range of moisture contents. It describes the results of a laboratory study using a standard-grade Ottawa sand (ASTM C778-80) and an industrial application where the results could be directly applied.

Methods

Time-domain reflectometry (TDR) technique

Davis *et al.* (1976) presented a method of determining the volumetric water content of soils by means of the electromagnetic pulse technique referred to as time-domain reflectometry. The apparent dielectric constant of soils for frequencies between 1 MHz and 1 GHz was found to be strongly dependent on volumetric water content and only weakly dependent on soil type, density, and temperature (above 0°C).

In a later paper, Topp *et al.* (1980) proposed an empirical relation between the volumetric water content, θ_v, and the apparent dielectric constant, K_a, for soils:

$$[1] \quad \theta_v = -5.3 + 2.92K_a - 5.5 \times 10^{-2}K_a^2 + 4.3 \times 10^{-4}K_a^3$$

The technique involves the propagation of electromagnetic pulses along a transmission line (two parallel metal rods) placed in the soil. Propagation velocity, V, is determined by measuring the travel time of an electromagnetic pulse transmitted along the transmission line for a known distance,

$$[2] \quad V = \frac{L}{t}$$

where L is the length of the transmission line (cm) and t is travel time (ns). The apparent dielectric constant, K_a, is related to the propagation velocity by the expression

$$[3] \quad K_a = \left(\frac{c}{V}\right)^2$$

where c is the velocity of light in a vacuum (30 cm/ns). The method of measuring travel time, using a time-domain reflectometer, has been described by Baker *et al.* (1982) and Topp *et al.* (1984).

Thermal conductivity—transient line heat source method

The thermal probe is the most common apparatus used in the transient method of measuring thermal conductivity of soils, either in the laboratory or *in situ*. It is inserted directly into the soil to be tested, but because of its size it causes little thermal

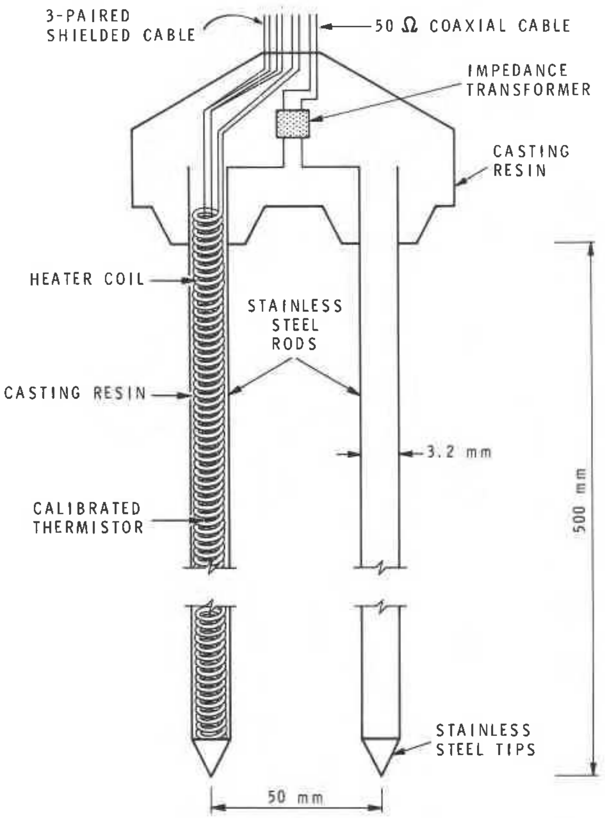

FIG. 1. Probe design.

disturbance. The probe consists of a steel tube containing a wire coil to produce heat at a constant rate and a temperature-sensing element (thermocouple or thermistor). The time rate of increase in probe temperature depends on the thermal conductivity of the surrounding soil.

In its simplest form the theory of the thermal probe method is that of a line heat source in a semi-infinite, homogeneous, isotropic medium. For a real thermal probe, the thermal response is affected by the finite length, diameter, and heat capacity of the probe as well as by the thermal contact resistance between the probe and the soil. For a limited intermediate time range, however, the temperature response is proportional to the logarithm of time, just as in the line heat source case. The relation can be written:

$$[4] \quad T = \text{constant} + \frac{q}{4\pi k} \ln t$$

where T is the probe temperature (°C) at time t (s), q is the power input per unit length of probe (W/m), and k is thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$). More detailed information about field measurements is available (Goodrich 1986).

Description of probe

The probe consists of two stainless steel tubes, one a thermal probe containing a wire heater coil along its full length and a precalibrated thermistor at mid-length inside the coil. The space between the heater coil, thermistor leads, and tube wall is filled with a casting resin. The other tube is empty and acts as the second conductor in a parallel-wire transmission line. Moulded casting resin forms the head of the probe and contains the lead wires from the tubes and the impedance transformer. A three-paired shielded cable and a 50 Ω coaxial cable connect the probe to the measurement instruments and readout equipment. Figure 1 gives details of the probe construction; Fig. 2 presents a schematic drawing of the associated instrumentation. The probe has proved to be a useful instrument for monitoring changes in thermal and moisture regimes in soil (Baker and Goodrich 1984).

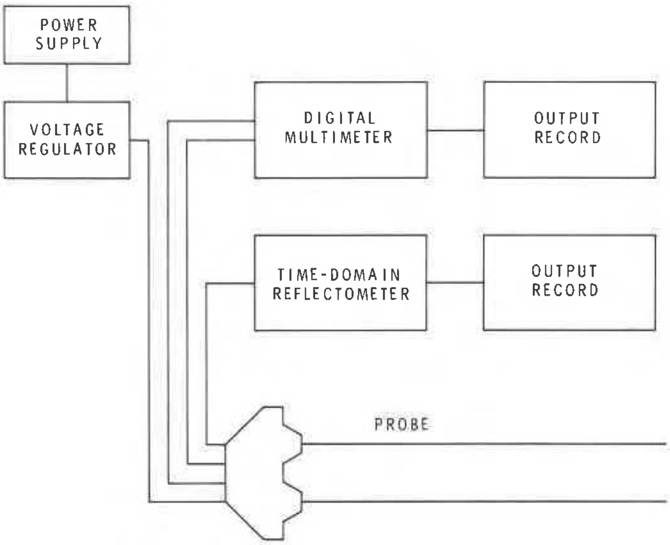

FIG. 2. Schematic of probe instrumentation.

Water content determination

Volumetric water content of soil, θ_v, is related to the gravimetric water content, w, by the expression

$$[5] \quad \theta_v = w \times \rho_d/\rho_w$$

where ρ_d = dry density of soil (t/m^3) and ρ_w = density of water = 1 t/m^3.

Laboratory experiments were undertaken with Ottawa sand placed in moulds at a uniform gravimetric water content and dry density. Combinations of gravimetric water contents and dry densities were chosen to obtain a range of volumetric water contents from 0 to 36%. Measurements were made when probe and soil temperatures reached equilibrium, typically after about 12 h.

Water content greater than 8% by volume

Figure 3 shows the relation of the apparent dielectric constant to volumetric water content for the sand specimens. Equation [1], proposed by Topp *et al.* (1980), is superimposed on the present authors' data points. It may be seen that the curve described by [1] flattens out at low water contents, indicating a lack of agreement between the theoretical curve and the laboratory data. The data points fall below the curve at volumetric water contents less than about 8%.

Water content less than 8% by volume

Figure 4 shows the relation of thermal conductivity to volumetric water content for the sand specimens. It may be seen that thermal conductivity is highly dependent on volumetric water content below 8%. An empirical relation for volumetric water content and thermal conductivity for the sand data is

$$[6] \quad \theta_v = 0.365e^{1.47k}$$

Although an exponential relation is probably appropriate in most cases, the coefficients in [6] are valid only for the soil

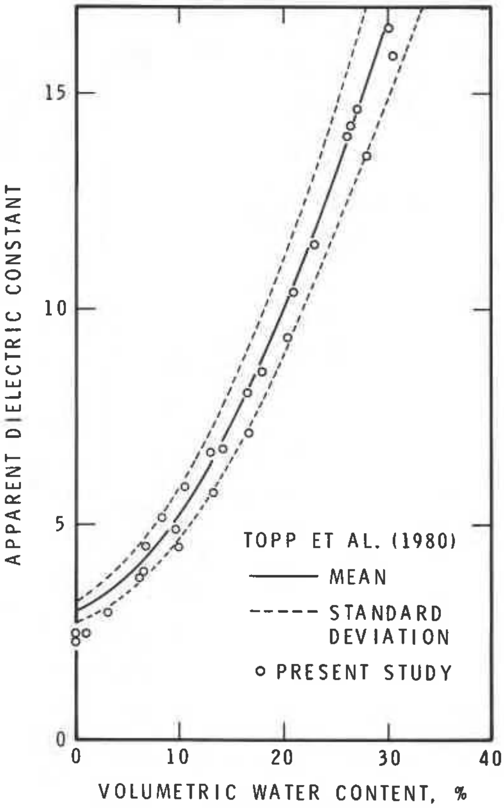

FIG. 3. Apparent dielectric constant of Ottawa sand versus volumetric water content; curves represent relation of Topp *et al.* (1980).

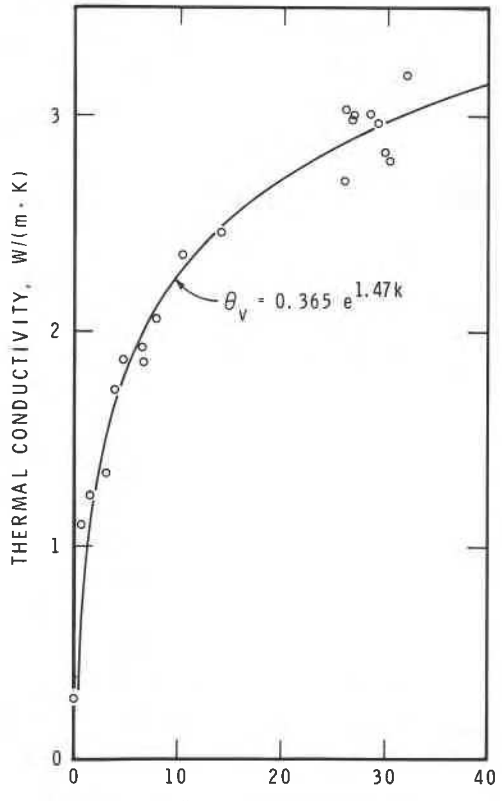

FIG. 4. Thermal conductivity of Ottawa sand versus volumetric water content.

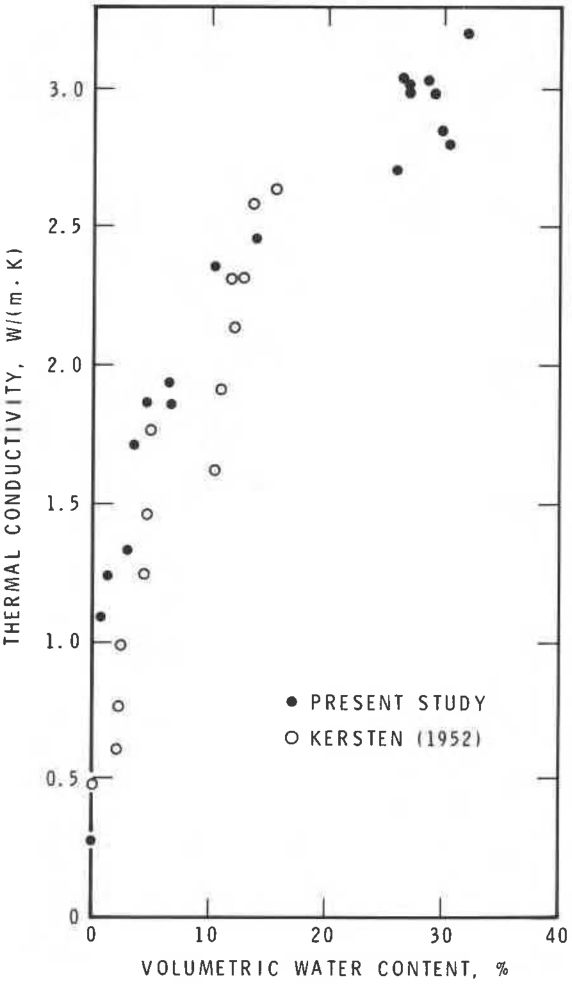

FIG. 5. Comparison with Kersten's data on thermal conductivity of sands.

used in this sequence of tests. Thermal conductivity depends also on soil type and density and on phase composition and concentration of dissolved salts. Figure 5 shows a comparison of thermal conductivity measurements for sandy materials with data published by Kersten (1952), who used a guarded hot plate method to measure the thermal conductivity of Fairbanks sand. This sand consisted of 60% quartz and 40% other minerals, whereas Ottawa sand is 100% quartz. In spite of the difference in material composition and test methods, the results of the present study are in reasonable accord with the Kersten data.

For very low water contents the thermal conductivity probe performed satisfactorily. For water contents between 8 and 25%, however, it was not possible to determine the thermal conductivity accurately since the temperature rise was not linearly proportional to the logarithm of time as expressed in [4]. This was thought to be due to moisture migration during the test as well as to nonuniform moisture distribution resulting from drainage within the sand sample. The power input to the heater coil was reduced, but the problem, though diminished, persisted. In one series of experiments clay was added to the sand in 10% proportion by weight (some of Kersten's (1952) sandy soils had up to 10% clay fraction by weight) in order to improve the contact resistance with the soil as well as its water retention characteristics, at the same time reducing the tendency for moisture migration under the imposed thermal gradients. This resulted in a slight improvement in the quality of the temperature response and permitted measurements to be extended to about 14% water content. Vapour transfer in unsaturated soils is a major problem in the measurement of thermal conductivity. The subject has been well reviewed by Farouki (1981).

Conclusions

This note is an extension of a previous paper (Baker and Goodrich 1984) emphasizing how the combined measurements of electromagnetic and thermal properties can be used to improve the determination of soil water content over the entire range from dry to full saturation.

Measurements of volumetric water content of soils using the time-domain reflectometry technique are most sensitive for the intermediate-to-high range of volumetric water contents. In field conditions, soil water content generally lies in this range and measurements can be made with an accuracy of about 2% by volume, with no need for calibration of individual soils.

Under some circumstances it is useful to be able to measure soil water contents at the low end of the moisture range. One such application would be in the measurement and control of the water content of moulding sand (green sand) used in foundries to cool metal castings. The volumetric water content of this sand must be controlled at about 1.5%. In such cases thermal conductivity might be a useful indicator. Complementing the time-domain reflectometry technique, this method becomes increasingly sensitive the lower the volumetric water content. A calibration curve is required, however, for use with a given soil type.

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