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Soil volumetric water content measurements using TDR technique

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Abstract
A physical model to measure some hydrological and thermal parameters in soils will to be set up. The vertical profiles of: volumetric water content, matric potential and temperature will be monitored in different soils. The volumetric soil water content is measured by means of the Time Domain Reflectometry (TDR) technique. The result of a test to determine experimentally the reproducibility of the volumetric water content measurements is reported together with the methodology and the results of the analysis of the TDR wave forms. The analysis is based on the calculation of the travel time of the TDR signal in the wave guide embedded in the soil.

Key words *TDR technique – soil moisture – hydrology*

1. Introduction

A physical model to measure some hydrological parameters is planned. The first idea was to drill a well inside the campus of the university deep enough to reach the water table (about 3 m) and with different types of soils facing each side of the well. The possibility of changing the soils investigated and the kind of measurements to be carried out was foreseen (Giudici *et al.*, 1991). The plan of the well was left because of the bad water quality found in repeated bacteriologic tests.

Nowadays the hydrological station in progress consists in two big containers made of plastic reinforced by fiber glass. Both containers have a 1.4 m diameter whereas the heights are 1.5 m and 2 m. Another two larger containers are foreseen in the same area. The 2 m height container (the first to be used) is going to be filled with homogeneous sand and the volumetric water content, matric potential and temperature are going to be measured each 30 cm depth. Furthermore the water table depth inside the container will be monitored and some useful meteorological measurements will be carried out in the area. All readings will be performed automatically at scheduled times.

The aim of the work in progress is to understand the mechanisms concerning both the infiltration of water and thermal diffusion in soils. The last process strongly depends on water content due to the dependence of thermal capacity and conductivity of soils on water content.

In this paper the measurement of the water content with electromagnetic waves (TDR) will be discussed.

To measure the vertical profile of the water content a TRASE SYSTEM of the Soilmoisture connected by means of a multiplexer to a set of buriable probes will be used. The trace of the microwaves signal travelling along the wave guide and its reflection at the end of the wave guide itself is called Time Domain Reflectometry trace or TDR trace. The methodology and the results of the analysis of the TDR trace, performed for different conditions, are reported.

Initially, a sandy soil of known granulometry will be considered in order to study simple situations.

Since the boundary effects present in an artificial system like the one described cannot be avoided, a test site to measure the same quantities was set up in a natural environment: the sandy beach near the Lido (Venice). At this second station, vertical temperature profiles and other meteorological measurements have been already collected for over a year (Pilan *et al.*, 1992).

2. Water content measurements

The measurements of apparent dielectric constants and volumetric water content of soils by means of the Time Domain Reflectometry technique are based on the evaluation of the speed by which a fast voltage pulse travels along a parallel transmission line inserted in the soil. The higher the dielectric constant of the material in contact with the transmission line, the slower is the speed of the voltage pulse (microwave). Because of the great difference among the dielectric constant of water and of the other constituents of a soil (air, mineral particle, etc.), the speed of travel of a voltage pulse in parallel transmission lines buried in a soil is essentially dependent on the volumetric water content of the soil (Topp *et al.*, 1980, 1988). By measuring the time required for the pulse to travel along a known length probe it is therefore possible to compute the dielectric constant of the soil from the relationship:

$$v = \frac{c}{\sqrt{K_a \mu}} \tag{2.1}$$

where:

– v is the velocity of the electromagnetic wave in the transmission line embedded in the soil;

– c is the velocity of the electromagnetic wave in the void;

– K_a is the apparent dielectric constant or relative permittivity of the soil;

– μ is the relative magnetic permeability of the soil.

As virtually all soils lack ferromagnetic materials, μ can be assumed equal to one. Therefore, using a probe of known length, the dielectric constant K_a can be obtained by means of a time measurement:

$$K_a = \left(\frac{c\Delta t}{\Delta L}\right)^2 \tag{2.2}$$

where:

– Δt is the time necessary to the signal to reach the end of the wave guide (travel time);

– ΔL is the probe length.

The travel time can be calculated by analyzing the TDR wave form.

The TDR wave form depends on both the type of the wave guide and the soil under investigation. In the TDR wave form the start time, at the beginning of the wave guide, and the reflection time, at the end of the wave guide, have to be clearly identified.

Finally, the soil water content θ can be measured knowing the function $\theta(K_a)$. Some slightly different polynomial relationships (Topp *et al.*, 1980; D'Urso, 1992; Heimovaara and de Water, 1993) or look-up table (*Soilmoisture*, 1990) can be used to compute $\theta(K_a)$. They give similar results but look-up tables have a wider volumetric water content range of application. However, considering particular soils and especially at low water content, the results may be quite different.

In the following, the procedure developed to calculate the travel time Δt to be used in (2.2) is described.

Initially the TRASE was tested by determining the reproducibility of the measurements experimentally. This was accomplished by measuring θ in a natural rural soil at a depth of about 25 cm over a long period (40 days in the period December 1991-January 1992). The probe (15 cm length) was installed horizontally and the measurements of θ were scheduled every thirty minutes (see fig. 1). During the first eighteen days the meteorological precipitations were practically absent: therefore no large fluctuations of the daily mean water content occurred (see the solid line in fig. 1). Afterwards a snow precipitation (2 cm) caused a rise in the water content followed by a slow trend towards the previous values. The linear regres-

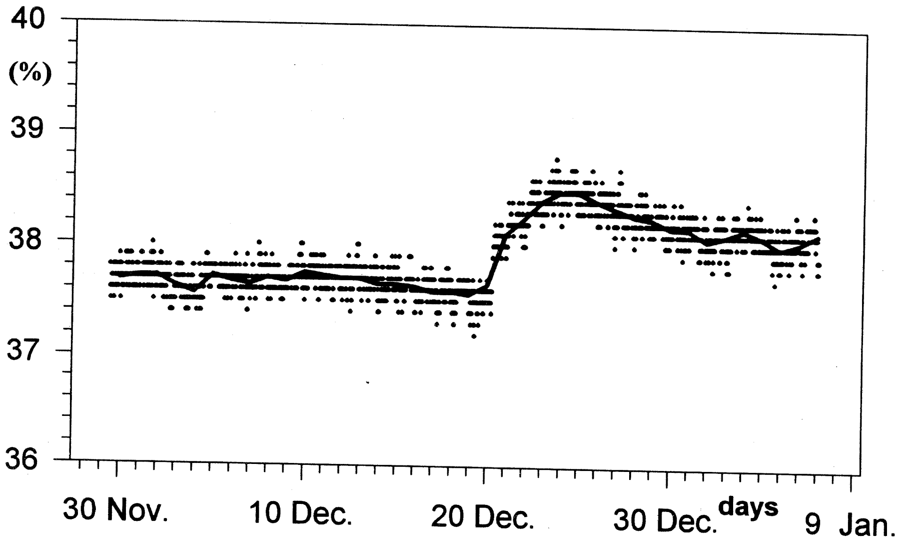

Fig. 1. Water content measurements (dots) taken every 30 min at 25 cm depth during the reproducibility test. The solid line is the daily mean value.

sion of the water content values of the first eighteen days gives a slope of $-3.4 \cdot 10^{-3}$%/day and an offset of 37.7%. The standard error of the linear regression is ± 0.1%; this value is similar to the standard error obtained by Heimovaara and Bouten (1990) during a ten day test. The error of the measurement depends on the water content value, the kind of probe used, the temporal variation of the soil condition etc. but the reproducibility of the measurement in the considered case is very good.

Soil volumetric water content can be measured by different length and different shape probes. The TRASE SYSTEM of Soilmoisture is delivered with a standard two rod connector probe (15 cm length). Inside the connector there is an impedence matching balun. A new kind of probe with three rods (20 cm length), called buriable probe, allows an acceptable impedence without balun. The outer conductor of the coaxial cable is connected to the two lateral rods while the inner conductor is connected to the central rod. These two probes give differences in TDR traces, mainly in the first part of the trace.

Figure 2a,b shows the different shapes of the TDR wave forms according to the probe (connector or buriable) and the attenuation of the signal due to a 20 m long cable. Figure 2a shows the typical TDR wave form obtained using the standard connector probe embedded in a meadow.

A specific procedure to perform the analysis of the TDR wave form has been developed. The main results of the procedure are the starting time (*i.e.* the time at which the electric pulse starts its travel along the probe) and the time at the reflection point (*i.e.* the reflection of the pulse at the end of the probe). The difference between the reflection time and the starting time gives the travel time. The soil dielectric constant (from eq. 2.2) and then the soil water content can be calculated using literature relationships or look-up tables. The following summarizes the analysis procedure:

1) determination of the minimum of the TDR wave form before the reflection point; in fig. 2a it is the absolute minimum of the curve, while in fig. 2b it is the second minimum, just before the definitive rise corresponding to the reflection of the signal;

2) expansion in Fourier series of the part of the curve on the left of the previously determined minimum together with its specular im-

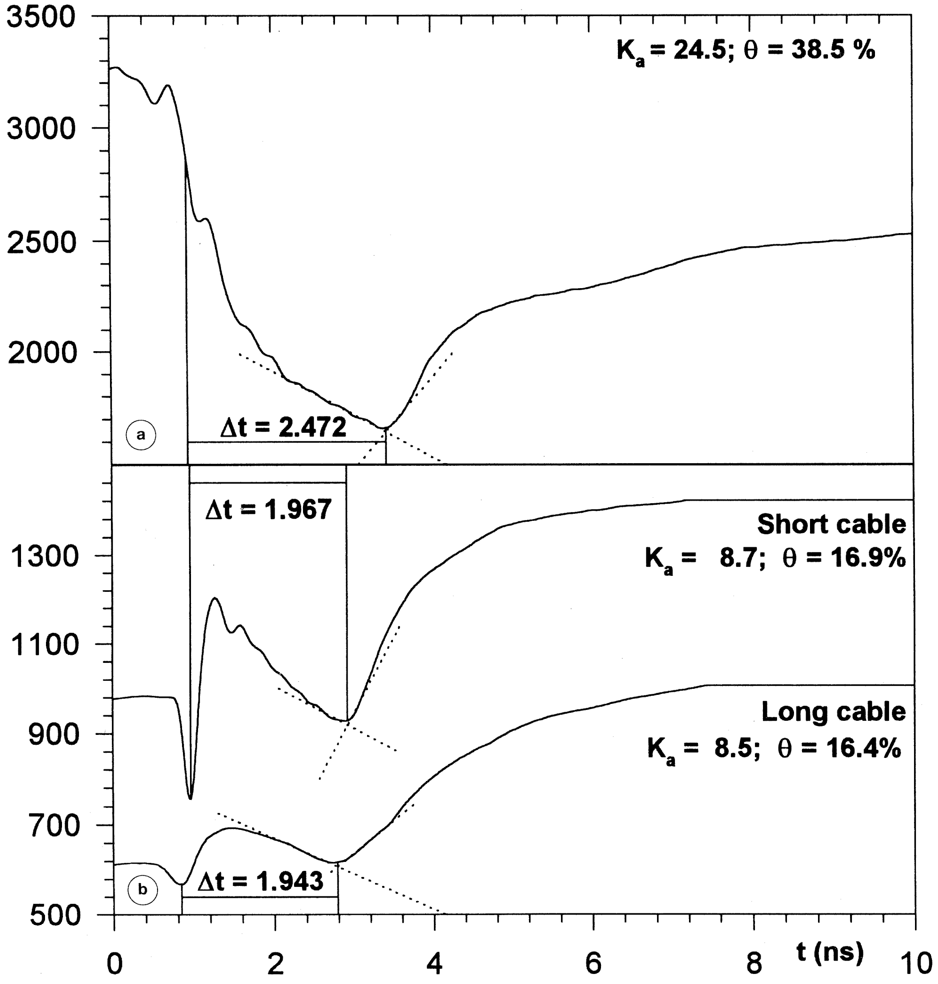

Fig. 2a,b. TDR traces obtained by means of different probes. The units of the y axis are instrumental units. Δt is the travel time obtained by means of the procedure described in the text; K_a is the soil dielectric constant and θ is the volumetric water content. (a) Shows the typical wave form of the connector probe (15 cm length). The upper and lower curves of (b) show the same measurement taken with the buriable probe (20 cm length) with (lower curve) and without (upper curve) a 20 m long cable; the attenuation of the signal is evident. The measurements in (a) and (b) were carried out in the same soil in different periods of the year.

age, to overcome the non periodicity of the TDR signal and have a continuous derivative function. The same was done for the right part of the curve;

3) computation of the derivatives of the two functions obtained by the previously quoted Fourier analysis; the use of the Fourier expansion allows the derivative function to be computed analytically overcoming the *noise* of the data;

4) determination of the steepest inflection points on the left and on the right of the minimum, found at the first step, by using the derivatives. The abscissa of the inflection point

on the left of the minimum is the sought for starting time for the connector probe wave form (fig. 2a). For the buriable probe the starting time corresponds to a *V* deep mark at the beginning of the trace due to the absence of the balun adapter (fig. 2b);

5) determination of the regression lines fitting:

a) a suitable part of the curve between the minimum and the inflection point on the right of the minimum itself;

b) a suitable part of the curve on the left of the minimum;

the abscissa of the point of intersection between the two regression lines is the searched for reflection time.

The difference between the two computed time values (starting time and reflection time) is the travel time Δt (see fig. 2a).

The described procedure can be used in automatic mode only when routine measurements have to be carried out. Non routine measurements need an interactive approach because of the criteria used in the linear regressions.

Table I reports $\theta(K_a)$ according to the previously quoted relationships for the measurements shown in fig. 2a,b. $\theta(K_a)$ values in fig. 2a,b are reported in the first column of table I; they were obtained interpolating the TRASE look-up table by a third degree polynomial relationship.

Measurements of the water content in activated sludge (extremely high water content) were used to verify the procedure. The mean volumetric water content (8 measurements) resulting from the procedure was 82.4%. The mass water content, obtained by weighting the sample before and after oven drying at 105°C, was lower (about 80%) as expected since the mud density was slightly greater than 1 g/cm^3.

Table I. Volumetric water content (%) obtained from $\theta(K_a)$ relationships of the quoted authors for the experimental measurements of fig. 2a,b.

	Look-up table	Topp	D'Urso	Heimovaara
K_a	$\theta(K_a)$	$\theta(K_a)$	$\theta(K_a)$	$\theta(K_a)$
24.5	38.5	39.5	41.3	37.5
8.7	16.9	16.2	18.0	16.9
8.5	16.4	15.8	17.6	16.5

3. Conclusions

The TDR technique is easy to use; it allows fast, non destructive, *in situ* measurements and real time monitoring of the water content in different dielectrics (*e.g.*, agriculture soil, activated sludge, etc.).

The described procedure for the TDR trace analysis can be used both in an automated and interactive way. The automated way is used when routine measurements in a known dielectric are performed. The interactive way can be used to improve the results when unknown or complex dielectrics have to be investigated. Finally the TDR trace allows a qualitative study of the moisture of the soil layer along its depth.

Soil water content measurements may be very useful to study soil thermal budget (Pugnaghi and Vincenzi, 1991). Soil thermal parameters change both in time and depth as they depend on the volumetric water content (Monteith, 1973; de Vries, 1975). Finally soil temperature profiles can help in monitoring shallow aquifers (Larson and Hsui, 1992; Taniguchi, 1993).

Further, soil moisture measurements can be used in the modelling and parameterization of the soil surface properties and processes to determine the heat and moisture exchanges among soil, vegetation and atmosphere (SVAT). The correct assessment of SVAT processes is a key aspect for numerical prediction of rain intensity and for the understanding of the hydrological cycle as a whole.

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