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"Open Ended Coaxial Probe for Soil Moisture Measurements"

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OPEN ENDED COAXIAL PROBE FOR SOIL MOISTURE MEASUREMENTS

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ABSTRACT

The interaction between an open ended coaxial line and a porous moisted medium is investigated. The phase of the reflection factor, function of the water content of the material, has been theoretically evaluated and experimentally measured at 3 GHz. The moisture content, measured with the standard gravimetric method, has been found in fairly good agreement with theory.

1 INTRODUCTION

The knowledge of the water content of the soil surface layers is very important in agriculture, hydrology and meteorology; indeed, the interaction between soil surface and atmosphere is responsible for the evapotranspiration phenomenon.

Water content evaluation can be carried out with remote sensors, either of passive or active type; alternatively, local sensor (in situ) can be used /1/. The main limitation of remote sensing is due to the penetration depth; that cannot be greater than 5-10 cm. Therefore, in situ sensors are necessary when the water content of deeper layers has to be measured.

Local monitoring and control of moisture content, possibly in real time, has a large interest in other topics too. They can deal with basic and applied research and with industrial applications (e.g. drying processes of materials).

In this work a general method is presented for water content measurement of porous media which is based on the use of an open ended coaxial line operating at microwave frequencies /2-4/. This type of in situ sensor seems to be very simple and easily adaptable to different situations; further on, it can be employed for real time measurements on materials of various compositions and structures.

2 THEORETICAL INVESTIGATION

A sketch of the probe operating in the porous medium is presented in figure 1. An extensive use of the coaxial line in the above mentioned fields requires an accurate and general enough modelling in order to:

i) optimize the dimensions of the coaxial line for the specific use;
ii) simplify the calibration procedure.

For this purpose a numerical model of the system has been developed, (fig. 2), on the basis of the physical properties of the porous medium and the coaxial line characteristics.

Porus medium modelling

Three phases, solid grain, air and water, are generally present in a moisted soil, as sketched in fig. 3.

The electromagnetic behaviour of the material can be described by a relation between the real part of the complex permittivity, ε', and the volumetric water content, Wc. Figure 4 depicts the variation of ε' with Wc for three different soils. For each medium it can be observed a weak increase of ε' up to a transition water content, W_t; then, for higher Wc, the slope of the curve increases sharply up to saturation. A large number of experimental results, carried out on soils of different types, has shown a similar electromagnetic behavio r, as evidenced by fig. 4.

Several formulas have been proposed in the literature /5/ for the evaluation of the electromagnetic properties of two phases media. The knowledge of the permittivities and of the volumetric fractions of each component is necessary.

The above mentioned formulas do not agree with the experiments at low water contents, i.e. when the water is bound to the solid grain. Therefore, at very low moisture levels the water is not free and its dielectric properties are similar to those of ice.

An empirical model, /6/, proposed to evaluate the complex permittivity of soils, gives a good agreement to the experimental data for the whole range of water content. According to this model, the permittivity of the soil water medium is given by:

$\varepsilon = Wc\,\varepsilon_x + (P - Wc)\varepsilon_a + (1-P)\varepsilon_r$

with $\varepsilon_x = \varepsilon_i + (\varepsilon_w - \varepsilon_i)\, Wc\, \gamma / W_t$

for $Wc < W_t$; while, for $Wc > W_t$,

$\varepsilon = W_t\,\varepsilon_x + (Wc - W_t)\varepsilon_w + (P - Wc)\varepsilon_a + (1 - P)\varepsilon_r$

with $\varepsilon_x = \varepsilon_i + (\varepsilon_w - \varepsilon_i)\gamma$.

The permittivities of air, water, solid and bound water (ice) are respectively $\varepsilon_a, \varepsilon_w, \varepsilon_r, \varepsilon_i$; Wc is the volumetric and W_t the transition water content , P is the porosity, defined by:

$P = V_v/V_t = 1 - d_d/d_r$

where V_v and V_t are respectively the void and total volumes, d_d and d_r are the dry and solid densities and γ is an empirical constant. Each type of soil requires the evaluation of W_t, γ /6/ and porosity P. The influence of the temperature on the model is considered in the permittivities of the constituents.

Theoretical analysis of the coaxial line

The theoretical analysis of the interaction between the probe and the medium has been carried out with the following hypotheses:

i) no losses are present in the homogeneous dielectric filling the line;

ii) an infinite flat metallic flange is supposed to be placed at the aperture of the line;

iii) the material under investigation, homogeneous, isotropic, linear, nonmagnetic, fills completely the right hand half space.

Dimensions and frequency of operation have been chosen in order to allow the propagation of only the TEM dominant mode. The opening in front of the medium has been replaced by a perfect conducting wall having an equivalent distribution of magnetic surface current (fig. 5).

The solution to the problem can be performed with a continuity assumption on the azimutal component of the magnetic field at z=0,

$H_\theta\,(r, z=0^-) = H_\theta\,(r, z=0^+)$ a<r<b.

As far as the field distribution in the aperture plane (z=o) is concerned, the contribution of the infinite higher order modes is taken into account. The modes can only be TM_{0n} because of the axial symmetry of the line.

The numerical solution of the problem needs a truncation of the infinite serie of modes /4, 7/; therefore, the continuity condition is satisfied only on the N circles in the aperture (point matching).

3 RESULTS

Theoretical results

The theoretical model of fig. 2 has been employed to evaluate the modulus and the phase of the reflection factor as a function of the water content.

The physical properties of two typical porous media are reported in table I, togheter with the parameter γ.

In order to study the influence of the temperature and of the ionic content of the water, the following cases have been considered:

a. Medium 1 at T=25°C;
b. " 1 at T=65°C;
c. " 2 at T=25°C;
d. " 2 at T=65°C;
e. " 1 at T=25°C with NaCl water solution of molality 0.1.

The permittivities of the components have been assumed as follows:

bound water : ε' = 3.2 , ε'' = 0.1;
solid grain : ε' = 5.5 , ε'' = 0.2;
water, 25°C, : ε' = 76.7 , ε'' = 12.04;
water, 65°C, : ε' = 64 , ε'' = 48.9;
NaCl water solution of molality 0.1, 25°C : ε' = 75.5 , ε'' = 18.12.

A commercial semirigid cable, with internal diameter Di=1.628 mm and external diameter De=5.283 mm, has been used. The permittivity of the filling material, teflon, is ε_c=2.1.

The modulus and phase of the reflection factor are presented in figures 6 and 7. It is evident the influence of the temperature, caused by the variation of the permittivity of free water. The modulus (fig. 6) is strongly influenced by the ionic content while the phase (fig. 7) is almost independent from it. On the other side, the variation of the phase with the water content is much steeper. The main conclusion of the present theoretical model is the convenience to use the phase of the reflection factor as the measurement parameter.

Experimental results

Some preliminary experimental tests were carried out with a coaxial cable, 8cm long, inserted in the porous medium inside an apposite container, as pictured in fig. 8. The reflection factor measurements were done with a HP 8410 network analyzer, at the frequency of 3 GHz. The water content of the porous medium was measured by the gravimetric method.

The material tested in the experiments was sand with dry and solid densities, respectively d_d=1.66 g/cm^3 and d_r=2.68 g/cm^3, and a porosity, P=0.38, similar to that of medium 1 of table I.

The probe was calibrated setting a zero phase value for the porous material saturated with water. The specimen was dried in the oven from the saturation point. At regular time intervals the container and the probe were wheighted with a precision balance and the phase of the reflection factor measured.

Fig. 9 reports the experimental results, ranging from saturation to dryness, as dots connected by a dashed line. The agreement with the theoretical predictions is considered good enough. The existing discrepancies are considered due to:

- not exact knowledge of some parameters (e.g. empirical γ, ionic content);
- absence of the flange at the aperture of the probe.

The second cause of error can be more easily evaluated with measurements on standard materials of known characteristics /8/.

4 CONCLUSIONS

The preliminary experimental results seem to confirm the reliability of the theoretical model presented for the probe-porous medium system, which is generally applicable without limitations on the cable dimensions and the working frequency. The model can be used as an efficient method for calibration purposes and it allows also the evaluation of the influence of some parameters (e.g. temperature, ionic content of water), which could be responsible for measurement errors. Finally, some uncertainties resulting from the not exact identification of the porous medium could be estimated.

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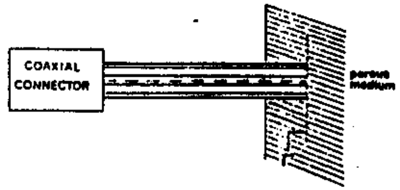

Fig. 1 : Sketch of the probe

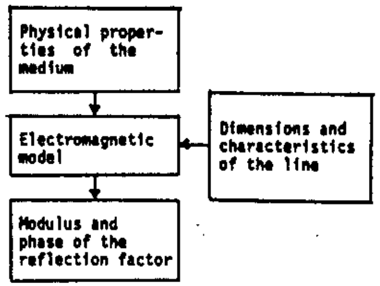

Fig. 2 : Porous medium - probe theoretical model

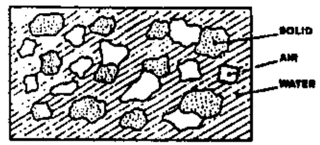

Fig. 3 : Three phases porous medium

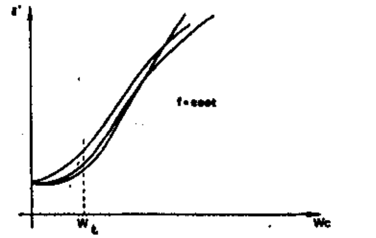

Fig. 4 : Typical behaviour of the permittivity of three soils as a function of the volumetric water content

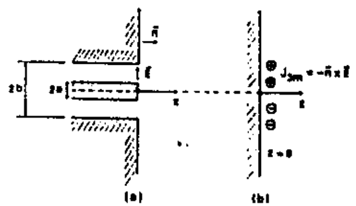

Fig. 5 : a) Aperture in conducting plane
b) Equivalent source

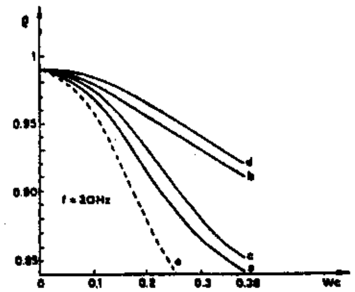

Fig. 6 : Modulus of the reflection factor versus water content. For the explanation of the five cases see the text under the subheading "theoretical results"

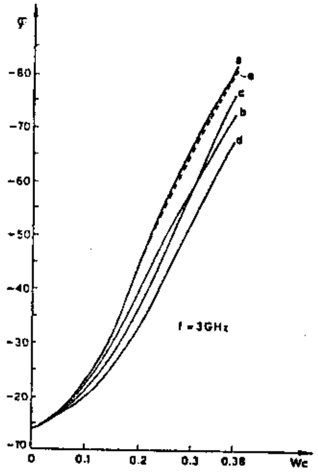

Fig. 7 : Phase of the reflection factor versus water content.
For the five cases see caption of fig.6

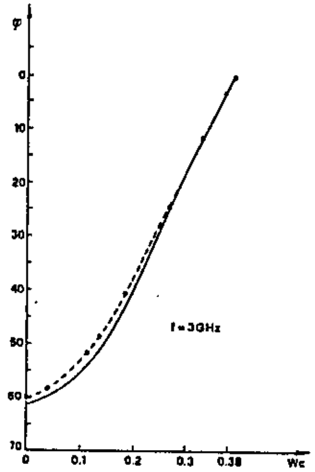

Fig. 9 : Experimental results compared with theoretical ones of case b.

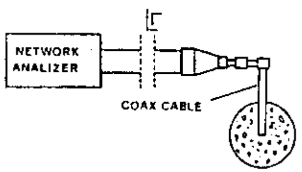

Fig. 8 : Measurement set-up

	Medium 1	Medium 2
Composition (in weight)	Sand + water	Sand 88%, silt 7,3%, clay 4,7% + water
Transition water content, W_t	0.17	0.20
Porosity, P	0.38	0.38
Empirical parameter, γ	0.5	0.4

TABLE I