Mathematical & Computational Applications, Vol. 8, No. 3, pp. 303-310, 2003
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A DIFFERENT METHOD DETERMINING DIELECTRIC CONSTANT OF SOIL AND ITS FDTD SIMULATION

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Abstract- In this study, a different method determining the dielectric constant of soil via probes is presented. The method is based on the principle of measuring pulse delay in a given matter. The experimental study, which was carried out basically using an HP8753A vector network analyser, was repeated for various soil mixtures having different values of wetness. The results obtained from the measurements have clearly shown that the dielectric constant of the soil was increasing almost proportionally with that of the moisture content in the soil. The suitability of the measuring method was also checked with a number of simulation results obtained directly using the finite difference time domain method (FDTD).

Keywords- Dielectric constant measurement, pulse delay, FDTD, simulation.

1. INTRODUCTION

The dielectric constant is defined as the relative permittivity of a given material. Since the dielectric constant is a parameter determining the electrical behaviour of the materials, it is often used in RF and microwave frequencies connected with most engineering applications, the physics and geophysics, etc.

The velocity of electromagnetic wave (EMW) is closely related with the dielectric constant of the medium in which it propagates. A lot of researches have been carried out so far concerning the dielectric constant of the soil and the results shown that the electromagnetic radiation was both delayed and attenuated in soil, depending on the frequency and the moisture rate in the soil. While the relative dielectric constant of water was found to be about 80 in lower microwave frequencies, the measured values of relative dielectric constant for different soil compositions are reported to vary between 4-40. In general, the dielectric constant of soil-water mixture is a function of temperature, frequency, geometric shape of the soil particles and the salt and moisture contents of the soil [1].

The importance of the knowledge about the dielectric constant is required especially for the radar applications. The dielectric constant is one of the most important factors that affect the special radar system's (GPR) performance used to specify the location and nature of the buried objects in a given medium (soil or others). Information of dielectric constant of working environment generally gives a clear clue in the selection of GPR systems as well as the correct evaluation and interpretation of the data obtained from the GPR. Thus, the GPR system needs to be calibrated carefully before the investigations owing to the varying nature of the soil compositions [2].

A few different measuring methods such as slotted line, waveguide, wave scattering and pulse delay techniques play an important part in the evaluation of dielectric constant in practice. The capacity measuring techniques are also commonly used to verify the dielectric constants. Because of its frequency band speciality as well as its quickness in measurements, the pulse delay technique is rather preferred compared with other measuring techniques [3,4]. In the literature, some simulations involving FDTD method was also used to determine the dielectric constant of a given material [5]. The two important features of the measuring technique proposed in this work may be summarised as follows: 1) For the GPR applications the frequency range was taken between 100MHz and 1500MHz. 2) The soil samples assumed to be non-ferromagnetic low loss materials gave results fitting well with the verified ones.

2. VELOCITY OF EMW IN A GIVEN DIELECTRIC MEDIUM

In general, we can express complex dielectric constant in a given medium as,

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

here, ε' is the relative permittivity of the materials and ε'' is the dielectric loss which depends upon the conductivity and frequency. If the dielectric constant and specific conductivity of a given material are ε_e and σ_e respectively, then using the Maxwell equations containing $rot\vec{\mathrm{H}}$, we can express;

$$rot\vec{\mathrm{H}} = j\omega\varepsilon_e\vec{\mathrm{E}} + \sigma_e\vec{\mathrm{E}} \tag{2}$$

or

$$rot\vec{\mathrm{H}} = j\omega\left[\left(\varepsilon_e' - j\varepsilon_e''\right) - j\frac{\sigma_e}{\omega}\right]\vec{\mathrm{E}}$$

or

$$rot\vec{\mathrm{H}} = j\omega\left[\varepsilon_e' - j\left(\varepsilon_e'' + \frac{\sigma_e}{\omega}\right)\right]\vec{\mathrm{E}}. \tag{3}$$

The right hand side of equation (3) shows that imaginary part ε_e'' and specific conductivity σ_e affect the loss tangent of the material. Thus, the real and imaginary components of complex dielectric constant can be rewritten as;

$$\varepsilon' = \varepsilon_e'$$

and

$$\varepsilon'' = \varepsilon_e'' + \frac{\sigma_e}{\omega}. \tag{5}$$

The imaginary part (ε'') of the dielectric constant is closely related with the dielectric loss. In practice, the effect of parameter ε'' is small enough and can be neglected for certain soil mixtures, having conductivities lower than 10 mS/m. Thus, the real component of equation (5) will represent only the dielectric constant in this case ($\varepsilon = \varepsilon'$). Also, relative magnetic permeability μ_r for most sedimentary soils in GPR applications (typical frequency band of 25-1500 MHz) is accepted to be unity [6].

On the other hand, the velocity of electromagnetic wave propagating in any given medium is generally calculated from the following equation:

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \tag{6}$$

Here, c is the velocity of light, ε_r is the relative dielectric constant and μ_r is the relative magnetic permeability [3,7].

3. THE MEASUREMENT OF PULSE TRANSMISSION DELAY

Since equation (6) is valid for electromagnetic waves propagating in any given medium, the dielectric constant for that medium can be determined by measuring the transmission delay of the wave. For the measurements a suitable network analyser and two specially selected coaxial type probes are used in the bench (Fig. 1).

Initially a Gaussian pulse generated by the network analyser is sent into the soil sample via one probe and it is received from the other probe as shown in Fig. 1. The dielectric constant of the test soil will directly be verified by comparing the pulse delay time in soil and in air. Holding the two coaxial probes in the air l distance apart and then measuring the pulse delay t_a, the velocity of the electromagnetic wave c can easily be related to l and t_a as follows;

$$c = \frac{l}{t_a} \tag{7}$$

Here, t_a represents the pulse delay time in the air as mentioned above.

Similarly, if the probes are placed in a given soil-sample, again keeping the distance l constant and the measurements are repeated, the velocity then will be;

$$v_s = \frac{l}{t_s} \tag{8}$$

Here, v_s and t_s represent the velocity of electromagnetic wave and pulse delay time respectively in a given soil mixture.

Now, dividing equations (7) and (8) side by side, we get;

$$\frac{c}{v_s} = \frac{t_s}{t_a} \tag{9}$$

But, we also know that $v_s = c/\sqrt{\varepsilon_s \mu_s}$, thus equation (9) can now be rearranged as follows;

$$\varepsilon_s = \left(\frac{t_s}{t_a}\right)^2 \varepsilon_a \tag{10}$$

or

$$\varepsilon_s = \left(\frac{t_s}{t_a}\right)^2 \tag{11}$$

where ε_s and μ_s parameters represent the relative dielectric constant and the relative magnetic permeability respectively in given soil mixture. $\varepsilon_a = 1$ and $\mu_a = 1$ represent the relative dielectric constant and the relative magnetic permeability respectively in the air. The value of relative magnetic permeability for certain soil compositions is also assumed to be μ_s=1 as reported in the literature [6].

Assuming now the distance l between the two probes are variable, the relative dielectric constant ε_s can be calculated in this case in terms of pulse delay t_s (by remembering $t_a = l/c$) as follows;

$$\varepsilon_s = \left(c \frac{t_s}{l} \right)^2 \qquad (12)$$

Here again, relative magnetic permeability μ_s=1 is assumed [6].

3.1. The experimental set up

The block diagram of the simple measuring set up is drawn schematically in Fig. 1. The most important component of the test bench is a precision time domain network analyser (HP8753A). The two open-ended coaxial type probes are employed as the transmitting and receiving antennas in the set up. The open ends of the transmitting and receiving probes are immersed into the test soil as indicated in Fig.1. The simplicity of the measuring set up enabling to get the reliable results in short time may be regarded as the main advantage of the proposed method.

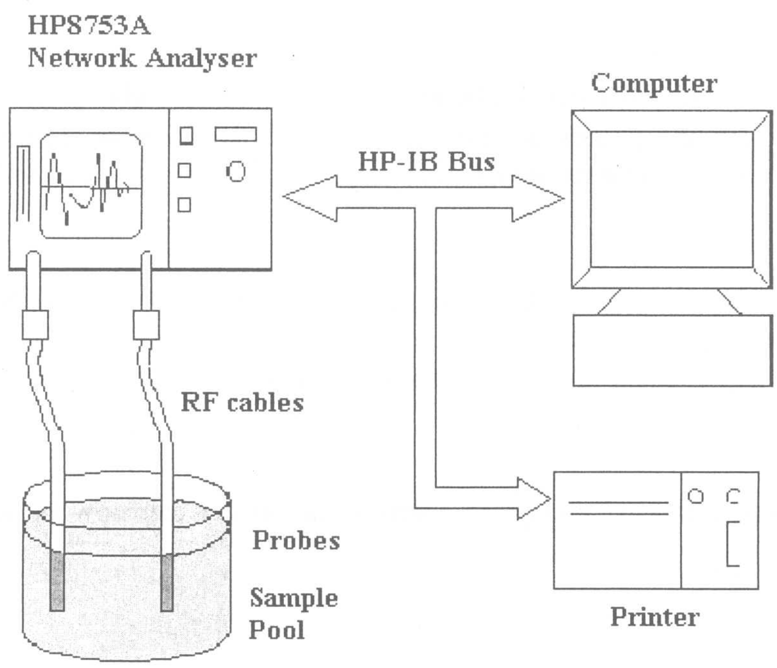

Fig. 1. The block diagram of the experimental set up for measurement.

3.2. The experimental results

To prepare the wet soil sample, a given soil composition was initially dried at 110°C for 24 hours continuously and then certain amount of water was added in the dry soil. To get a homogenous composition, the wet soil was then left to rest for about 1 hour. The basic properties of the wet soil samples are reported elsewhere [8]. Using the soil so prepared, the network analyser was operated in time domain mode over a frequency range of 100-1500 MHz and the transmission delay of the pulse was measured.

The dielectric constant for the sample was calculated according to equations (11) and (12). Similar measurements were undertaken for different wet soil samples and the related dielectric constants are obtained. Table 1 lists the calculated values of the dielectric constants of five different wet soil samples. Fig. 2 represents the characteristic curves of these five different wet soil samples in question.

Table 1. The resultant values of relative dielectric constant from calculation.

Water	The relative dielectric constant of soil samples				
W_w[kg]	Sample1	Sample2	Sample3	Sample4	Sample5
0,000	2,90	2,76	2,33	4,98	3,24
0,220	3,75	3,90	4,63	9,80	11,31
0,330	5,06	6,57	7,29	15,07	16,93
0,440	7,29	10,81	8,85	27,60	31,08
0,550	9,92	17,03	21,67	35,41	39,83

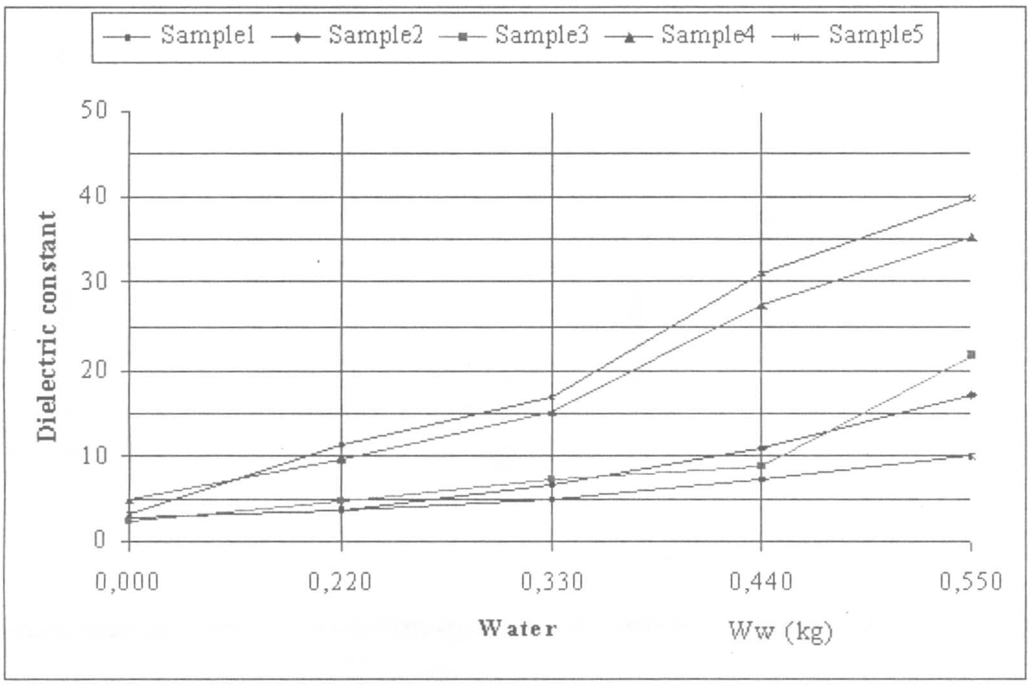

Fig. 2. The change of dielectric constant of different wet soil samplesas a function of the amount of water added.

4. FDTD SIMULATION OF PULSE DELAY

To verify the correctness of the measured results given above (Section 3.2), some simulation works are also undertaken by employing the well known FDTD method [9]. For the simulations, the parameters selected are as follows;

Analysis region: (y,z)=[-5,5]*[-5,5],

Observation time: T=10,

Time step: Δt =0.01.

The pulse source located at (y,z) =(-3,-1.5) as;

$F=\chi(-3-y)*\chi(3.1+y)*\chi(-1-z)*\chi(2+z)*\chi(0.2-t)*20$

The calculations are prepared for four different values of the relative dielectric constants namely 1, 2, 4 and 5 as specified below;

$\varepsilon=1$,
$\varepsilon=1+\chi(5-y)*\chi(y+5)*\chi(-z)*\chi(5+z) \leq 2$,
$\varepsilon=1+3*\chi(5-y)*\chi(y+5)*\chi(-z)*\chi(5+z) \leq 4$

and

$\varepsilon=1+4*\chi(5-y)*\chi(y+5)*\chi(-z)*\chi(5+z) \leq 5$.

Here, $\chi(.)$ is Heaviside step function.

The propagation of pulse in different medium and in different observation times are shown in Fig. 3 and Fig. 4. Fig. 5 shows the pulse wave at a certain location in different medium while l is kept constant. According to the pulse delays (in relative time) in Fig. 5, the dielectric constants obtained from equation (11) are listed in Table 2.

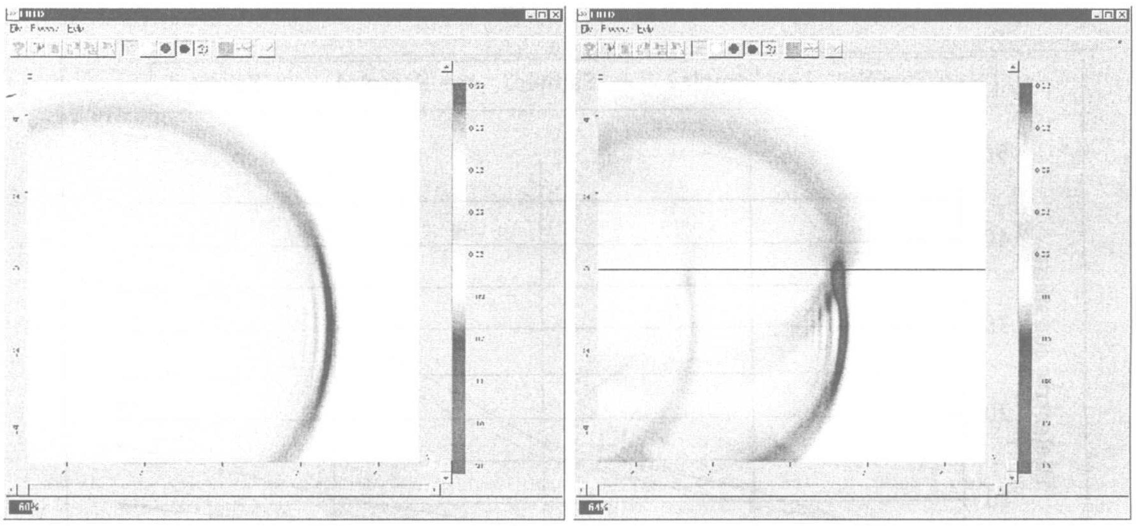

Fig. 3. The pulse wave for $\varepsilon=1$, t=0.60T (left) and $\varepsilon=2$, t=0.64T (right).

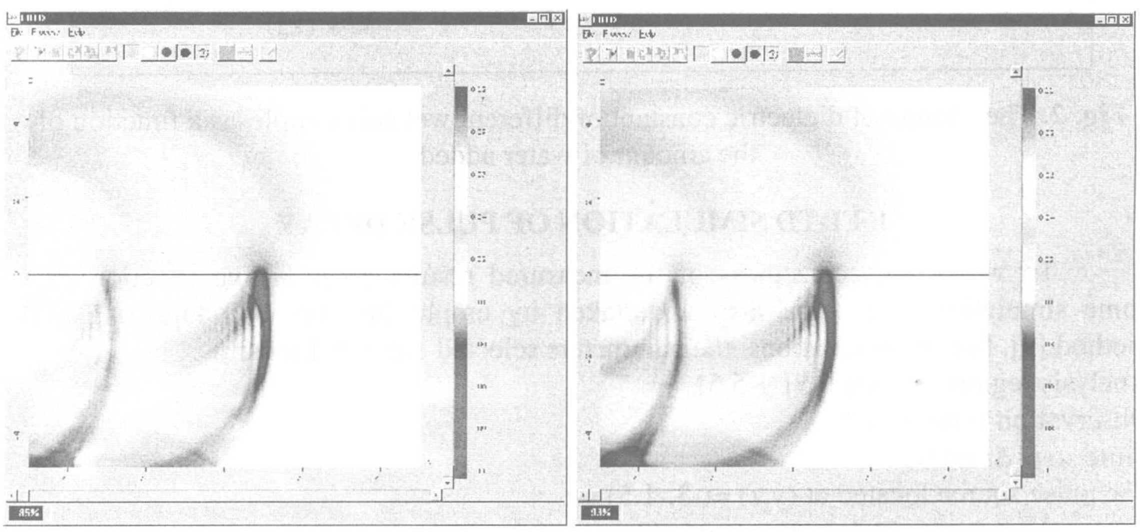

Fig. 4. The pulse wave for $\varepsilon=4$, t=0.85T (left) and for $\varepsilon=5$, t=0.93T (right).

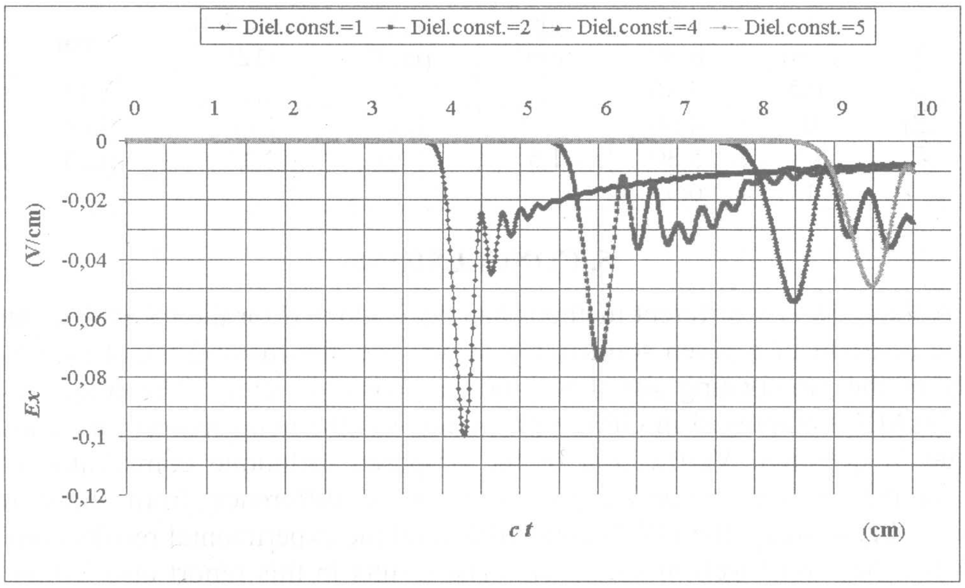

Fig. 5. The pulse wave at location (y,z)=(1,-1.5) in different medium.

Table 2. The dielectric constants related with Fig. 5 and equation (11).

ε	**ct_h [cm]**	**ct_t [cm]**	**Equation (11)**	**Error**
1	4,29	4,29	1,00	0,00
2	4,29	6,05	1,99	-0,01
4	4,29	8,51	3,93	-0,07
5	4,29	9,51	4,91	-0,09

Fig.6 shows the similar characteristic curves to that of Fig. 5. In this case, while l is varying, ε is kept constant. For the calculations in this case, equation (12) is used and the results obtained are tabulated in Table 3.

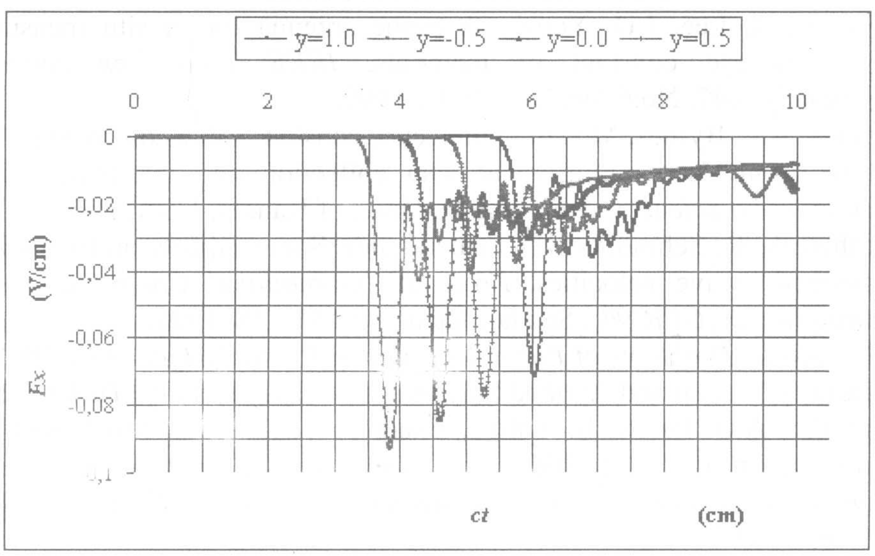

Fig. 6. The pulse wave at location (y,-1.5) for ε=2.

Table 3. The dielectric constants related with Fig. 6 and equation (12).

	y [cm]	*ct* [cm]	Δy [cm]	$c\Delta t$ [cm]	**Equation (12)**	**Error**
Diel.cons.=2	-0,5	3,86	0,5	0,73	2,13	0,13
	0	4,60	1	1,45	2,09	0,09
	0,5	5,30	1,5	2,19	2,13	0,13
	1	6,05				

5. CONCLUSIONS

Although a few different methods had been adopted for the measurements of the dielectric constant of a given soil sample in practice, the method based on time delay property of the propagating signal was preferred in this study. The frequency range (100-1500 MHz) employed in GPR applications was the main reason for choosing the technique in question. Verification of the proposed technique comprising a special FDTD simulation was suspected to be the basic difference from those reported previously. In the study, the FDTD simulations and the experimental results both clearly proved that they were well in agreement. The results in this report also exhibited that the dielectric constant increases almost proportionally with that of the moisture content in the wet soil (Fig. 2).

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