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Dielectric parameters of dry and wet soils at 14.89 GHz

Anirbid Ghosh, Jitendra Behari & Supriyo Pyne

School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110 067

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Dielectric parameters of a number of samples distributed over a wide geographic range of Indian soils have been measured at 14.89 GHz. A waveguide method involving a two-point solution of a transcendental equation, found to be successful for low and medium loss dielectrics, has been adopted for measurement on dry and wet soil samples. The method can also be applied for other frequency ranges and in the estimation of soil moistures.

1 Introduction

In microwave remote sensing of soil moisture, both active (scattering coefficient) and passive (emissivity), the most important parameter is the dielectric constant of soils[1]. Various percentages of soil-water mixtures give rise to a large dielectric constant variation (between 3 and 20 or more). Hence a thorough knowledge of dielectric properties of different types of soils is necessary for efficient use of microwave remote sensing technique for soil-moisture estimations.

In the present work, dielectric permittivity (both real part and imaginary part) of soil samples, collected from different regions of India, have been measured at various moisture contents at 14.89 GHz. The measurements were carried out by the waveguide method, involving a two-point solution of a transcendental equation. Effects of soil textures on such measurements, if any, have also been examined.

2 Materials and methods

The two-point method is a technique involving measurement of reflection coefficient in a waveguide. This method is suitable for low and medium loss dielectrics and is at present adopted for measurement of soil complex permittivity at different moisture contents.

A set up for measurement, as shown in Fig.1, has an empty short-circuited waveguide with a probe located at a voltage minimum D_R. The same waveguide, containing a sample length l_ε, has the probe located at a new voltage minimum D.

The transcendental equation obtained by impedance matching and adopting simplifications can be written as [2]

$$\frac{\tan \kappa (D_R - D - l_\varepsilon)}{\kappa l_\varepsilon} = \frac{\tan \kappa_\varepsilon l_\varepsilon}{\kappa_\varepsilon l_\varepsilon} \qquad \ldots (1)$$

where $\kappa (= 2\pi / \lambda_g$, λ_g being the guide wavelength) is the propagation constant.

All the measured quantities are contained in the left hand side of Eq. (1), while the right hand side is in the form (tan A)/A. Once the measurements have been performed, the complex number, $A = \kappa_\varepsilon l_\varepsilon$, can be found by the solution of the transcendental equation and from it we can calculate κ_ε. The relative permittivity ε_r follows directly from the relationship,

$$\kappa_\varepsilon = 2\,\pi / \lambda\, [\, \varepsilon_r \mu_r - (\lambda / \lambda_c)^2]^{1/2} \qquad \ldots (2)$$

where μ_r is the permeability of the medium, and λ_c the cut-off wavelength.

Considering the fact that the tangent function is periodic in nature, there exists an infinite number of solutions for Eq. (1). Therefore, it becomes necessary to perform a second identical experiment with a sample of different length $l_{2\varepsilon}$. The proper solution will then be the one common to the two sets of solutions. We thus get an "intersection point" (defined by x and θ) for the particular case[2].

The calculation of complex dielectric constant involves the computation of the phase constant (Φ)

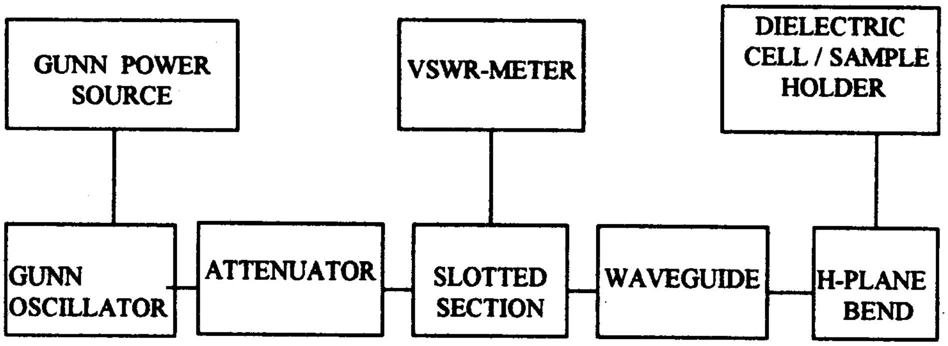

Fig. 1—Schematic diagram of the KU-band set up used for measuring ε' and ε'' by the two-point point.

$$\Phi=2\,\kappa(D-D_R-l_\varepsilon) \quad \ldots (3)$$

Also the reflection coefficient, $|\Gamma| = \dfrac{r-1}{r+1}$ ... (4)

where r is the voltage standing wave ratio.

The complex number can be determined as

$$C\underline{/\varphi} = \frac{1}{j\kappa l_\varepsilon}\,\frac{1-|\Gamma|e^{j\Phi}}{1+|\Gamma|e^{j\Phi}} \quad \ldots (5)$$

where $j = \sqrt{-1}$ and $C\underline{/\varphi}$ is the complex value of the angle.

In order to solve Eq. (5), the C-φ graph was used and the corresponding x and θ values were noted directly (solutions for two different sample lengths respectively).

These values of x and θ were then used in the calculation of Y from Eq. (6). For the same soil sample, the closest possible values of Y for different lengths were chosen for further calculations.

$$Y=(x/\kappa l_\varepsilon)^2 \;\underline{/2\,(\theta-90°)} \quad \ldots (6)$$

The values of ε' and ε'' calculated from the values of x and θ are as follows

$$\varepsilon'=\frac{(x/\kappa l_\varepsilon)^2\cos\theta'+(\lambda_g/\lambda_c)^2}{1+(\lambda_g/\lambda_c)^2} \quad \ldots (7)$$

$$\varepsilon''=\frac{(x/\kappa l_\varepsilon)^2\sin\theta'}{1+(\lambda_g/\lambda_c)^2} \quad \ldots (8)$$

In Eqs (7) and (8), $\theta' = 2\,(\theta-90°)$.

The entire calculation was done with the help of a PASCAL program fed into a PC AT-486 computer.

Wilting coefficient was calculated by using the Wang and Schmugge model[3]. According to this model wilting coefficient (W_t) is written as

$$W_t = 0.06774 - 0.00064 \cdot \text{sand}\,(\%) + 0.00478 \cdot \text{clay}\,(\%) \quad \ldots (9)$$

The values of wilting coefficient (W_t) are given in Table 1.

It may be mentioned here that though the model is based on the American soil conditions, its dependence is only on the texture of the soil concerned, giving it the character of universal applicability. Previous works suggest that the model can also be used successfully even on Indian soils[4]. So we have used the model using the textures of the soils under investigations, irrespective of their origin.

3 Sample collection and analysis

The present work was carried out with eleven different soil samples collected from different parts of India (Table 1). The soils were collected from the subsurface of the soil (3-5 cm beneath the soil surface). After collecting soil samples from three/four locations within the field, the same were mixed together so as to get a composite soil sample in a particular test area.

Three of the samples were collected from Delhi. Two of these were from the Jawaharlal Nehru University campus — one was collected from an agricultural field [JNU (1) — alluvial soil] and another from a relatively barren spot [JNU

Table 1—Results of textural analysis and values of curve fitting data and wilting coefficient

Place of origin	Percentage			Textural class	ε'		ε''		Wilting coefficient
	Clay	Silt	Sand		*a*	*b*	*a*	*b*	
JNU Campus (1), New Delhi	9.90	52.00	38.10	Silt loam	3.20	0.31	0.56	0.23	0.09
Khajjiar, Dist. Chamba, H.P.	19.10	32.90	48.00	Loam	3.07	0.21	0.33	0.20	0.13
Medical College, Belgaum	20.50	10.00	69.50	Sandy clay loam	2.33	0.18	0.34	0.11	0.12
Pune University, Pune	14.50	10.00	75.50	Sandy loam (I)	2.95	0.33	0.33	0.21	0.09
IIT, Mumbai	12.50	9.00	78.50	Sandy loam (II)	3.49	0.36	0.45	0.22	0.08
Nizamuddin, New Delhi	9.10	10.60	80.30	Loamy sand (I)	3.10	0.30	0.34	0.14	0.06
JNU Campus (2), New Delhi	9.90	5.90	84.20	Loamy sand (II)	2.90	0.28	0.30	0.17	0.06
Botanical Garden, Pune	8.90	5.20	85.90	Loamy sand (III)	3.00	0.33	0.43	0.21	0.06
Glacier, Gangotri	7.21	0.74	92.05	Sand (I)	2.85	0.24	0.27	0.13	0.04
Meraman Beach, Goa	3.90	2.00	94.10	Sand (II)	2.80	0.27	0.25	0.13	0.03
Kovalam Beach, Kerala	3.80	2.10	94.10	Sand (III)	2.60	0.26	0.30	0.14	0.03

(2) — red loamy sand]. The third sample (river bed alluvium) from Delhi belonged to a spot on the banks of river Yamuna at Nizamuddin.

Two of the samples were collected from Pune. Samples from Pune were black cotton soils of the Deccan region collected from agricultural fields located at the Pune University campus and the Botanical Garden, Pune. The sample from Mumbai were dark brown alluvial soils collected from the campus of Indian Institute of Technology, Mumbai. The Belgaum sample from Karnataka was a red sandy clay loam of the lower Deccan bordering the Western Ghat ranges.

The collection included two beach sands — one from Goa on the Konkan coast and the other from Kovalam (near Thiruvananthapuram) on the Malabar coast. The other two samples were collected from the Himalayan mountains — one from Gangotri glacier moraine and another from Khajjiar in Himachal Pradesh (brown mountain soil).

Symbols I, II and III used in Table 1 and Fig. 2 indicate similar types of soils but having somewhat varying texture.

The samples were first air dried and then passed through a 2-mm sieve for further textural analysis. The results of textural analysis are given in Table 1.

After addition of water of measured quantity, the samples were allowed to stand for 24 h to facilitate internal drainage and subsequent homogeneous mixing of soil and water. These soil samples were then used for the estimation of dielectric parameters and gravimetric soil moisture.

4 Results and discussion

The values of ε' and ε'' for each soil sample obtained by the two-point method were plotted against the volumetric moisture content ($x_{\rm v}$) as shown in Fig. 2. The plots were obtained with the help of a curve fitting technique. The general guiding equation for these curves is of the form, $Z = a * \exp (x_{\rm v} / b)$ with the coefficients a and b assuming closely placed but differing values in each case, and Z represents ε'or ε''as the case may be. The scattering of the data points on the curves was found to be less than 5%, proving the homogeneity in the results obtained. The values of the coefficients a and b are given in Table 1.

A study of Table 1 reveals that the value of coefficient a, which decides the $x_{\rm v} = 0$ intercept of a curve, is very closely spaced for any group of curves both for ε' and ε''. However, the value of coefficient b, which determines the slope of the curve, seems to vary a lot with soil texture. This

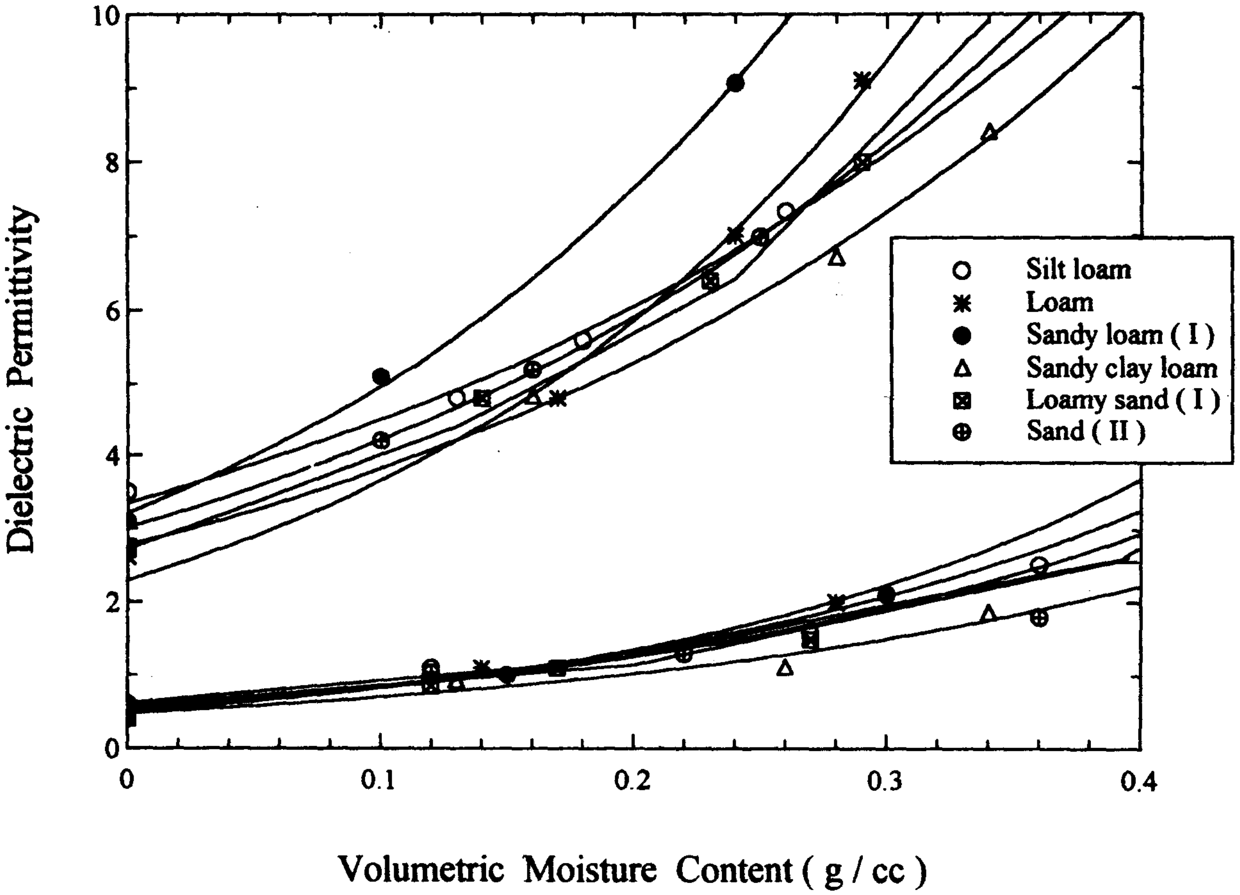

Fig. 2—Dependence of dielectric permittivity on soil moisture and texture.

implies that under dry conditions, soil texture has little effect on the value of dielectric permittivity, but this behaviour changes with increase in the water content.

The general behaviour of soil as a function of moisture content and soil texture can be summarized as follows:

(i) $\varepsilon'$is seen to increase gradually (for all the samples) with increasing moisture content up to wilting coefficient W_t. Beyond W_t the increase is rapid. W_t is observed to be dependent on the clay content of the sample as has also been pointed out by previous investigators (Hallikainen *et al.*[5], Geiger and Williams[6], Hoekstra and Delaney[7], Wang *et al.*[8], Rouse[9], Alex and Behari[4], Alex and Behari[10], to mention a few). This is due to large specific surface area of clay particles in comparison to other basic components of soil, silt and sand. The large specific surface area of clay particles enables soil to retain greater moisture in the form of bound water. The dielectric permittivity of bound water is very low compared to that of the bulk free water. When water is added to a clayey soil a greater portion of it is adsorbed as bound water relative to silt and sand. This phenomenon results in wet clayey soils having a lower net dielectric constant than wet silty and sandy soils at the same moisture level resulting in a higher wilting coefficient for the former.

(ii) The value of ε''soil is noticed to be higher for samples having higher sand content. This is due to the bound water factor and the salinity factor. Sand having a lower specific surface area has more of free water than bound water at a given moisture content resulting in a higher dielectric constant. Secondly, the low specific surface area results in a lower cation exchange for sand as compared to clay. This means that sandy soils are not as open to various physico-chemical processes as clayey soils are, resulting in a lower salinity of the soil-water mixture in the case of sand. The presence of mineral salts decreases the dielectric constant of water, and conversely as in this case, their absence makes it high.

It is observed that, like the dielectric constant (ε'), the loss factor (ε'') also increases with increase in moisture content. The dielectric loss is proportional to the sand content and inversely proportional to the clay content. Clayey soils in general have lower loss factor (ε'') at any given moisture level and are characterized by a higher wilting coefficient.This phenomenon is explained by the larger specific surface area of clay particles. As the water content is increased, the specific ionic concentration falls leading to an increase in the loss factor (ε'') finally reaching the wilting coefficient, beyond which the increase is sharp.

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