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A dielectric approach to determine water content in soil using microwave transmission technique at J-band

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Abstract

The water content in three different types of soil has been measured in laboratory by using microwave transmission technique at room temperature. The measurement is very sensitive to volumetric water content. It is observed that there is slow increase in dielectric constant at lower per cent of water content, whereas it increases sharply at higher water content and becomes constant at certain value of water content in soil. It is interesting to observe that these variations have been found to be strongly dependent on the texture of soils. The value of dielectric constants decreases with the presence of excessive water due to ionic effect.

Keywords: Soil samples, dielectric constant, soil water content, transmission line waveguide method.

1. Introduction

The dielectric constant is the most important parameter in microwave remote sensing for the study of dry and wet soils and in microwave remote sensing of soil moisture, both active and passive. Various percentages of soil–water mixtures give rise to a large dielectric constant variation. Hence thorough knowledge of dielectric properties of different types of soils is necessary for efficient use of microwave sensing technique for soil moisture estimation. The basis for microwave remote sensing of soil moisture is strong dependence on its moisture content due to the large contrast between the dielectric constant of water (80) and that of dry soil (3–5) [1]. The dependence of soil dielectric properties on moisture can be observed with either passive or active microwave sensors through its effect on the soil emissivity and reflectivity. Emissivity is the important parameter, which provides information about soil. All the natural objects such as soil with 0°C temperature absolute are capable of emission, absorption and transmission. The emitted radiation from soil depends upon its dielectric constant, surface roughness, chemical composition, physical temperature, frequency of polarization, and angle of observation. The dielectric constant of soil varies with the amount of moisture content present in the soil. The emissivity of the soil also varies with different moisture contents. A knowledge of the emissivity of the soil is useful for the efficient use of soil [2]. The dielectric properties of soil depends on the presence of water content, temperature, texture, minerals and the organic matters present in it.

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Knowledge of water content in soil is fundamental requirement in many applications in the field of agriculture, forestry, hydrology, and civil engineering. This needs measurements in the laboratory and sometimes continuous field monitoring also at several depths and in different locations.

There are two different techniques to measure the soil water content—direct and indirect methods. Direct measurement method involves the removal of the soil water by evaporation, leaching, or a chemical process and subsequent determination of the amount removed. Direct measurements are beset with problems principally due to the necessity for destructive sampling. Measurements cannot be repeated on the same sample of soil; hence, replicate samples must be taken from a plot at any one time to determine the variance of the measurements at that time and so to permit the analyst to ascertain whether they differ significantly from determinations on other occasions. The need for replication can result in the handling of very large number of samples. Practical difficulties are compounded if determinations deep in the profile are required. Further repeated sampling within the same area may well cause unacceptable damage to a crop or soil.

Indirect methods (nondestructive methods) like time domain, and frequency domain transmission line depend on the monitoring of some soil property, which is dependent on water content. One of the important methods is based on measurement of dielectric properties of soils. In these methods, instrumentation is placed in or on the soil or mounting some sensors on a platform on the surface of soil. Although these methods require calibration to determine water content, they have the advantage of *in-situ* measurements, and these can be repeated in the same positions at various times. There are several techniques to measure the dielectric properties of materials [3].

At microwave frequencies (generally about 1 GHz and higher), transmission line waveguide, coaxial line, resonant cavity, and free space techniques are commonly used. The experimental techniques of the dielectric measurements can be categorized as reflection or transmission types using resonant or nonresonant systems, with open or closed structures for sensing the material samples [4].

Transmission line techniques are not cumbersome because they do not require special sample preparation. The dielectric properties can be measured easily by this technique with the use of slotted line and standing wave indicator [5]. The transmission line techniques are suitable for inhomogeneous dielectric materials. In addition, they may be easily implemented in industrial applications for continuous monitoring and control. These techniques are more sensitive and accurate. At microwave frequencies, the effect of ionic conductivity gets negligible as compared to dielectric losses [6].

In the present work, an experimental method based on transmission line is described to measure the dielectric constant of different types of soil. From these values, the water content in soil is estimated. In Section II, the theory used in the experimental technique is described. Section III discusses the experimental work and Section IV deals with results and discussion.

2. Theory

The microwave transmission line waveguide technique is used to measure the dielectric constant of soil. As the dielectric permittivity of water is an order of magnitude grater than the corresponding values of soil constituents, changes in dielectric constant can be attributed to change in water content in nonexpanding soils [7].

In an alternating electric field, permittivity varies with applied frequency. This frequency dependence can be described by the complex permittivity

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

where ε' is the dispersive part and ε'', the absorptive part of permittivity.

Because of the relatively high frequency of the system the real part ε' of permittivity is frequency dependent on the water content in the soil. At 1 GHz, the values of ε'' are very small and not of so much interest for the determination of the water content in soil. Equation (1) is a function of the water content in the porous materials. The real part ε' can be expressed as

$$\varepsilon' = \lambda_O^2 \left[\frac{1}{\lambda_c^2} + \frac{\beta^2 - \alpha^2}{4\Pi^2} \right] \tag{2}$$

where λ_0 is free space wavelength, λ_c, the cutoff wavelength, and α and β are the attenuation and phase constants, respectively. These can be measured experimentally [8]. Using these values, the value of dielectric constant (ε') can be determined by using eqn (2).

3. Experimental procedure

The experimental technique used to measure the dielectric constant and water content is credited to Roberts and Von Hipple [9] and the fixed frequency method to Gopal Krishna [10]. A least-squares fit programme of Sobhanadri [11] is used to calculate the dielectric constant. A J-band microwave transmission line waveguide set-up is used for this purpose. The experimental set-up of J-band waveguide transmission line is shown in Fig. 1. The dielectric constants of soil have been measured at a fixed frequency of 7 GHz and at room temperature. The soil samples were collected from non-irrigated farming lands (called dry soil) of Fattepure, Sendra and Karmad, which are 30 km away from Aurangabad city. They have negligible water content. The samples help to understand the actual water content

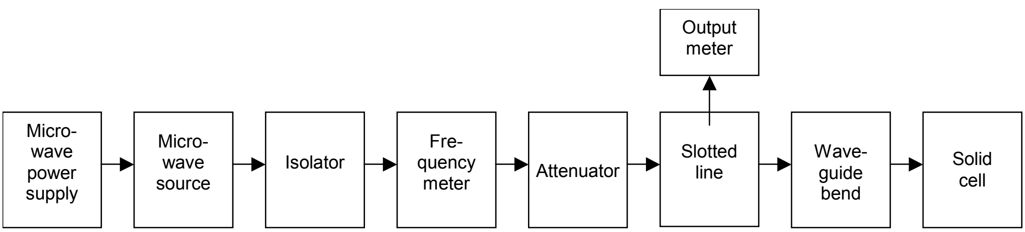

FIG. 1. Experimental set-up of microwave J-band waveguide transmission line.

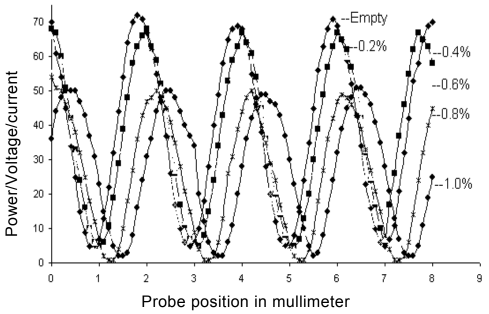

FIG. 2. Standing wave patterns of soil sample at Fattepure with increasing water content.

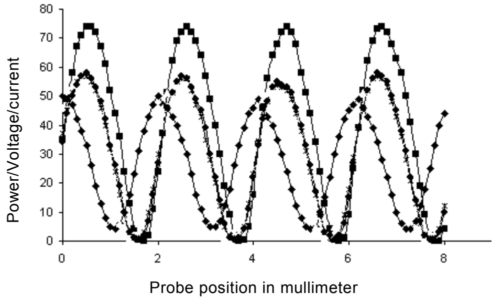

FIG. 3. Standing wave patterns of soil sample at Sendra with increasing concentration of water.

required for the plant growth and to study their physical and chemical properties. These samples are a mixture of sand, silt and clay with a very high percentage of clay. The soil sample under measurement of known volume was placed in the empty solid dielectric cell, and well pressed by a laboratory-developed mechanical system to remove air and discontinuities in the sample. The solid cell with the sample was connected to the opposite end of the source of microwave bench set-up. The signal generated from the microwave source was allowed to incident on the soil sample. The soil sample reflects part of the incident signal through the soil from its front surface. The values of power at different points of standing waves have been measured as a function of probe position. About 80–100 points were recorded for a single standing wave pattern. The least-squares fit has been used to determine the values of λ_0, λ_c, α and β for the sample.

Firstly, switching on the microwave transmission line the standing wave pattern was recorded for empty cell. The soil under measurement was placed in the cell, pressed, and connected to the other end of the microwave bench set-up. The measurements were done for three different lengths of the collected soil. The same procedure is applied for other soil samples also. Fitting these standing wave patterns of dry soil samples into the least-squares fit programme, the dielectric constant was determined. From measured value of dielectric constant of dry soil, the water content has been determined by assuming a ‘dry’ soil sample still contains an unknown and unspecified amount of water (hygroscopic and crystal-bound water) [12]. Then standing wave patterns of the above-mentioned soil samples were recorded with adding volumetric water content (Figs 2–4). Fitting these standing wave patterns in the least-squares fit programme the dielectric constant has been measured (Table I). From these dielectric constants, the water content in soil has been determined.

4. Results and discussion

It is observed from Table I that there is an increase in dielectric constant and soil water content with the addition of water, and this variation is slow at lower volumetric water content range (Fig. 5). This increase may be due to the addition of high dielectric constant liquid (water) to the soils. At this lower range of water content addition of water to the soil has a little effect on the soil, as the water becomes bounded with the soil. Due to this increase in soil moisture there is small increase in dielectric constant. The variation in dielectric

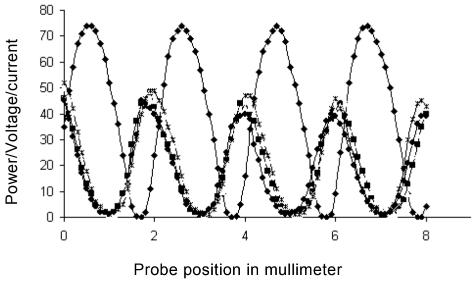

FIG. 4. Standing wave patterns of soil sample at Karmad with increasing concentration of water.

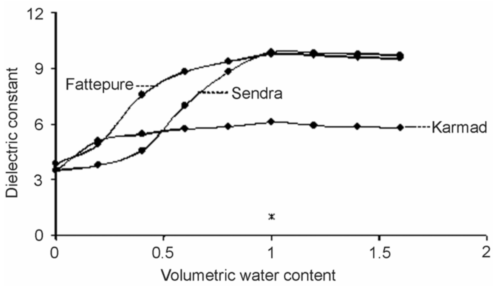

FIG. 5. Variation of dielectric constant of soil with volumetric water content.

constant and soil water content with increasing volumetric water for the three samples is very similar to the work of Behari [13], Vyas and Gadani [14], and Srivastava and Mishra [15].

Table I shows continuous increase in dielectric constant with increase in water content up to 1.0%, and this increase is faster than that of lower range. This may be due to higher value of dielectric constant of water. Due to greater in water content some of the soil is replaced with water. The water content will also be increased. Due to larger presence of this high dielectric constant liquid at this range there is fast increase in dielectric constant and water content. It is observed that the water (moisture) content increases faster after 6–8%. This is in agreement with the earlier investigation of Dunlap and Makower [16] and Topp *et al.* [17].

It has also been observed from Table I that after 1% of water content there is decrease in dielectric constant and water content. The reason may be with further increase in water content (above 1%) the total water content in the soil is more or it may get saturated. At this saturation point of water into soil chemicals, minerals, organic matter, and water-soluble compounds from soil will get dissolved in it. The water present in the soil along with these factors forms an electrolyte solution of higher concentration. According to the theory of electrolyte solution, the dielectric constant of solutions (liquids) decreases at higher concentration of electrolyte solution. Due to this reason there may be decrease in dielectric con-

Table I
Variation in dielectric constant and soil water content with addition of volumetric water for the soil sample at (a) Fattepure (b) Sendra, and (c) Karmad at 7-GHz frequency

Sl no.	Volumetric water content (θ)			Dielectric constant (ε')			Percentage change in soil water content (%)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
0	0.0	0.0	0.0	3.85	3.50	3.51	20.00	20.00	20.00
1	0.2	0.2	0.2	4.90	3.80	5.10	25.45	21.71	29.05
2	0.4	0.4	0.4	7.54	4.56	5.44	39.16	26.05	30.99
3	0.6	0.6	0.6	8.69	6.98	5.74	45.14	39.88	32.70
4	0.8	0.8	0.8	9.32	8.80	5.86	48.41	50.28	33.39
5	1.0	1.0	1.0	9.77	9.87	6.11	50.75	56.40	34.81
6	1.2	1.2	1.2	9.69	9.81	5.94	50.33	56.05	33.84
7	1.4	1.4	1.4	9.57	9.76	5.85	49.71	55.77	33.33
8	1.6	1.6	1.6	9.49	9.72	5.78	49.29	55.54	32.93

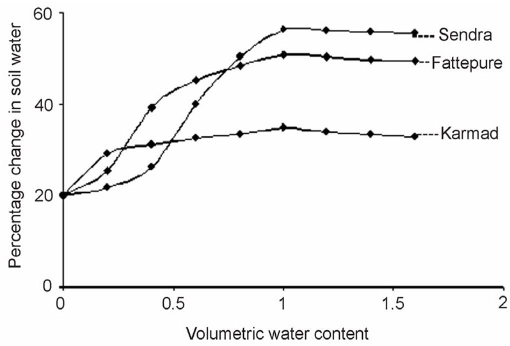

FIG. 6. Variation in volumetric soil water content with addition of water.

stant, when water content is more than 1% of volumetric water content. This is in agreement with the earlier investigations of electrolyte solutions by Hasted [18]. The variation in soil water content with increasing volumetric water content for the three soil samples is shown in Fig. 6.

The variation in dielectric constant and water content is different, though the addition of water to the three soil samples is equal (Table I). The variation in dielectric constant and water content is higher in samples at Fattepure and Sendra than that of sample at Karmad. This may be due to greater presence of chemical compounds, organic matters, minerals, and water soluble salts in samples at Fattepure and Sendra over that of Karmad. Another reason may be the clay present in soil samples at Fattepure and Sendra may be more than that of Karmad. According to Hallikainen *et al.* [19], the soil texture shown to have an effect on dielectric behavior of soil, that is moisture retentive capacity of clayey soil, is more than that of sandy soil [20]. Due to these reasons, the dielectric constant and water content are higher in samples at Fattepure and Sendra over that of Karmad.

From this work, it is clear that it is possible to determine water content in soil using dielectric method. Dielectric constants are not only sensitive to water content, but are also to texture of soils.

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