CHAPTER-3
PRINCIPLES AND TECHNIQUES FOR DETERMINING
DIELECTRIC PROPERTIES OF SOILS

3.1  Introduction

The measurement methods relevant for any desired application depend on the nature of the dielectric material to be measured, the frequency of interest and the degree of accuracy required. Microwave measurements and the dielectric properties of materials are having increasing application as new electro-technology in the fields such as agriculture, space research and food processing industries. Further, these measurements of the bulk dielectric properties (dielectric constant, dielectric loss factor, etc.) are helpful for understanding, explaining and empirically relating certain physico-chemical properties of the test material. Therefore, in this chapter, an attempt is made to present and explain the relevant experimental techniques used in our investigations. The details about scientific methods of soil collection, preparation of red soil samples, etc., are also elaborated. A brief review of the literature based on measuring techniques and their comparison is also discussed in this Chapter.

3.2  Methods of Measurement of Dielectric Properties

The measurement of dielectric properties has gained importance because it can be used for monitoring the specific properties of materials undergoing physical or chemical changes. Nelson S. O. [1, 2] reviewed the methods of measuring the dielectric properties of granular and powdered materials at microwave frequencies and the factors affecting the dielectric properties of materials, such as frequency, moisture content, temperature, and bulk density. At microwave frequencies, generally about 1 GHz and higher, there are basically four methods for measuring the dielectric constant of materials, viz.,

(i) Waveguide- cell method (Transmission line method)
(ii) Free space transmission method
(iii) Cavity resonance method.
(iv) Network analyzer and dielectric probe method
These dielectric property measurement techniques can be categorized as reflection or transmission types using resonant or non-resonant systems, with open or closed structures for sensing the properties of material samples [3]. Waveguide and coaxial line transmission measurements represent closed structures while the free-space transmission measurements represent open-structure techniques. According to Nelson S.O. [4], resonant structures can include either closed resonant cavities or open resonant structures operated as two-port devices for transmission measurements or as one-port devices for reflection measurements. A general comparison/review of the microwave dielectric measurement techniques has been made by several investigators [4 - 9]. These four methods are briefly described below.

3.2.1  Waveguide- cell method (Transmission line method)

Studies to characterize the dielectric properties of materials were initially made at the Massachusetts Institute of Technology [10, 11]. The values of $\varepsilon'$ and $\varepsilon''$ were derived from transmission line theory, which indicated that these properties could be determined by measuring the phase and amplitude of a reflected microwave signal from a sample material placed against the end of a short-circuited waveguide.

Waveguide-cell method is suitable over the frequencies ranging from 500 MHz-110 GHz using waveguides of different dimensions. For a waveguide structure, rectangular samples that fit into the dimensions of the waveguide at the frequency being measured are required. For coaxial lines, an annular sample needs to be fabricated. The method can be used for solid, liquid and semi-liquid samples. The thickness of the sample should be approximately one-quarter of the wavelength of the energy that has penetrated the sample. This technique is easy to use and its analysis can be done manually as well as with the help of suitable computer programs. Since the shift in wavelength is related to the dielectric constant, a guess must first be made as to the magnitude of the dielectric constant. Dielectric sample holder design for a particular material of interest is an important aspect of the measurement technique. The overall equipment cost is low and it can provide fairly good accuracy.

3.2.2  Free-space transmission method

Free-space technique do not require special sample preparation and thus it is grouped under non-destructive and contact-less measuring methods. Therefore, they are particularly suitable for materials at high temperature and for inhomogeneous
dielectrics. In addition, these techniques may be easily implemented in industrial applications for continuous monitoring and control, e.g., moisture content determination and density measurement [3,12].

In this method, a sample is placed between a transmitting antenna and a receiving antenna, and the attenuation and phase shift of the signal are measured. The results of which can be used to translate the material dielectric properties. Accurate measurement of the permittivity over a wide range of frequencies can be achieved by free space techniques. In most systems, the accuracy of $\varepsilon'$ and $\varepsilon''$ determined depends mainly on the performance of the measuring system and the validity of the equations used for the calculation. The usual assumption made during this technique is that a uniform plane wave is normally incident on the flat surface of a homogenous material, and that the planar sample has infinite extent laterally, so that diffraction effects at the edges of the sample can be neglected. However, the sample size needed is large and it should be in the form of large flat sheets.

3.2.3 Cavity resonance method

The cavity resonator is usually calibrated with materials whose dielectric properties are known, usually with organic solvents such as methanol, ethanol, etc. A cavity can be used for a small frequency range and different cavities are required to achieve a wide range (500 MHz-10 GHz). If the transmission line is enclosed (i.e., it is a waveguide), the permittivity of a material can also be measured without the resonator by putting it directly inside the waveguide. The method applies to all liquid, solid and semi-solid materials, but not to gases since their permittivities are too low. It can measure both storage part and loss part of the dielectric material. This method has high precision in measuring loss tangent for low loss material. There are, however, problems with the sample preparation of solid materials. This method is usually preferred for low loss dielectric materials and small sample sizes.

3.2.4 Network analyzer and dielectric probe method

This method gives data for a wide frequency range, ranging from 200 MHz to 20 GHz. It is extremely fast method, especially when a wide frequency range is to be covered. This method is very convenient to use for liquid and semi-liquid samples and can provide direct result with the help of computer software. In this method, the sample size needed is very small and the substance measured must be homogeneous.
Further, this technique does not require any sample preparation. However, the equipments needed are very costly and the accuracy is relatively lower than the waveguide cell method. It cannot resolve tan δ for low loss material.

The particular method used depends on the frequency range of interest and the type of target material. The choices of measurement equipment and sample holder design depend upon the dielectric materials to be measured, the extent of the research, available equipment, and resources for the studies. Out of these four methods, we have selected the waveguide-cell method. This method is perhaps the best known and is most widely used. It is useful over wide range of frequencies (500 MHz - 110 GHz) and can measure both real and imaginary part of dielectric constant of solids, liquids and semi-liquids. Further, this method gives comparatively more accurate results for the samples having low tan δ values similar as in our present experiments. Details about the C-Band and X-band microwave set up, waveguide-cell method, soil sampling and sample preparation techniques, general procedure and various formulae needed in determining dielectric parameters of soils, etc. are elaborated below.

### 3.3 Description of C-Band and X-Band Microwave Set Up

Fig. 3.1 shows block diagram of C-band / X-band microwave set up used for measuring dielectric constant of Soil Samples. Brief description of the each components used in this measurement setup is given below. The working principle, operation and shape of the C-band components with the corresponding model of X-band components are same except their sizes. It is because the design of component size is directly related to the wavelength of the source/band used. Hence the C-band components are bigger in size than their corresponding model of X-band components.

![Block diagram of C-band (3.95GHz to 5.85 GHz) / X-band (8.2 to 12.4 GHz) microwave bench setup for measurement of dielectric constant of Red Soils.](image)
3.3.1 Gunn power supply (Model X-110)

Gunn power supply comprises of a regulated D.C power supply (0 to 12 volts) and a square wave generator designed to operate Gunn oscillator model 2152 and Pin-modulator model 451 simultaneously. It is quite stabilized and has extremely low ripple. The voltage is set at its lowest value when tuning on and off to avoid spikes which could damage the Gunn diode. The power supply has been so designed to protect Gunn diode from reverse voltage application, over transient and low frequency oscillations by the negative resistance of the Gunn diode.

3.3.2 Gunn oscillator (Models C-2152 and X-2152)

Gunn oscillators are solid state microwave energy generators. These consist of waveguide cavity flanged at one end and microwave driven plunger fitted on the other end. It utilizes a Gunn diode which works on the principle that when a D.C voltage is applied across a sample of n-type Gallium Arsenide, the current oscillates at microwave frequencies. Normally they are capable of delivering 0.5 watt at 10 GHz but as frequency of operation is increased the microwave output power gets considerably reduced.

3.3.3 Pin modulator (Models C-451 and X-451)

Model C-451 and X-451 Pin-modulators are designed to modulate the Carrier Wave (CW) output of Gunn oscillator. It is operated by the square pulses derived from the Ultra High Frequency (UHF) connector of the Gunn power supply. It consists of a pin diode mounted inside a section of waveguide flanged on its both end. A fixed attenuation vane is mounted inside at the input part to protect the oscillator.

3.3.4 Isolator (C-6021 and X-6021)

An isolator is a non-reciprocal transmission device and is used to isolate one component from reflections of other components in the microwave circuits. An ideal isolator completely absorbs the power for propagation in one direction and provides transmission in the opposite direction. Thus, the isolator is also called unidirectional microwave component. Isolators are used to improve the frequency stability of microwave generator such as (Gunn + Pin) systems in which the reflection from the load affects the generating frequency. An isolator placed between the generator and load prevents the reflected power from the unmatched load returning to the generator.
3.3.5 Frequency meter (C-4155 and X-4155)

The frequency meter is used to measure or to standardize the frequency of a microwave system. It is used to measure frequency of signal propagating through transmission waveguide. It works on principle of cavity resonance. Frequency meters are made of tunable resonant cavity of particular size. This cavity is connected to the source of energy through a section of waveguide. The cavity absorbs some power at resonance. Tuning of the cavity is achieved by means of a plunger connected to a micrometer.

3.3.6 Variable attenuator (C-5020 and X-5020)

In general, any device that attenuates the signal is called as attenuator. In principle, even a normal waveguide or co-axial transmission lines can also be kind of attenuators as they may attenuate little signal level. When this attenuation is undesirable it is termed as insertion loss. In case if attenuation is desirable, it is actually termed as attenuation.

We have used variable attenuator having 0-20 db range. It consists of a movable lossy vane inside the section of a waveguide. The movement of this vane is coupled to a micrometer. Attenuators are also used for adjusting power levels and isolating a source from the load.

3.3.7 Slotted line (C-6051 and X-6051) with probe (C-6055 and X-6055)

The slotted line is an important measuring instrument at microwave frequencies. It is designed to measure the standing wave pattern of the electric field intensity, which is a function of longitudinal position in the guiding structure. Tunable probe is designed for use with slotted sections. A probe is mounted on a carriage and it slides along the outside section of the waveguide, which has a longitudinal slot. The depth of penetration into a waveguide section is adjustable by the bottom knurled knob of the probe. The tip of the probe pick up the RF power from the line and this power is rectified by crystal detector. The movement of the probe is done with the help of PC-Based slotted line control and data acquisition system. A visual representation of standing wave pattern is obtained due to atomization arrangement.

3.3.8 Solid dielectric cell (C-930 and X-930)

Solid dielectric cell consists of a section of waveguide flanged on both ends and one end is terminated with a polished fixed reflector. Its length varies with the
selection of the band. The Soil samples of desired length are placed in contact with polished fixed reflector. The E-Plane bend is very often connected between other end of solid dielectric cell and slotted line in order to have the perfectly flat and smooth upper surface of the red soil sample. The cross section of bent waveguide is kept throughout uniform to give Voltage Standing Wave Ratio (VSWR) less than 1.05 for the frequency bands studied.

Other details of dielectric constant measurement set up (C-Band and X-Band) can also be seen from the photographs given in Fig.3.2 and 3.3 respectively.

Fig.3.2 Photograph of automated C-band microwave bench setup for measurement of dielectric constant of Red Soils.

Fig.3.3 Photograph of automated X-band microwave bench setup for measurement of dielectric constant of Red Soils.
3.4 Soil Sampling Techniques

Soil is a heterogeneous body. Therefore, it is not possible to collect a soil sample which would be representative of the heterogeneous land. So, first of all the heterogeneity of the land is minimized by dividing the land into smaller units. It is, therefore, important that samples are representative of the soil for the area under investigation. Unless this is ensured, sampling may be the greater source of error in the whole process. Moreover, variations of slope, colour, texture and management practices should also be taken into account and separate sets of composite samples should be collected from each such area. In the present investigations, we have collected red colored Top-Soil (depth ranging between 0-20 cm) samples. Further, while collecting these soil samples, the complete information about the site is essential for understanding their dielectric properties and also for fertilizer recommendations. Such information includes soil water status, cropping history, fertilizers used, other cultural practices, etc.

Table 3.1 and 3.2 provide the detailed information about soil sampling locations and also the soil color, sample number assigned, crop history, etc. In Fig.3.4, the North Maharashtra, West Maharashtra and Konkan region of Maharashtra is highlighted and shown by an arrow in a map of Maharashtra State (India).

Table 3.1. Geographical Information

<table>
<thead>
<tr>
<th>Districts of North, West Maharashtra and Konkan</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude, (m)</th>
<th>Average Rainfall/Year (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jalgaon</td>
<td>21°01’ N</td>
<td>75°34’ E</td>
<td>209</td>
<td>690</td>
</tr>
<tr>
<td>Dhule</td>
<td>22°53’ N</td>
<td>74°46’ E</td>
<td>239</td>
<td>640</td>
</tr>
<tr>
<td>Ratnagiri</td>
<td>17°08’ N</td>
<td>73°19’ E</td>
<td>44</td>
<td>1948</td>
</tr>
<tr>
<td>Raigadh</td>
<td>18°28’ N</td>
<td>73°14’ E</td>
<td>38</td>
<td>1016</td>
</tr>
<tr>
<td>Satara</td>
<td>17°58’ N</td>
<td>73°43’ E</td>
<td>1353</td>
<td>1624</td>
</tr>
</tbody>
</table>
Table 3.2 Details of soil sampling sites and soil samples

<table>
<thead>
<tr>
<th>Districts of North, West Maharashtra and Konkan</th>
<th>Sampling Sites</th>
<th>Soil Colour</th>
<th>Sample Nos. Assigned as per Clay %</th>
<th>Irrigated/Non-Irrigated</th>
<th>Crops Grown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dhule</td>
<td>Haranmal</td>
<td>Red</td>
<td>S1</td>
<td>Semi-Irrigated</td>
<td>Cotton, Bajara</td>
</tr>
<tr>
<td></td>
<td>Aamli</td>
<td>Red</td>
<td>S3</td>
<td>Irrigated</td>
<td>Cotton, Jwari, Rice</td>
</tr>
<tr>
<td>Jalgaon</td>
<td>Parola</td>
<td>Red</td>
<td>S2</td>
<td>Irrigated</td>
<td>Cotton, Bajara</td>
</tr>
<tr>
<td>Ratnagiri</td>
<td>Narabe</td>
<td>Deep Red</td>
<td>S4</td>
<td>Semi-Irrigated</td>
<td>Rice, Cashew, Coconut</td>
</tr>
<tr>
<td>Raigadh</td>
<td>Sai</td>
<td>Deep Red</td>
<td>S5</td>
<td>Semi-Irrigated</td>
<td>Rice, Cashew, Jwari</td>
</tr>
<tr>
<td>Satara</td>
<td>Mahabaleshwar</td>
<td>Deep Red</td>
<td>S6</td>
<td>Semi-Irrigated</td>
<td>Rice, Strawberry</td>
</tr>
</tbody>
</table>

Fig. 3.4 A map showing soil sampling sites from North Maharashtra, West Maharashtra and Konkan region of Maharashtra State
3.4.1 Preparation of soil samples

In the present study, the red coloured topsoil samples were collected from six different locations. These locations are situated in the Northern, Western Maharashtra and Konkan region of Maharashtra State (India). These topsoil samples are first sieved by gyrator sieve shaker (size 425µm) to remove the coarser particles. The sieved out fine particles are then dried in the hot air oven (Fig. 3.5, a) to a temperature around 110°C for about 24 hours in order to completely remove any trace of moisture. Such dry samples are then called as oven-dry or dry base samples when compared with wet samples. Soil samples of various gravimetric moisture contents (upto 30%) are prepared by adding an exact amount of distilled water to the known mass of the oven dry soil. The single pan precision balance (Fig. 3.5, b) having digital readout accuracy of 0.1 mgm is used for weighing the sample. The soil-water mixtures are well mixed and are kept in a closed container for proper settling over several hours. These samples of desired gravimetric MC(%) are then inserted into the solid dielectric cell for measuring their dielectric properties. Proper care was taken to expose the moist soil to the atmospheric air as little as possible.

(a)                                                                (b)

Fig.3.5 Photograph of (a) Hot air oven (b) Single pan precision balance
3.4.2 Soil testing

The soil parameters like pH and EC are determined by using Digital Soil Testing kit (MODEL-161) shown in Fig 3.6. The detailed soil analysis reports for the remaining parameters of the red soil samples used in this study were obtained from Soil Science Division, College of Agriculture, Pune, Rahuri and Dhule. Important physical properties such as soil texture, bulk and particle density and chemical properties such as pH, EC, OC, CaCO$_3$ available macronutrients N, P, K, Ca, Mg, micronutrients Fe, Mn, Zn, Cu, etc. of the red soil samples are determined.

![Fig. 3.6 Soil Testing Kit](image)

3.5 Method of Measurement of Dielectric Properties

The wave-guide cell method is used to determine the dielectric properties of these red soil samples. An automated microwave set-up in the TE$_{10}$ mode with Gunn source operating at desired C- and X band frequencies, PC-Based slotted line control and data acquisition system are used for this purpose. It consists of Microcontroller (8051) and ADC-12 Bit- MCP (3202) Visual-Based software. The main advantages obtained due to atomization are increased resolution of output, reduction of backlash error in slotted line, visual representation of standing wave pattern. The sample lengths are usually taken in the multiples of $\lambda/4$. It is very important parameter and inaccuracy in its measurement may lead to serious errors. The solid dielectric cell
(Fig. 3.7) connected to the opposite end of the source and red soil samples are inserted in close contact to the electrically shorted end of dielectric cell.

![Fig. 3.7 The solid dielectric cell](image)

The signal generated from the microwave source is allowed to incident on the soil sample. The red soil sample reflects part of the incident signal from its front surface. The reflected wave combined with incident wave to give a standing wave pattern. These standing wave patterns are then used in determining the values of shift in minima resulted due to before and after inserting the sample. Fig. 3.8 shows standing waves in the waveguide with and without sample. The dielectric constant is calculated by measuring the standing wave ratio of the dielectric material and the shift in minima of the standing wave pattern in a rectangular waveguide. This shift takes place due to change in the guide wavelength when a dielectric material is introduced in waveguide. Experiments were performed at room temperatures ranged between $30^\circ$-$35^\circ$ C. By substituting these values of shift in minima, VSWR, waveguide dimensions, guide wavelength, etc. in a well designed computer programs, the values of dielectric constant and dielectric loss of red soils are determined. In order to improve the accuracy of these results, average of several readings is taken. The theoretical background of Wave-Guide Cell Method or von-Hippel Wave-Guide Method for measuring of dielectric constant of solids soils is given below.

![Fig.3.8 Standing waves in the waveguide with and without sample](image)
3.5.1 Basic theory of wave-guide cell method/von-Hippel wave-guide method

The method consists of reflecting microwaves at normal incidence in TE_{10} mode from a dielectric sample placed against a perfectly reflecting surface. The reflection sets up standing waves in space in front of the sample. The separation of the first minimum from the face of the sample will depend upon wavelength of the EM wave in the sample and on sample dimensions (thickness) and hence on dielectric constant. Further, the change in wavelength shall cause shift in the minima and in turn a change in half power width of the standing wave pattern. Also, losses in the dielectric shall decrease to VSWR (E_{max}/E_{min}) and so tanδ may be related to this decrease in VSWR.

To proceed, consider that an EM wave travelling through medium 1 (air) strikes normally to the medium 2 (dielectric), a part of it is reflected and the rest gets transmitted (Fig. 3.9). A standing wave pattern is thus produced in medium 1.

The transverse electric field component in this partial reflection case is given by

\[ E_y = [ E_0 e^{j\omega t - \gamma_1 x} ] [ 1 + \Gamma_0 e^{2\gamma_1 x} ] \]  \hspace{2cm} .... (3.1)

Where \( \gamma_1 \) is the propagation constant in medium 1 and is the sum of attenuation constant \( \alpha_1 \) and phase shift constant \( \beta_1 \).

\[ \gamma_1 = \alpha_1 + j \beta_1 \]  \hspace{2cm} .... (3.2)

The reflection coefficient \( \Gamma_0 \) is given by

\[ \Gamma_0 = |\Gamma_0| e^{-2j\psi}, \]  \hspace{2cm} .... (3.3)

Where \( \psi \) is the phase of reflection coefficient.

The input impedance \( Z_{(0)} \) at the boundary ( \( x = 0 \) ) is given by

\[ Z_{(0)} = \frac{Z_1}{1 - \Gamma_0} \]

\( Z_1 \) is the impedance of medium 1.
Fig. 3.9 Standing Waves in a waveguide (a) without dielectric (b) loaded with dielectric of any length (c) loaded with dielectric of length $\lambda_d/2$ ($\lambda_d$ is the wavelength of microwaves in the dielectric).

### 3.5.2 Loss-less dielectric

Consider a solid sample (oven-dry red soil) of length $l_e$ loaded in a rectangular waveguide against short circuit that touches it well. In Fig. 3.10 (b) and (c), $D$ and $D_R$ are respectively the positions of first minimum of the standing wave pattern when waveguide is loaded and unloaded with the dielectric sample. The respective distances
from the short circuit will be \((1 + l_e)\) and \((l_R + l_e)\). Now looking from A towards right and left, the impedances are equal, so

\[
Z_0 \tan \beta l = Z_{\varepsilon} \tan \beta_{\varepsilon} l_{\varepsilon} \quad \ldots \quad (3.4)
\]

Where, \(Z_0\) and \(Z_{\varepsilon}\) are respectively the characteristic impedance of empty and dielectric-filled waveguides. Also, the \(\beta\) and \(\beta_{\varepsilon}\) are their respective propagation constants. Similarly from Fig. 3.9 (b),

\[
Z_0 \tan \beta (l_R + l_e) = 0 \quad \ldots \quad (3.5)
\]

Now, consider the expression

\[
\tan \beta (D_R - D + l_e) = \tan \beta \left\{(l_R + l_e) - (1 + l_e) + l_e\right\}
\]

Expanding the tangent sum angle and making use of Eq. (3.5), we get,

\[
Z_0 \tan \beta (D_R - D + l_e) = Z_{\varepsilon} \tan \beta_{\varepsilon} l_{\varepsilon} \quad \ldots \quad (3.6)
\]

Again recalling the relation

\[
\frac{\tan \beta (D_R - D + l_e)}{\beta l_{\varepsilon}} = \frac{\tan \beta_{\varepsilon} l_{\varepsilon}}{\beta_{\varepsilon} l_{\varepsilon}} \quad \ldots \quad (3.7)
\]

Eq. (3.7) suggests a method for measuring dielectric constant. Quantities on the LHS are all experimentally measurable \((\beta = 2\pi/\lambda_g)\). Thus value of \(\tan \beta_{\varepsilon} l_{\varepsilon} / \beta_{\varepsilon} l_{\varepsilon}\) is known and hence value of \(\beta_{\varepsilon} l_{\varepsilon}\) can be known from the standard tables. Since \(\tan \left(\beta_{\varepsilon} l_{\varepsilon}\right)/(\beta_{\varepsilon} l_{\varepsilon})\) is a multivalued function, so correct value has to be selected. This is done in two ways.

(i) When approximate value of dielectric constant is known, select that value, say \(\beta_{\varepsilon}\), and compute dielectric constant from the relation

\[
\beta_{\varepsilon} = \frac{2\pi}{\lambda_0} \left(\varepsilon' \mu_r - \frac{(\lambda_0)^2}{(\lambda_c)^2}\right)^{1/2} = \frac{2\pi}{\lambda_d}
\]

where \(\lambda_c = 2a\) is cut-off wavelength, \(\lambda_0\) is free-space wavelength, \(\lambda_d\) is guide wavelength when it is filled with the dielectric. \(\varepsilon'\) is relative dielectric constant and \(\mu_r\) is the relative permeability.

\[
\varepsilon' = \frac{(a/\pi)^2 \left(\beta_{\varepsilon} l_{\varepsilon}/l_{\varepsilon}\right)^2 + 1}{(2a / \lambda_g)^2 + 1} \quad \ldots \quad (3.8)
\]
If this value is close to the approximately known value, then the value obtained is true value, otherwise try another solution and so on.

Fig.3.10 Illustration of Wave-Guide Cell Method for measuring dielectric constant
(a) Double minimum width (b) Position of minimum with shorted waveguide without dielectric (c) Position of minimum with shorted waveguide with dielectric.

(ii) If approximate value of the dielectric constant is not known, a second identical experiment is to be performed with the sample of a different length. The proper solution of the trancedental Eq. (3.7) is common to the two sets of solutions and is thus the point of intersection of the two curves drawn for each sample between dielectric constant $\varepsilon'$ and the solutions for $\beta_{\varepsilon l}$. Eq. (3.8) is used to find out the values of dielectric constant of oven-dry red soils.
3.5.3 For lossy dielectrics

Eq. (3.7) can be modified for lossy (complex) dielectrics. In these cases, we determine voltage standing wave ratio and compute reflection coefficient in complex form. The phase difference ($\Phi$) in the waves travelling in the guide with and without dielectric is

$$\Phi = 2\beta (\Delta x - l_e) \quad \ldots \quad (3.9)$$

$\Delta x$ is the shift in minimum. Now reflection coefficient is given by

$$\left| \Gamma \right| = \frac{S - 1}{S + 1} \quad \ldots \quad (3.10)$$

where $S$ is VSWR. Further, if we define

$$C = \frac{1}{j\beta l_e 1 + |\Gamma| e^{j\Phi} X \angle 0} \quad \ldots \quad (3.11)$$

then admittance is given by

$$Y_e = \frac{(X)^2 \angle 2(\theta - 90^\circ)}{(\beta l_e)^2} = g_e + j\beta_e \quad \text{(say)} \quad \ldots \quad (3.12)$$

g$e$ and $\beta$e are related to $\varepsilon'$ and $\varepsilon''$ as

$$\varepsilon' = \frac{g_e + (\lambda_{gs}/2a)^2}{1 + (\lambda_{gs}/2a)^2} \quad \ldots \quad (3.13)$$

and

$$\varepsilon'' = -\frac{\beta_e}{1 + (\lambda_{gs}/2a)^2} \quad \ldots \quad (3.14)$$

However, it is to be noted that quantities $\psi$, $\theta$ and $(X/\beta l_e)^2$ fall into ranges $0 < \psi < 180^\circ$, $45^\circ < \theta < 90^\circ$, $(X/\beta l_e)^2 > 1$, proper values of $X \angle 0$ is that value which yields the same value of $Y_e$ for the two samples. Eq. (3.13) and (3.14) are mainly used to determine the values of dielectric constant and dielectric loss of the red soils. By knowing these two dielectric parameters, the other parameters can easily be estimated by using appropriate formulae given below.
3.5.4 Important formulae

(a) Dielectric constant ($\varepsilon'$)

$$\varepsilon' = \frac{g_{\varepsilon} + (\lambda_{gs}/2a)^2}{1+(\lambda_{gs}/2a)^2}$$ .... (3.13)

(b) Loss factor ($\varepsilon''$)

$$\varepsilon'' = -\frac{\beta_{\varepsilon}}{1+(\lambda_{gs}/2a)^2}$$ .... (3.14)

From the measurement of dielectric constant and dielectric loss, other dielectric parameters can be obtained by using following equations:

(c) Loss Tangent

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$ .... (3.15)

(d) Microwave conductivity ($\sigma$)

$$\sigma = \omega\varepsilon_0\varepsilon''$$ .... (3.16)

(e) Relaxation time

$$\tau = \varepsilon''/\omega\varepsilon'$$ .... (3.17)

(f) Estimations of emissivity by using emissivity model

In the present research work, the emissivity model is used for estimation of emissivity from the measured values of dielectric constant for soils. Because this model is simple to use and it gives reasonable accuracy [13].

The emissivity $e_p(\theta)$ for vertical polarization (VV) can be written as

$$e_p(\theta) = 1 - r_p(\theta) = 1 - \left| R_p(\theta) \right|$$ .... (3.18)

$$e_p(\theta) = 1 - \frac{\varepsilon'\cos\theta - \sqrt{\varepsilon''\sin^2\theta}}{\varepsilon'\cos\theta + \sqrt{\varepsilon''\sin^2\theta}}$$ .... (3.19)

and the emissivity $e_p(\theta)$ for horizontal polarization (HH) can be written as
\[ e_p(\theta) = 1 - r_p(\theta) = 1 - |R_p(\theta)| \quad \ldots \quad (3.20) \]

\[ e_p(\theta) = 1 - \frac{\cos \theta - \sqrt{\varepsilon^* - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon^* - \sin^2 \theta}} \quad \ldots \quad (3.21) \]

Where,
- \( a \) = Inner width of rectangular waveguide.
- \( \lambda_{gs} \) = wavelength in the air-filled guide.
- \( g_\varepsilon \) = real part of the admittance
- \( \beta_\varepsilon \) = imaginary part of the admittance
- \( \omega \) = \( 2\pi f \) = angular frequency
- \( f \) = the microwave frequency
- \( \varepsilon_0 \) = permittivity of free space
- \( \theta \) = Angle of observation
- \( e_p(\theta) \) = Emissivity of the surface layer
- \( r_p(\theta) \) = Reflection coefficient
- \( R_p(\theta) \) = Fresnel reflection coefficient

Estimations of emissivity values for all red soil samples are made by using emissivity model at different incident angles for vertical and horizontal polarizations. Eqs. (3.18)- (3.21) are used to estimate the emissivity of soils having various MC (%) for vertical and horizontal polarizations by knowing their values of dielectric constants.

(g) Estimations of scattering coefficient by using perturbation model

Different models are to be used depending on the nature of the surface. For waveguide cell method, the surface of the soil inside the waveguide is smooth; hence the perturbation model is quite suitable [14-15]. The perturbation method requires the surface standard deviation to be less than about 5% of the electromagnetic wavelength. Accordingly, in the present case, the surface standard deviations for C- and X-bands are about 1.8 mm and 0.92 mm respectively. The corresponding surface correlation lengths are around 12.7 mm and 6.5 mm respectively. In order to apply perturbation model, the necessary conditions to be satisfied are,

\[ K \sigma < 0.3, \text{ and} \]
The backscattering coefficient is given by
\[
\frac{\sqrt{2}}{l} \sigma < 0.3
\]

Where,
- \( k \) = Wave number = \( 2\pi/\lambda \)
- \( \sigma \) = Surface standard deviation
- \( l \) = Surface correlation length

In the present case
\[
k\sigma = 0.15 \text{ and } kl = 1.0
\]

The backscattering coefficient is given by
\[
\sigma_p^\phi(\theta) = 8K^4 \sigma^2 \cos^4 \theta \times |\alpha_{pp}(\theta)|^2 W(2K \sin \theta)
\]
\[\ldots \quad (3.22)\]

\( p = v \) or \( h \)

where,
\[
|\alpha_{hh}(\theta)|^2 = \Gamma_h(\theta)
\]
\[\ldots \quad (3.23)\]

\[
\alpha_{vh}(\theta) = (e^2 - 1) \left[ \frac{\sin^4 \theta - (\sin \theta)^2}{\sin^4 \theta - (\sin \theta)^2} \right]
\]
\[\ldots \quad (3.24)\]

\[
|\alpha_{hh}(\theta)|^2 = \Gamma_h(\theta)
\]

is the Fresnel reflection coefficient for horizontal polarization.

\[
\alpha_{vh}(\theta) = \frac{\sin^2 \theta - (\sin \theta)^2}{\sin^2 \theta - (\sin \theta)^2}
\]
\[\ldots \quad (3.25)\]

and \( W(2K \sin \theta) \) is the normalized roughness spectrum, which is the Bessel transform of the correlation function \( \rho(\zeta) \), evaluated at the surface wave number of \( 2K \sin \theta \).

The normalized roughness \( = W(2K \sin \theta) \), is given by the following equation
\[
W(2K \sin \theta) = 0.5 \lambda^2 \exp[(k \lambda \sin \theta)^2]
\]
\[\ldots \quad (3.26)\]

Eqs. (3.22)-(3.26), are used to estimate the scattering coefficient of soils having various MC (%) for vertical and horizontal polarizations by knowing their values of dielectric constants.

By using these principles, experimental techniques and the formulae given in this Chapter, the dielectric, emissive and scattering properties of the dry and moist red soils at C- and X-band microwave frequencies are determined. The results relating to these investigations are outlined in the Chapters 4 and 5.
References


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