Measured Electrical Constitutive Parameters of Soil as Functions of Frequency and Moisture Content

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Abstract—**The measured electrical constitutive parameters (effective relative permittivity and effective conductivity) for "Georgia red clay" are presented. These results are for the frequency range 50 MHz–1.25 GHz and for six samples with water contents by dry weight ranging from approximately 0–30%. These electrical parameters should be useful in designing and characterizing broadband systems whose performance is dependent upon or affected by the earth, such as ground-penetrating radars.**

I. Introduction

For many years the electrical constitutive parameters (conductivity, permittivity, and permeability) of earth materials, rock, soil, etc., have been measured and reported in the literature. Fairly extensive collections are available that summarize these results [1]–[3]. An examination of these results, however, shows that many measurements are for a material in a single state, such as a soil with fixed water content, and are for a single electrical frequency. Few parametric studies are available in which both the state of the material and the frequency are varied over wide ranges. Relevant to this work are the published studies of Hipp [4] and Jesch [5], for which soil moisture content is varied with measurements made over the frequency ranges 30 MHz to 4 GHz (Hipp) and 300 MHz to 9.3 GHz (Jesch). In addition, there are a number of investigators who have measured the electrical properties of soils using time-domain reflectometry (TDR) [6]–[10]. In general, these investigators only determine the permittivity of the soil, and then only as an average value over a band of frequencies. Measurements such as those presented in this paper are particularly useful in designing and characterizing broadband systems whose performance is dependent upon or affected by the electrical parameters of the earth. An example of the former is a ground-penetrating radar where a base-band pulse, such as a monocycle, is used to detect objects buried in the earth.

In this paper, we report measurements of the electrical constitutive parameters of a particular soil, "Georgia red clay," over the frequency range 50 MHz to 1.25 GHz for various moisture contents. Frequencies in this range are the most useful for ground penetrating radars. These measurements complement those of previous investigators which are at higher, microwave frequencies [11].

II. Sample Description, Preparation, and Measurement

Several samples of soil were obtained from a single location in Cobb County, GA. These samples were thoroughly mixed together to obtain an average, representative sample for the location. Locally this soil is referred to as "Georgia red clay," but it is actually an orange-tan, micaceous, very fine to medium sandy silt (ML by the Unified Soil Classification System). The soil was baked in an oven

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TABLE I
PHYSICAL PARAMETERS FOR SOIL SAMPLES

Sample	Water Content by Dry Weight θ_m (%)	Bulk Density ρ_b (gm/cm^3)	Volume Fraction of Water θ_v (%)
1	0	1.46	0
2	2.5 (2.0)	1.45	3.6
3	5.0 (4.8)	1.48	7.4
4	10.0 (9.6)	1.51	15.1
5	20.0 (18.9)	1.43	28.6
6	30.0 (28.7)	1.45	43.5

until dry (150° C with periodic stirring for 3 h). A portion of the dried soil of known mass was then mixed with a known mass of distilled, deionized water to obtain a sample with the desired "water content by dry weight." The low-frequency conductivity of the distilled deionized water was measured at the frequency 1 kHz and found to be less than $\sigma_{LF} = 2.0 \times 10^{-4}$ S/m.

Each sample to be measured was packed into the transmission line cell, described later, to roughly the desired mass density. The electrical constitutive parameters of the sample were then measured. Finally, as a check, a portion of the sample was removed from the cell and the "water content by dry weight" again determined.

The physical parameters for the six samples measured are summarized in Table I. These parameters are described in terms of the mass, volume, and density of the soil (m, v, ρ) and its constituents: solid particles (m_p, v_p, ρ_p), water (m_w, v_w, ρ_w) and air (m_a, v_a, ρ_a), with the assumptions $m_a \approx 0$ $(\rho_a \approx 0)$ and $\rho_w \approx 1.0$. The "water content by dry weight," $\theta_m = m_w/m_p$, for the samples ranges from $\approx 0\%$ to 30%. An estimate in the uncertainty for this quantity is given by the difference in the value for which the sample was mixed and the value obtained from the later measurement described above, which is enclosed in parentheses in the table. Notice that all of these values are lower; this is probably the result of water being evaporated from the samples. The uncertainty is greatest for the sample with the lowest water content (2.5%); this is probably due to the difficulty in uniformly mixing such a small amount of water into the dry soil.

The "bulk density," $\rho_b = m_p/V$, is practically the same for all samples. Since the density of the particles, ρ_p, is a constant, this implies that the volume fraction of particles, $V_p/V = \rho_b/\rho_p$, is practically the same for all samples. This situation can be visualized as follows: Consider a fixed volume containing a certain mass (volume) of dried soil. As water is added to this volume to change the moisture content of the soil, the water displaces air. This changes the density of the soil but not the volume fraction of particles. All measurements were made at the room temperature 24°C (75°F).

All of the samples measured are assumed to be nonmagnetic: permeability $\mu = \mu_o = 4\pi \times 10^{-7}$ H/m. Their electrical behavior is then completely described by the real effective conductivity $\sigma_e(\omega)$ and the real effective relative permittivity $\epsilon_{er}(\omega) \equiv \epsilon_e/\epsilon_o$ $(\epsilon_o = 8.85 \times 10^{-2}$ F/m). Notice that both of these quantities are functions of the angular frequency ω.

The transmission line cell used to measure the electrical constitutive parameters of the soil samples is shown in Fig. 1. It is a section of 50 Ω precision coaxial air line (General Radio GR900) with one end open and shielded. The material to be measured is placed in the cell and must extend a distance of about 2 b (twice the inner radius of the outer conductor) beyond the end of the center conductor to contain the fringing field. The input admittance of the cell is measured over a range of frequencies, and these data are used to obtain the constitutive parameters of the material as a function of frequency. The method of inversion used in this process is describec in detail elsewhere [12].

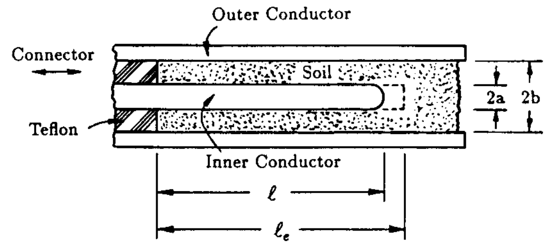

Fig. 1. Transmission line cell.

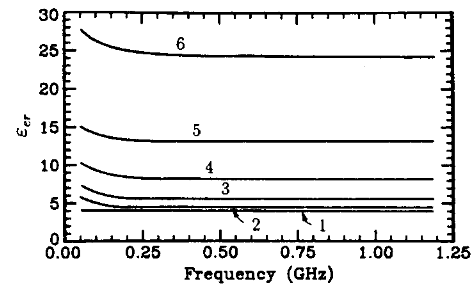

Fig. 2. Measured relative effective permittivity of soils as a function o frequency. The number on each curve corresponds to the sample number i: Table I and is for the water content by dry weight, θ_m: (1) $\approx$ 0; (2) 2.5% (3) 5.0%; (4) 10.0%; (5) 20.0%; (6) 30.0%.

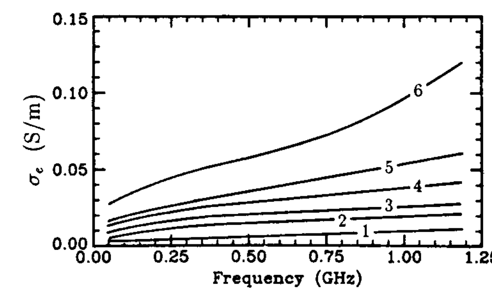

Fig. 3. Measured effective conductivity of soils as a function of frequency The number on each curve corresponds to the sample number in Table I anc is for the water content by dry weight, θ_m: (1) $\approx$ 0; (2) 2.5%; (3) 5.0%; (4 10.0%; (5) 20.0%; (6) 30.0%.

The measured results for the six soil samples are presented in Figs. 2 and 3. These graphs show the effective relative permittivity, ϵ_{er}, and the effective conductivity, σ_e, as functions of the frequency. Foı each parameter, the smooth curve is a fit to 25 equally spaced points measured over the frequency range 50 MHz to 1.25 GHz.

III. DISCUSSION

The results in Figs. 2 and 3 clearly show the effects of increasing the water content of the soil. The relative permittivity and conductivity both increase with increasing water content. The relative permittivity is fairly independent of frequency except at the lowest frequencies measured, $\lesssim$ 250 MHz, where it increases with decreasing frequency. This phenomenon is often observed with heterogeneous materials and is attributed to various mechanisms at the particle level, such as electrochemical effects at the particle-water interface [13]–[18]. The effective conductivity increases with increasing frequency, and this phenomenon is thought to be associated

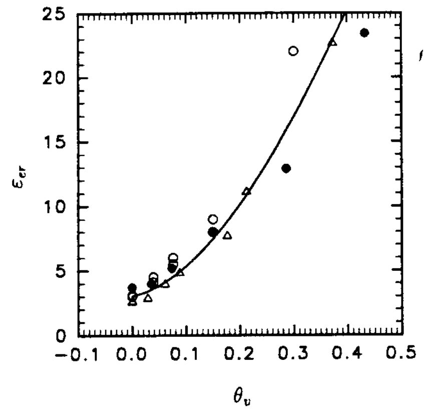

Fig. 4. Effective relative permittivity of various soils versus volume fraction of water, frequency 1 GHz. • This Study, o Results from [4], Δ Results from [5], — Topp's Equation [6].

with the increase in the loss in the water phase due to the dipolar relaxation of the water molecules [14].

In Fig. 4 the effective relative permittivity, ϵ_{er}, for the soil samples measured in this study, "Georgia red clay," are graphed as a function of the "volume fraction of water," $\theta_v = V_w/V$, using solid dots. The results are for the frequency 1 GHz, and, as seen from Fig. 2, are indicative of the permittivity over the frequency range 250 MHz $\lesssim f \lesssim$ 1.25 GHz. In this range, the permittivity is fairly constant, because the frequency is above the region where the heterogeneous nature of the soil causes dispersion and below the region where the dipolar relaxation of the water molecules causes noticeable dispersion in ϵ_{er}. Selected results from the studies of Hipp [4] and Jesch [5] are also graphed in Fig. 4. These measurements were chosen for the comparison because they were made using comparable transmission line cells (GR900 line) and similar frequencies to those in this study. The open circles are for "gray San Antonio clay loam" and "reddish-brown Puerto Rico clay loam" [4], while the open triangles are for "sand" and "sandy loam" [5]. Only the results that have values of "bulk density," ρ_b, similar to those for this study ($1.40 \leq \rho_b \leq 1.55$) are graphed.

The grouping and common trend of these data indicate the strong correlation between the volume fraction of water and the effective relative permittivity of soils. These results are particularly striking when one considers that they are for a variety of soils and were measured using different techniques. Similar behavior has been reported by other investigators [11], [19]. The curve (solid line) in Fig. 4 is for the empirical equation obtained by Topp as a fit to the measured permittivity of four mineral soils [6]. Unlike the other measurements presented in Fig. 4, these measurements were obtained using TDR in a manner in which the frequency dependence of the permittivity and electrical conductivity were not taken into account. In some sense, they represent an average permittivity over a band of frequencies. The measured points in Fig. 4 are seen to be in general agreement with this curve.

Unfortunately, an equation as simple as Topp's cannot be obtained for the effective conductivity for soils. This parameter is strongly dependent on factors in addition to θ_v, e.g., the salinity of the water. The dispersion exhibited by this parameter over the frequency range of interest, Fig. 3, also makes predictions based on a single frequency less useful.

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