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A Simple Coaxial Waveguide Fixture Designed for the Measurement of Dielectric Properties of Contaminated Soil

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Abstract: A coaxial transmission/reflection measurement system is used for the dielectric characterization of soils and contaminated soils from 300 MHz to 800 MHz. The sample holder is a circular coaxial waveguide fixture designed to accommodate significant volumetric samples of material. The complex permittivity of soil and contaminated soil is given for dry, wet, and contaminated (petroleum-based) silt loam.

Keywords: coaxial waveguide, permittivity measurement, soil measurements, ultra-high frequency

I. INTRODUCTION

Scattering of electromagnetic waves by embedded dielectric, inhomogeneous objects is an important research area in subsurface sensing. Geophysical methods, such as surface geophysics and borehole geophysical logging, can be used to aid in characterizing changes in subsurface features [1].

Contamination of soil by organic fluids - such as petroleum-based oils, benzine, gasoline, kerosene, etc - is receiving greater interest in an increasingly environmentally-concerned world. Detection of spills, along with mapping the volumetric extent of such spills for remediation purposes, is an expensive process since the gold standard for such detections is laboratory analysis of bore-hole samples. The use of radio frequency mapping procedures offers the potential for fully volumetric mapping of soil contamination without the need for expensive laboratory analysis. The ultra-high frequency (UHF) band offers a good compromise between physical dimensions of the necessary equipment, resolution, and propagation length per unit power. Before using any of the geophysical methods available, a better knowledge of the dielectric properties of the media in the UHF band is required.

Many researchers have collected soil electrical property data in their different fields of study. Some methods used for permittivity and permeability measurements include cavity resonators, free-space, open-ended coaxial-probe, dielectric resonator, and transmission-line techniques[2]. With the use of modern network analyzers and frequency sweep techniques, the transmission/reflection (TR) method is presently widely used for the measurement of solid materials In this study, TR method is used for the dielectric measurement of petroleum-contaminated soil.

II. BACKGROUND

The TR method was first introduced by Nicholson and Ross [3] and improved by Weir (now known as the Nicholson-Ross-Weir or NRW method), Baker-Jarvis, Courtney, and others [4]-[7]. In the TR method, a material sample is placed in a section of a waveguide or coaxial line and an incident electromagnetic field is applied. The two-port complex scattering parameters are measured at the ports of the fixture and via a calibration process, the scattering parameters at the faces of the sample are determined. From these data, the permittivity and permeability of the material is obtained via inversion using the NRW method. In developing the scattering equations, only the fundamental waveguide mode is assumed to propagate, and hence there is a need for a sufficient stand-off distance between the sample and the material sample so that higher-order modes are quenched. Note that while all soil samples are expected to be nonmagnetic, the extracted value of permeability may be compared to unity to judge the quality of the measurements.

The two-port cell presented is designed to be used for the dielectric characterization of soil and contaminated soil at a frequency range of 300 MHz to 800 MHz. It can be fabricated relatively inexpensive and can accommodate significant volumetric samples of material. The values for complex relative permittivity $(\varepsilon_r = \varepsilon_r' - j\varepsilon_r'')$ are calculated using the TR method. The goal of this work is to determine if sufficient contrast between uncontaminated and contaminated soil exists for wide area spill detection with either a borehole or ground-penetrating radar (GPR). If so, the ability to detect, and hence remediate, contaminated soil will be significantly improved along with a reduction in cost.

III. MEASUREMENT PROCEDURE

A. Coaxial Waveguide Fixture

The sample holder, shown in Fig. 1, is a symmetric coaxial waveguide fixture designed using brass. It is intended to operate in a frequency range between 100 MHz to 1 GHz.

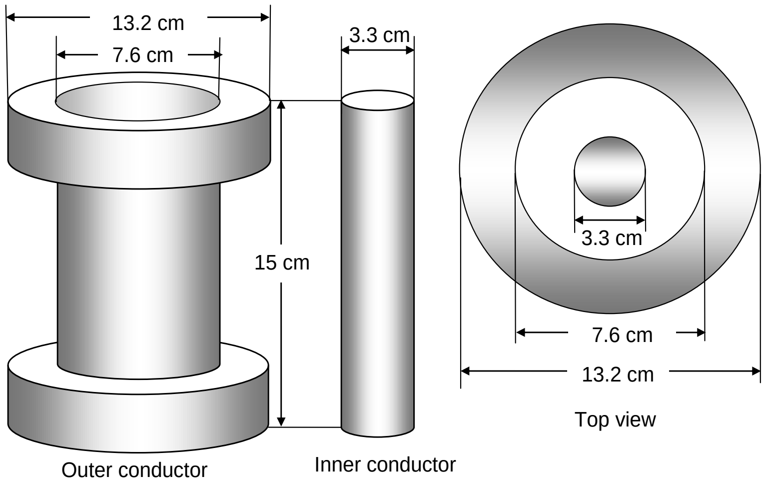

Fig. 1.Dimensions of the coaxial waveguide sample holder.

The length of the sample holder is a half-wavelength of the signal for the transverse electromagnetic (TEM) mode at the highest frequency of interest. The distributed electromagnetic parameters of the coaxial line fixture are determined using the equations established in [8]. The fixture has a distributed inductance and capacitance of L=1.704x10^{-7} H/m, C=6.528x10^{-11} F/m, respectively. Hence, the characteristic impedance of the fixture is Z_0 = 51.08 Ω. The propagation constant γ is j2.095 rad/m at 100 MHz, j10.477 rad/m at 500 MHz, and j20.954 rad/m at 1 GHz. The TE_{11} mode cutoff frequency of 1.785 GHz is the lowest cutoff frequency of all higher-order modes. Since the intended frequency range of operation is below the TE_{11} mode cutoff frequency, the TEM mode is the only propagating mode in the empty test fixture within the frequency range of interest.The total volumetric capacity of the sample holder is approximately 552 cm^3. This volume permits homogenization of the material properties even with relatively large (order of millimeter) solid phase constituent materials in the soil mixture.

B. Experimental Setup

The sample holder is connected to an HP 8753D Vector Network Analyzer (VNA) using an ASTM D 4935 flanged coaxial fixture [9]. The experimental setup is shown in Fig. 2. The VNA is used for determination of the S-parameters of the sample, as calibrated with a Thru-Reflect-Line (TRL) method [10]. These are subsequently processed using TR method to obtain the required EM properties.

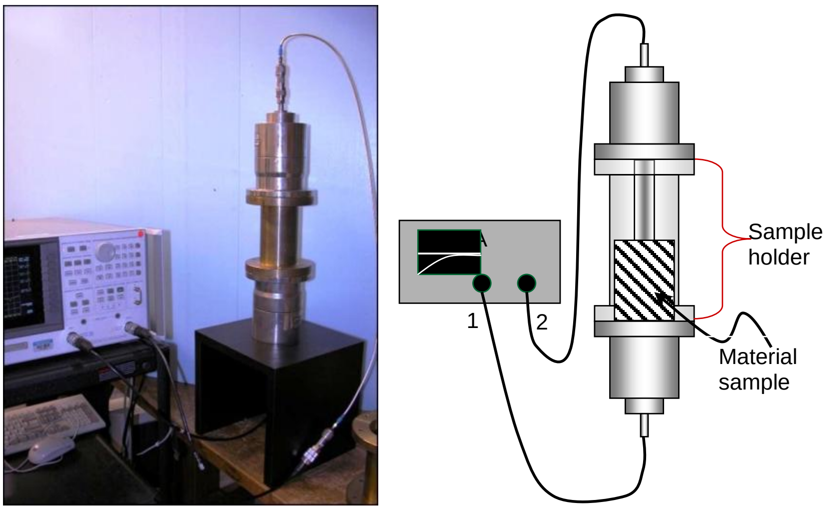

Fig. 2.Measurement setup.

To test the system, two Plexiglas samples with lengths 9.5 cm and 4.75 cm were machined to fit snugly inside the coaxial fixture. The samples were placed as shown in Fig. 2. The average measured permittivity value with respect to frequency for both samples is ε_r= 2.58-*j*0.002. This value is in accordance with the typical value for Plexiglas [11].

C. Sample Preparation

Samples of dry, wet, and contaminated silt loam soil were prepared. All soil was silt loamy soil with 15% clay, 5% sand and 80% silt. The collected soil was heated in an oven at 105°C for 24 hours to obtain the dry soil samples. The weight of the dry soil samples was measured and a predetermined amount of distilled water was then added to achieve the desired volumetric moisture content. After weighing the wet soil samples, they were sealed and the water was allowed to redistribute for 24 hours. After that, the volumetric moisture content of the sample was determined using the method described in [12]. Since these values are bulk densities, the air spaces between the soil particles are ignored.

IV. EXPERIMENTAL RESULTS

First, the permittivity of the dry soil sample was measured. The obtained value of permittivity was compared to the predicted value using the dielectric model for soils developed by Peplinski, et al. [13]. Fig. 3 illustrates the measured and predicted relative complex permittivity of dry soil. As seen, the dry soil is non-magnetic as assumed with a nominal permittivity of 2.1 with very low loss. The measured loss tangent across the frequency range is 0.0151.

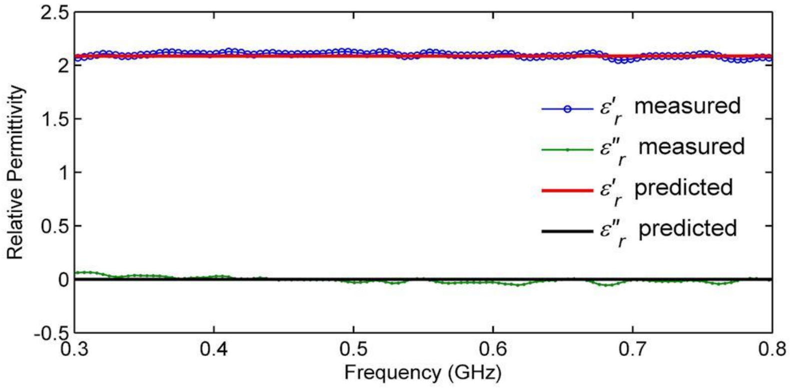

Fig. 3.Complex relative permittivity and permeability of dry soil sample.

Wet soil samples were prepared by adding 10% and 25% volume of moisture to the dry soil samples. Results for these wet samples are presented in Figs. 4 and 5. A reasonable increase in permittivity values is obtained as the water content of the sample increases. The results obtained from the experimental data are in good agreement with the values predicted from the Peplinski model.

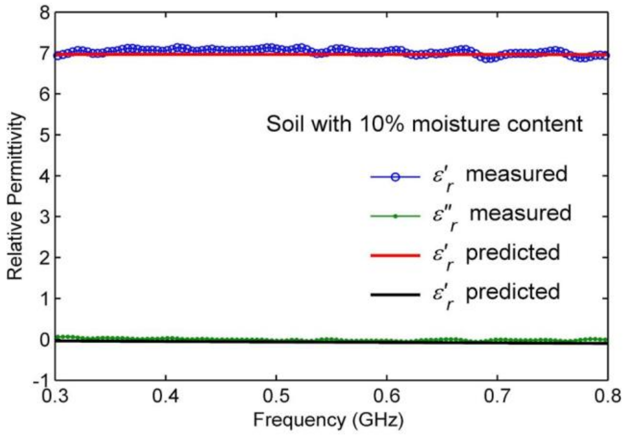

Fig. 4.Complex relative permittivity of soil with 10% moisture content.

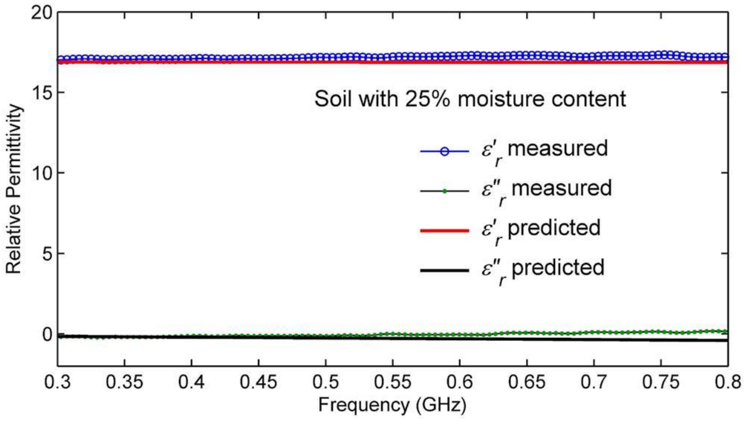

Fig. 5.Complex relative permittivity of soil with 25% moisture content.

Samples of contaminated silt loam soil were prepared following the same procedure as with the wet silt loam soil samples. The contaminant used is motor oil (SAE 30) with a relative permittivity of 2.2. This value is close to the relative permittivity of dry soil. Samples of dry soil with 25% oil content were measured. The results were compared with the predicted values calculated using the Maxwell Garnett mixing rule presented in [14]. Fig. 6 shows that there is insufficient change in permittivity values to distinguish between dry and contaminated soil considering that a nominal uncertainty is 5-10% for these types of measurements.

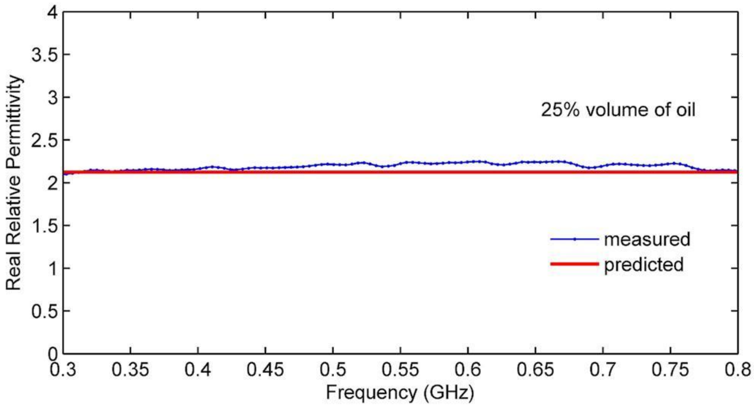

Fig. 6. Real relative permittivity value for dry soil with 25% oil content.

Motor oil (as a contaminant model) was added to wet soil samples. When an organic liquid like oil is introduced to water-wet soil, the contaminant displaces the air and some of the water from the soil pores. Soil particles remain wetted by water and the contaminant emerges as a dispersed phase [15]. At a macro-scale, the oil does not appear to separate from the water due to the soil. Mixtures of 25% oil and soil with 10% and 25% moisture content were measured and the results are presented in Fig. 7. A significant difference, e.g. greater than the nominal uncertainty in the measured data, with regards to the permittivity values was observed between the wet soil and wet soil with oil contamination (please compare Figs. 4, 5, and 7).This is an indication that if wet soil is present, it will provide sufficient contrast to distinguish contaminated from uncontaminated soil.

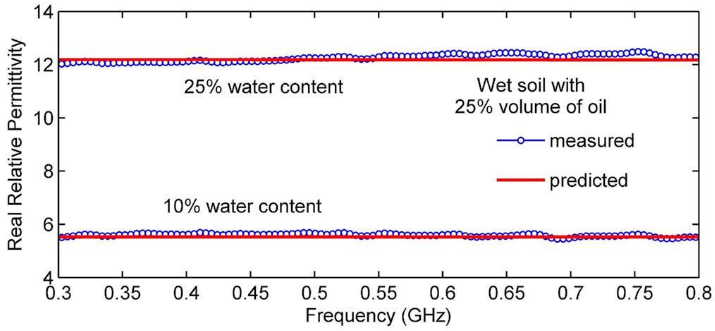

Fig. 7.Results for a mixture of 25% volume of contaminant in soil with 10% and 25% volumetric moisture content.

Measured results are compared with the predicted values calculated using the mixing rules for moist and high-loss materials presented in [14]. As GPR signals travel through the soil, they are attenuated at a rate determined by the complex dielectric constant of the soil. The power attenuation in dB/m is given by

$$\text{Power attenuation} = 8.6855\frac{2\pi f}{c}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)}$$

where$c$ is the speed of light 2.997×10^8 m/s.Fig. 8 shows how changes in frequency relate to radar wave attenuation in different soils. As frequency increases, the attenuation of the GPR signals in both wet and contaminated soils increases rapidly. High frequency radar is often used to enhance resolution since resolution increases with frequency, but as shown in this figure, signal attenuation increases quite dramatically at higher frequencies.

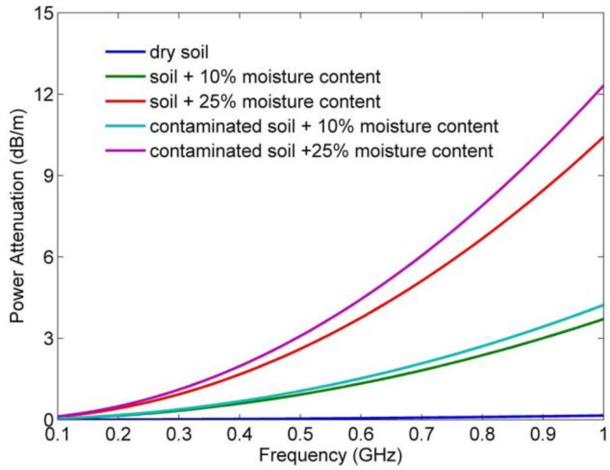

Fig. 8.Power attenuation in dry, wet and contaminated soil in a frequency range of 100 MHz to 1 GHz.

V. CONCLUSION

The primary goal of this work is measurement of the complex permittivity for dry, wet, and contaminated (dry and wet) silt loam soils. A coaxial test fixture was fabricated and used to make the measurements. Various water and contamination concentrations were investigated and compared to nominal permittivity data for dry silt loam soil. The increase in relative permittivity for the soil with moisture matched predicted results [15]. The measured contrast between dry soil and dry soil contaminated with oil was within the nominal uncertainty of the experiment and hence it is not expected that a rise in permittivity for dry soil contaminated with fairly high volumetric concentrations of oil will allow sufficient contrast for either radio frequency bore-hole or GPR mapping. There was however a significant difference between the measured permittivity for wet soil and that of wet soil contaminated with oil. Hence, it is reasonable that this permittivity contrast can be used as a discriminator for detecting contamination plumes. This is significant since contamination in an aquifer is one of the most environmentally challenging issues facing the world. Research into the discrimination capabilities of a radar system using this ground-truth will be the subject of future research.

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