Theoretical Notes

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Low-Field Electrical Characteristics of Soil

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ABSTRACT

The low-field electrical characteristics (conductivity and dielectric constant) have been measured as a function of frequency from 1 kHz to 10 MHz for soil samples obtained from the Siege Development Facility (SDF) at Albuquerque, New Mexico. These results are compared to similar data obtained by J. H. Scott (ref. 1) for various soil samples and water content and to the universal soil impedance model of Longmire and Smith (ref. 2).

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1. J. H. Scott, 'Electrical and Magnetic Properties of Rock and Soils,' Note 18, Electromagnetic Pulse Theoretical Notes, AFWL EMP 2-1, April 1971. Also U.S. Geological Survey Technical Letter, Special Project 16, May 26, 1966.

2. C. L. Longmire and K. S. Smith, 'A Universal Impedance for Soils,' Theoretical Notes, Note 247, October 1975.

SECTION I

INTRODUCTION

If an electromagnetic pulse is incident on the surface of the earth, electrical currents will be induced on any buried conductors and cables in the vicinity. If the magnitude of the incident electric field is not too large ($\lesssim 1$ MV/m), the penetration of the incident field into the soil and its coupling to the buried conductors will be governed by the linear, low-field electrical characteristics of the soil (electrical conductivity σ and relative dielectric constant $\varepsilon_r = \varepsilon/\varepsilon_0$). However, if the incident fields are considerably greater than about 1 MV/m, it is possible for the soil to break down electrically and conduct significantly larger currents.

A program has been performed by JAYCOR for the Air Force Weapons Laboratory to measure both the low-field linear characteristics and the high-field breakdown characteristics for samples of soil obtained from the Siege Development Facility at Albuquerque, New Mexico. The present paper presents the low-field characteristics of the soil as a function of frequency and water content. The high-field breakdown characteristics will be presented in a separate document (ref. 3).

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3. JAYCOR report, in preparation. (To be Theoretical Notes, Note 316, 12 January 1981.)

SECTION II

TEST SAMPLES

For this program, three different batches of soil were received from the Siege Development Facility. The site where the soil samples were taken is illustrated in Figure 1. The first two batches were small quantities (about a gallon each). The second of these batches was taken after a rainstorm in Albuquerque and had a rather high water content (≈16% by volume). The third batch was a large quantity for filling a large cylindrical test chamber. All of the results presented in this paper are for samples prepared from the first small batch of soil.

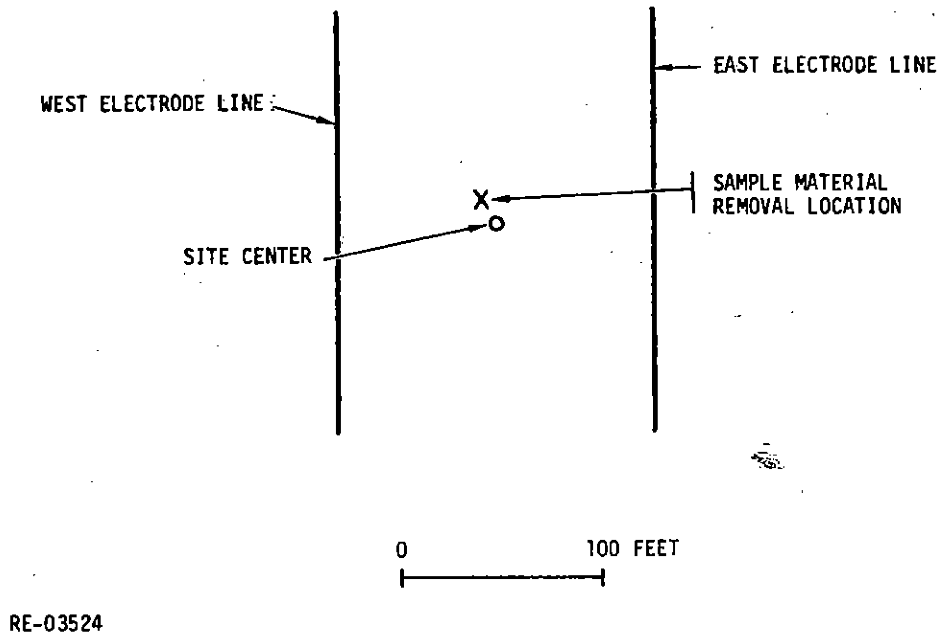

Figure 1. SDF Site Showing Origin of Sample Material

In its as-received condition, the soil contained clods of dirt, small rocks, and pieces of organic material. Before preparing the test samples, the soil clods were pulverized and then the mixture was strained through a 1/16 x 1/16 inch mesh screen to remove the pebbles and the larger organic debris. To obtain the desired water content, the screened soil was either dried or more water was added as required. The water content was calculated from the change in weight of the samples from the dry to the wet condition.

All of the test samples used in this portion of the program were cylindrical in shape with diameters from 5 to 10 cm and lengths from 0.5 to 5.1 cm. They were all constructed in the following manner. The cylindrical sides of the samples were high-resistivity rigid plastic tubes. The top and bottom electrodes were flat metallic plates constructed to fit snugly inside the plastic cylinders. The outer edges of the electrode plates were rounded to minimize concentration of the electric field at the sample edges. An illustration of a test sample is shown in Figure 2. The required weight of soil for a given sample area and the desired sample length was calculated using a density of 1.5 g/cm^3. This weight of soil was then loaded into the cylindrical sample chamber and compacted by tapping the upper electrode while the sample was subjected to a weight load that approximated the pressure at approximately one meter soil depth. The sample thickness was then measured and the material density calculated. The sample-to-sample variations in the calculated density using this procedure was ~1.5 g/cm^3 ± 5 percent. The electrical characteristics of the samples presented in this report were measured immediately after they were constructed (within 5 to 10 minutes).

Several kinds of electrodes were tried in an attempt to provide the best-possible electrical contact between the electrodes and the soil. Some of the electrodes that were tried were bare aluminum and brass, aluminum and brass with a thin layer of conducting uncured Ag epoxy, and aluminum with a thin layer of Redux cream, a Hewlett-Packard product that is used to make electrical contact to humans for electrocardiograms. The bare metal electrodes produced results that indicated rather severe contact polarization effects at low frequencies due to poor electrical contacts between the electrodes and the soil. Coating the bare metal electrodes with a thin layer of uncured conductive Ag epoxy improved the contacts, presumably due to an enhanced surface contact area. The best results were obtained with the Redux cream on aluminum electrodes and all of the results presented herein are for these contacts. The metal electrodes themselves were 1 mil thick aluminum plates attached to rigid brass electrodes with Ag epoxy.

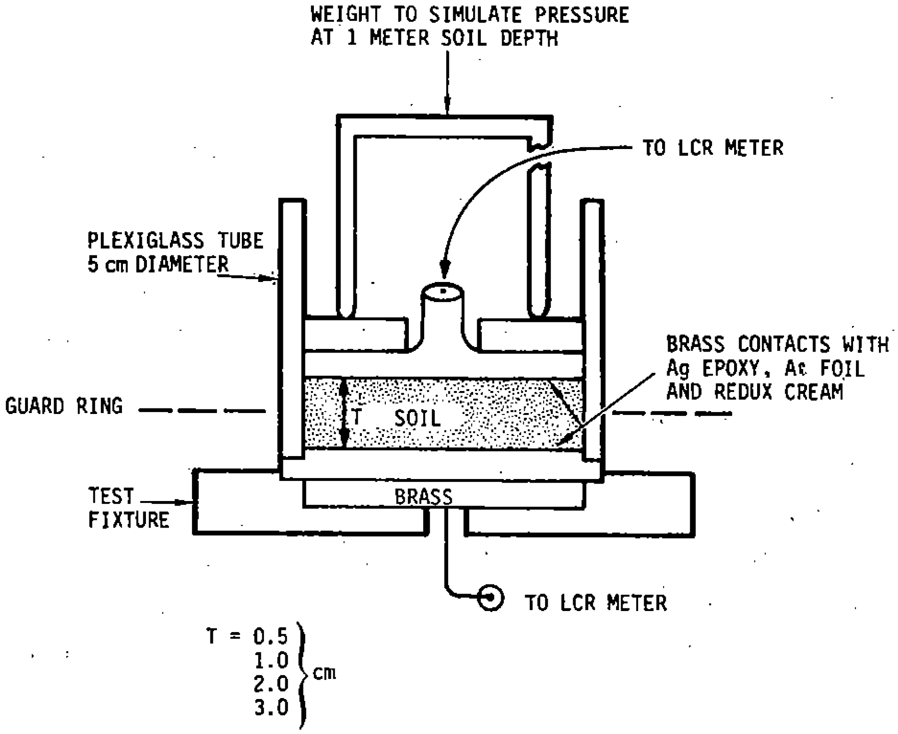

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Figure 2. LCR Test Fixture

SECTION III

TEST PROCEDURE

The frequency dependence of the electrical conductivity and relative dielectric constant of soil samples were measured using commercial Hewlett-Packard LCR meters. An HP 4274A meter was used over the frequency range of 10^2 to 10^5 Hz and an HP 4275A meter from 10^4 to 10^7 Hz.

A guard ring around the sample was used to minimize the effects of fringing fields. The effectiveness of this guard ring was demonstrated using a 0.5-inch thick by 2-inch diameter air-dielectric sample in which the effective relative dielectric constant (based on a planar calculation) went from 1.6 without the guard ring to essentially unity with the guard ring.

Additional verification of the compatibility of the measuring instrument with the sample cell geometry was demonstrated by measurements on a material with a known moderate dielectric constant, Teflon ($\varepsilon_r \sim 2.1$), and H_2O with a known relatively large dielectric constant of ~80. The results of these measurements are shown in Table 1. The agreement with the accepted values for ε_r for these materials is quite good.

Table 1

RELATIVE DIELECTRIC CONSTANT MEASURED FOR AIR, TEFLON, AND WATER SAMPLES USING HP 4275A LCR METER

		ε_r	
Frequency (Hz)	**Air**	**Teflon**	**Water***
1×10^4	1.0	2.19	88
2×10^4	0.99	2.19	85
4×10^4	0.99	2.19	83
1×10^5	0.98	2.18	81
2×10^5	0.98	2.18	79
4×10^5	0.98	2.17	77
1×10^6	0.97	2.17	76
2×10^6	0.98	2.17	76
4×10^6	0.97	2.18	76
1×10^7	1.0	2.30	81

* Water sample was prepared by reverse osmosis; conductivity over this frequency range was 3.7 to 5.3×10^{-4} mho/m.

SECTION IV

EXPERIMENTAL RESULTS

The experimental data are presented in two groups. The first group consists of one very dry sample ("0"% H_2O) and three samples of different lengths (0.5 to 5.1 cm) with water contents of about 4% H_2O by volume. The second group of samples were all 2 cm long and had water contents from 2.9 to 8.5% H_2O by volume.

For each sample, curves are presented for the electrical conductivity σ, the relative dielectric constant ε_r, and the ratio of the peak displacement current to the peak conductivity current ($\varepsilon_r \varepsilon_o \omega / \sigma$) for CW excitation. The curves for the first group of samples are given in Figures 3, 4, and 5, and for the second group in Figures 6, 7, and 8. These results are discussed and compared to the results of Scott (ref. 1) and the universal soil impedance model of Longmire and Smith (ref. 2) in Section V.

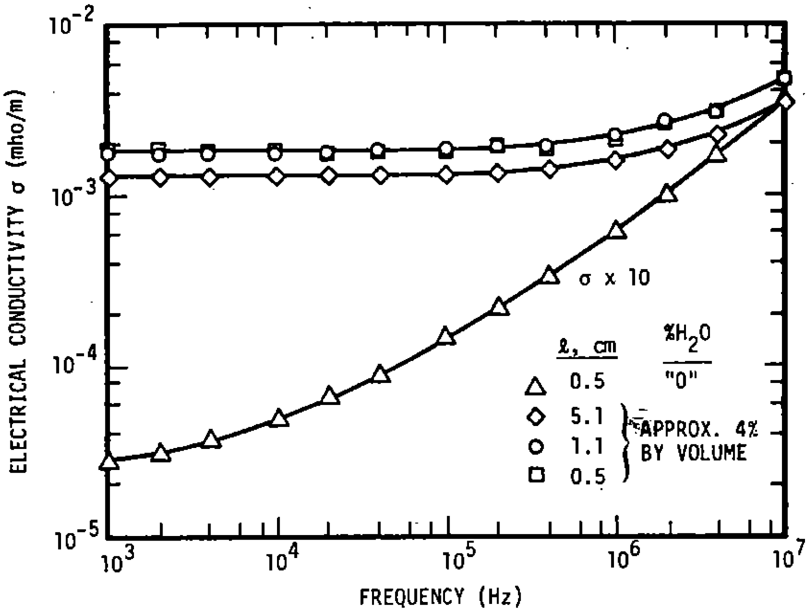

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Figure 3. Electrical Conductivity of Soil Versus Frequency for Different Sample Lengths

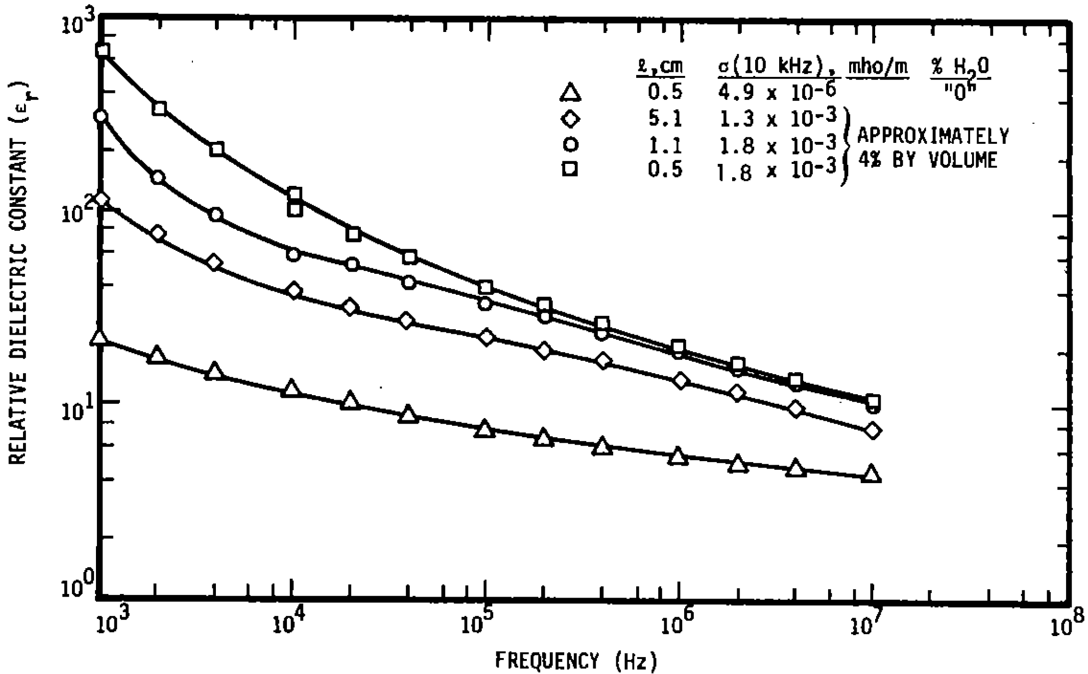

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Figure 4. Relative Dielectric Constant of Soil Versus Frequency for Different Sample Lengths

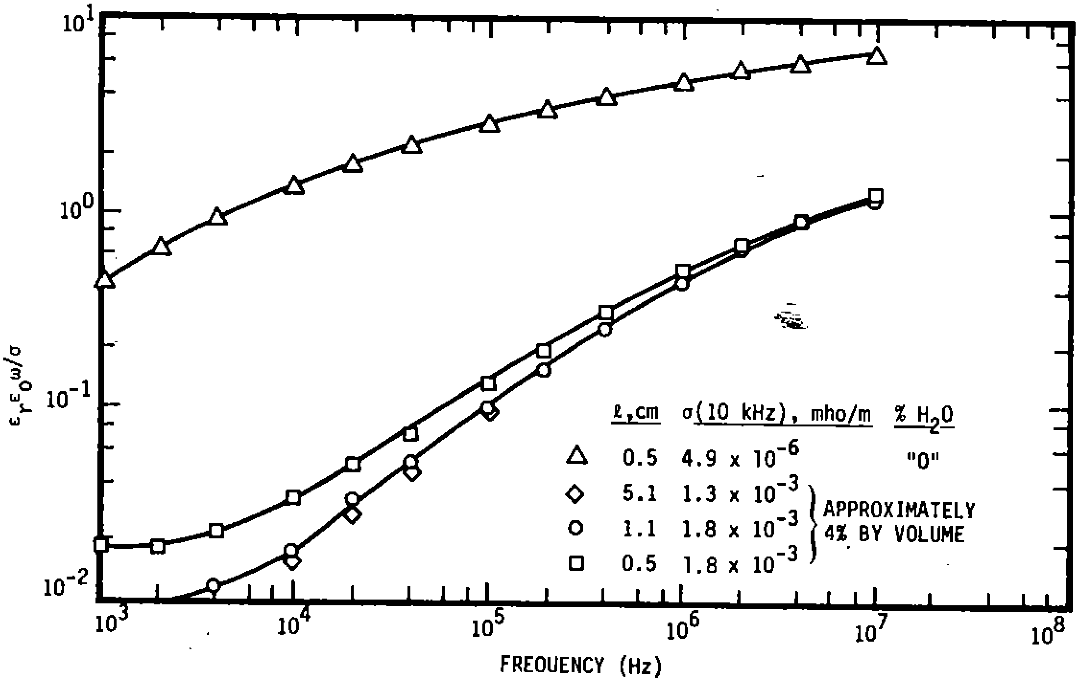

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Figure 5. Ratio of Displacement Current to Conductivity Current Versus Frequency for Different Sample Lengths

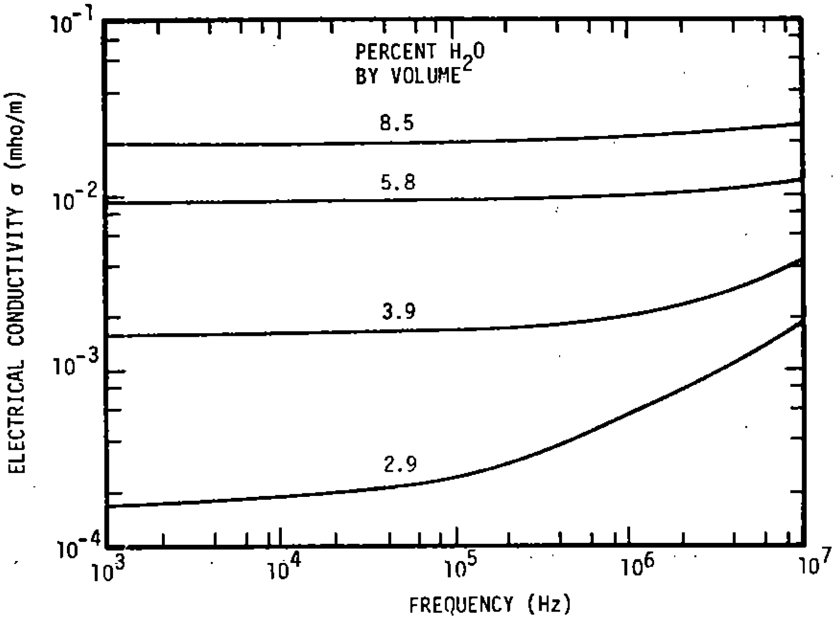

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Figure 6. Electrical Conductivity of Soil Versus Frequency for Different Water Contents (Sample Length = 2 cm)

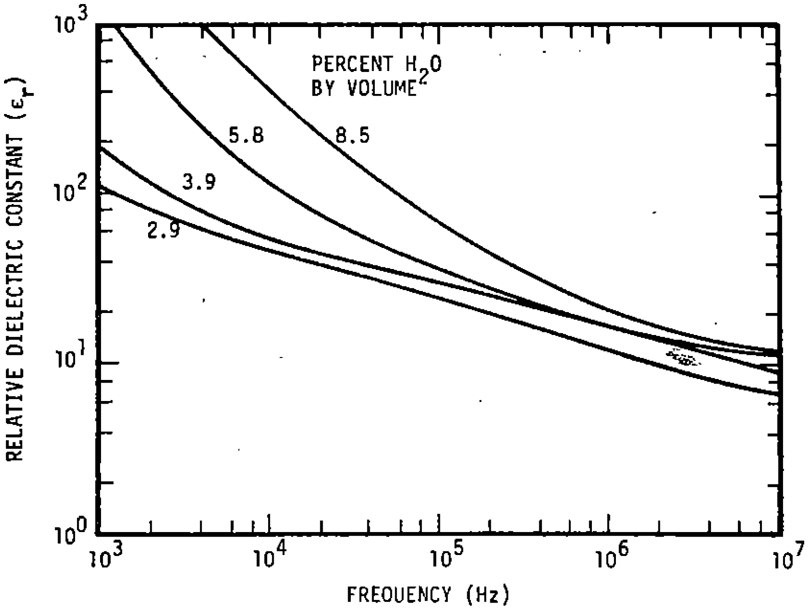

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Figure 7. Relative Dielectric Constant of Soil Versus Frequency for Different Water Contents (Sample Length = 2 cm)

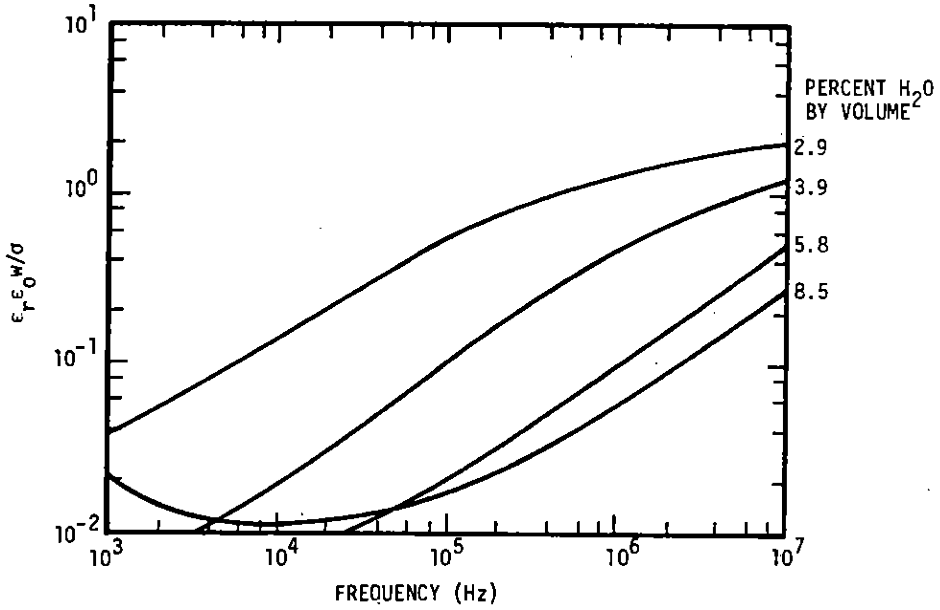

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Figure 8. Ratio of Displacement Current to Conductivity Current Versus Frequency for Different Water Contents (Sample Length = 2 cm)

SECTION V

DISCUSSION OF DATA

J. H. Scott had previously measured σ and ε_r for several different soil types and water contents versus frequency from 10^2 to 10^6 Hz. He noted that water content was the major factor which determined the electrical properties of the different soil types. Therefore, he averaged his data for the different soil types with water content as a parameter. Using these averaged electrical characteristics, Longmire and Smith developed a universal soil impedance model as a function of frequency and water content. Curves of the averaged experimental data and the fit of the universal soil impedance model are reproduced from reference 2 in Figures 9 and 10.

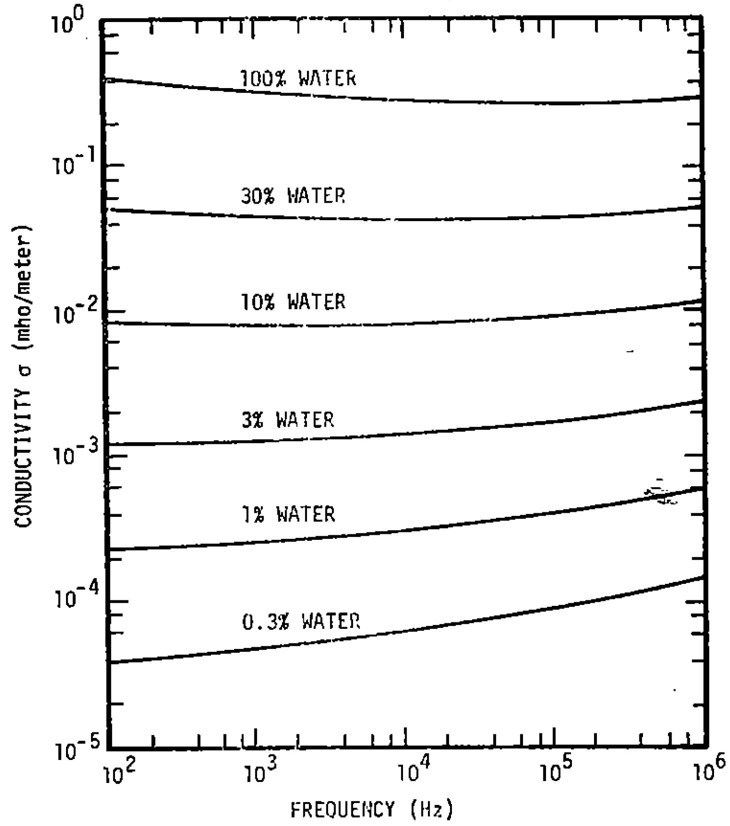

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Figure 9. Electrical Conductivity of Soils (Water Content is Percent by Volume).

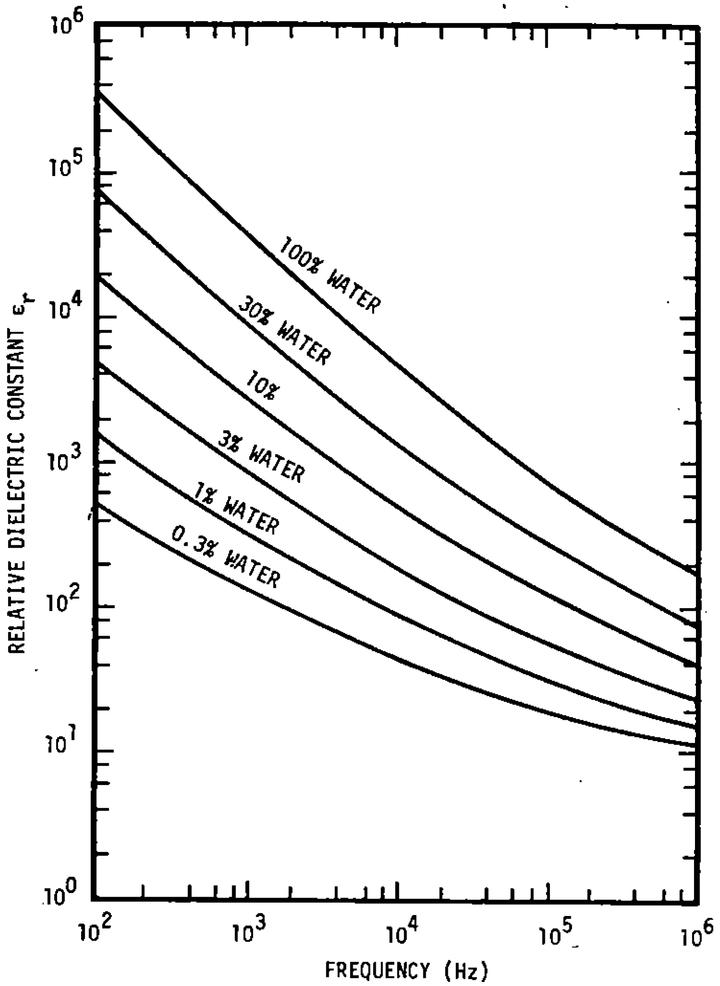

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Figure 10. Relative Dielectric Constant of Soils (Water Content is Percent by Volume).

Comparison of the data from reference 2 (Figures 9 and 10 in this report) with the present data (Figures 3, 4, 6, and 7) indicates some significant differences between the two sets of results. First, the electrical conductivity in the present data has a significantly stronger dependence on water content over the range from 3 to 9% H_2O by volume than does the data of reference 1. This dependence is illustrated more clearly in Figure 11 where σ at 10^4 Hz is plotted versus water content for the two sets of data.

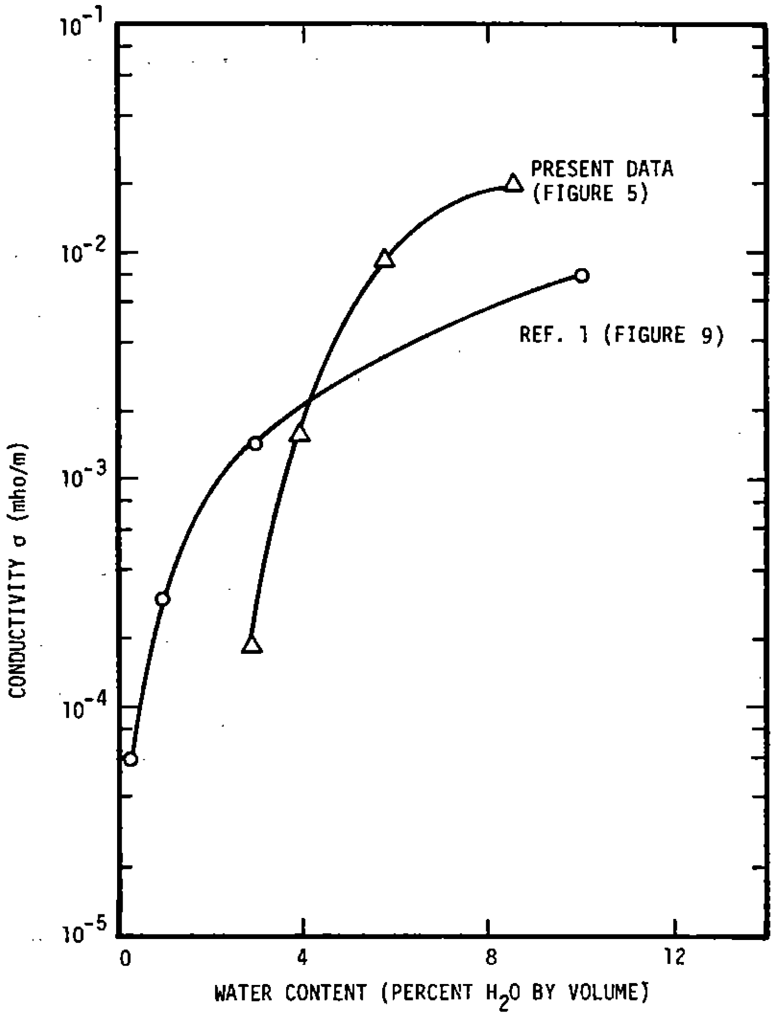

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Figure 11. Electrical Conductivity σ at 10^4 Hz Versus Water Content

There are a couple of possible reasons for this difference. One obvious possibility is inaccuracy in measuring either σ or the water content. However, the use of an LCR meter is so straightforward that errors in σ seem unlikely. In addition, in the present work, two different meters were used over different frequency ranges and the two sets of readings agreed at the overlapping frequencies, around 10^4 Hz.

The following is the sequence of events used in the present work to determine the water content of the samples. First, a sample of the as-received soil was weighed and then completely dried in a breaker over a flame. From the change in weight before and after drying, the as-received water content was about 4% by volume. To construct samples with more water than the as-received soil, a measured amount of water was added to a weighed sample of soil and the water content was calculated. To construct samples with less water than the as-received soil, a weighed sample of soil was heated until the loss in weight corresponded to the desired water content. As a check on this water content, some of the soil was then completely dried out and the amount of water lost was measured. The sum of the water lost in the two weighing processes agreed with the as-received water content. Thus, in Figure 11, it is fairly definite that the present sample with 2.9% water had at least that much water and was not around 0.7% H_2O, as would be inferred from Scott's data for the same measured σ. In Scott's experiments (ref. 4), the base water-content condition was fully saturated material. Dryer samples were obtained by air drying for 15 hours for one reduced water content and then an additional 21 hours for another water content. Thus, except for any differences between air drying and heating, his measurement of water content should be comparable to ours.

Probably the source of the difference is the actual soil composition. Figure 12 is a reproduction of a figure from reference 4. It will be noted that different types of soil and rock were used over different ranges of water content. For example, topsoil was used from 20 to 50% H_2O, and alluvium from 7.5 to 25%. Of greater interest, the conductivity in the range of 1 to 2% H_2O was determined from sandstone, shale, and quartz monzonite, all of which were apparently in solid (rock) form for the test samples. Thus, in addition to the density of the low-H_2O-content samples being higher than the present samples, they had some degree of crystallinity. Eberle (ref. 5) suggests a parameter of S_W = [Vol H_2O/Vol pores in the soil] as a correlation parameter for soil samples. This parameter would change drastically with soil density for the same water content by volume. Thus, it is not surprising that the measured σ for our sand-like material at about 2% H_2O by volume should be different from the measured σ for rocks with the same water content.

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4. J. H. Scott, R. D. Carroll, and D. R. Cunningham, "Dielectric Constant and Electrical Conductivity of Moist Rock from Laboratory Measurements," U.S. Dept. of the Interior Geological Survey, Sensor Simulation Notes, Note 116, August 17, 1964.

5. W. R. Eberle, "The Effects of Water Content and Water Resistivity on the Dispersion of Resistivity and Dielectric Constant in Quartz Sand in the Frequency Range 10^2 to 10^8 Hz," U.S. Geological Survey, Theoretical Notes, Note 82, August 1970.

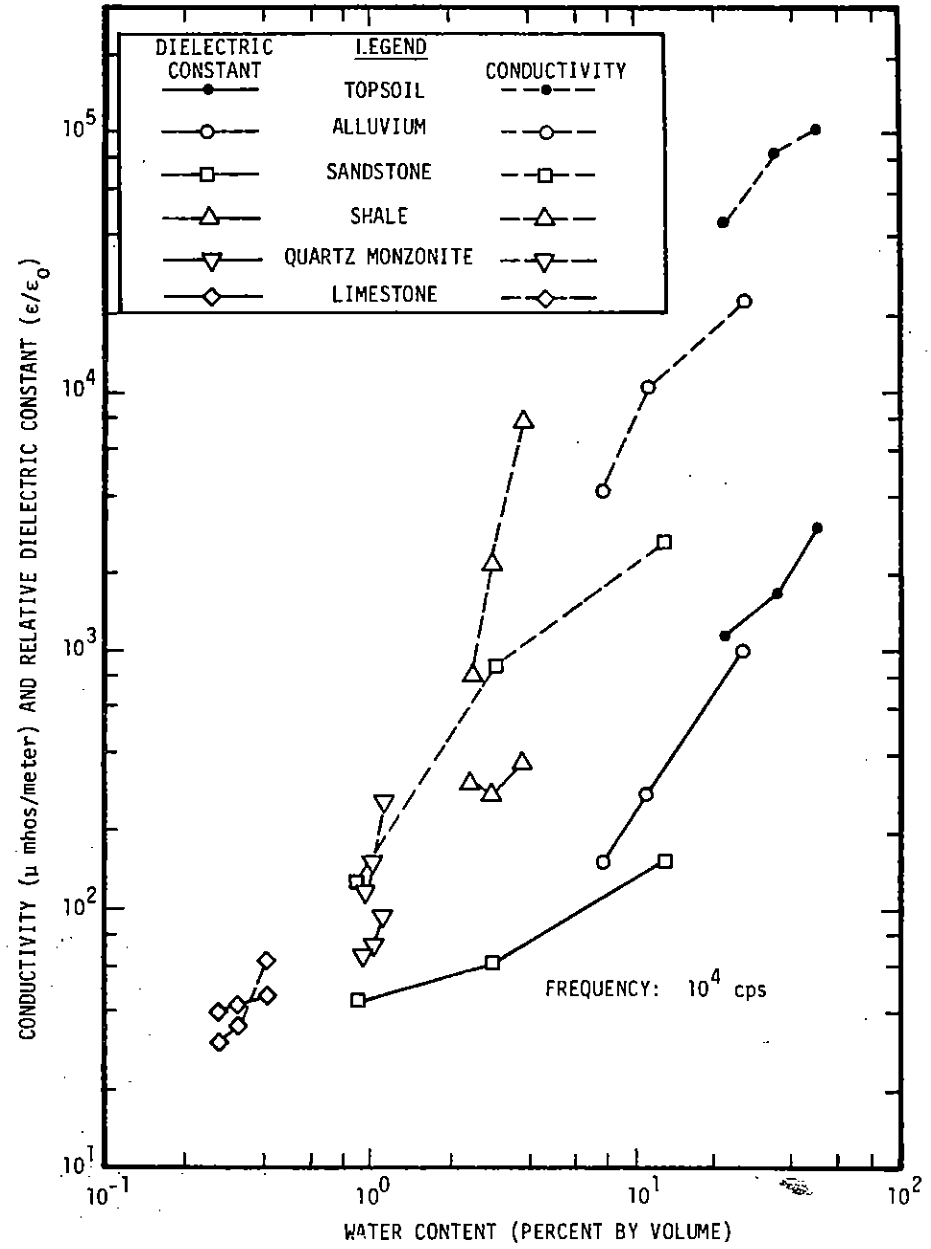

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Figure 12. Reproduced From Reference 4. [Values of relative dielectric constant and conductivity measured at 10,000 cps for several rock types and plotted as a function of water content. Samples were fully saturated when first measurements were made, air dried for 15 hours before second measurements were made, and air dried for 21 additional hours before third measurements were made.]

Our samples probably come closest to Scott's alluvium samples in granular form and density. Scott's curve for alluvium in Figure 12 gives indications of bending below his average curve at lower water contents and could follow the curve for the present samples in Figure 11.

To compare the present results for ϵ_r with Scott's results, some of the present data are superimposed on Scott's curves in Figure 13. The "0"% curve follows the trend of Scott's data both in magnitude and variation versus frequency. The 2.9% curve falls very close to Scott's 0.3% curve over the frequency range from 10^3 to 10^6 Hz. This result would be consistent if conductivity is the primary factor that determines ϵ_r since Figure 11 shows that our 2.9% H_2O sample has about the same conductivity as Scott's 0.3% H_2O samples.

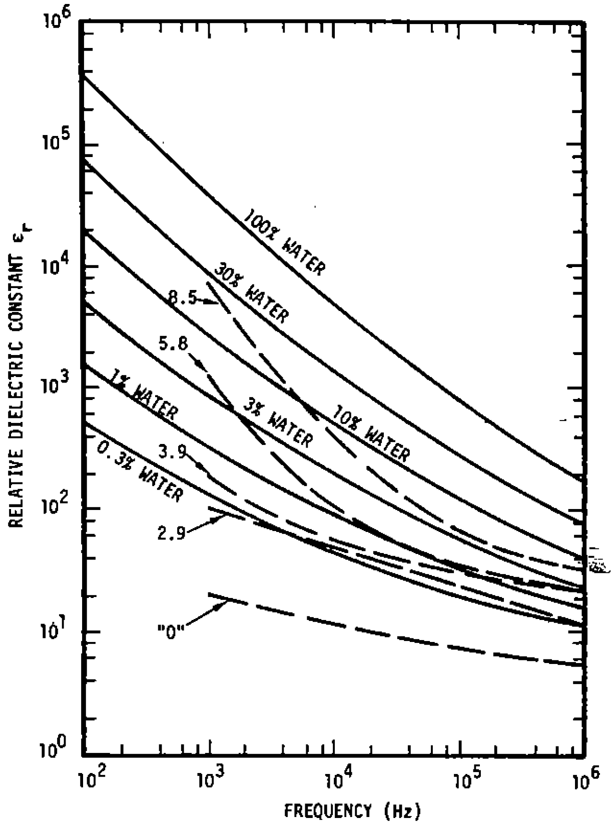

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Figure 13. Relative Dielectric Constant of Soils. Solid curves are from Scott's data from Figure 10. Dashed curves are present data from Figures 4 and 7.

The magnitudes of ε_r at 10^6 Hz for 3.9, 5.9, and 8.5% H_2O are in reasonable agreement with the corresponding values from Scott. However, the present curves are considerably flatter versus frequency than Scott's curves for 8.5% H_2O from 10^6 Hz down to 10^5 Hz, for 5.8% H_2O down to 10^4 Hz, and for 3.9% H_2O down to 10^3 Hz. Below these lower frequency bounds, the present ε_r curves for the three highest water contents are steeper than Scott's curves for comparable water contents. It is possible that these steeper ε_r curves at low frequencies are due to contact polarization effects. According to reference 6, when there is a significant amount of contact polarization, the ε_r curves at low frequencies should show a consistent shift as a function of sample length, which can be used to subtract out the contact capacitance and deduce the bulk values of ε_r. The method of reference 6 was used in an attempt to subtract out the contact polarization effects for the samples with difficult lengths in Figures 3 and 4. There was considerable scatter in the results, apparently because the different samples had different water contents. However, the corrected results came quite close to the curve for the 5.1 cm sample so that curve can be assumed to have little polarization.

In reference 2, it was pointed out that σ and ε_r are not completely independent quantities. If one of these parameters is specified over the frequency range, the variation of the other parameter with frequency is fixed, except for an additive constant. The relations between σ and ε_r can be used as a rough check on the self-consistency of the experimental data. Specifically, according to Reference 2, the change in conductivity $\Delta\sigma$ over a small frequency range (Δf) around some central frequency f_c is given roughly by

$$\begin{aligned}\Delta\sigma(\text{mho/m}) &\simeq -2\pi\varepsilon_o(\text{f/m})f_c(\text{Hz})\Delta\varepsilon_r \\ &= -5.5 \times 10^{-11}\ f_c\Delta\varepsilon_r\end{aligned} \tag{1}$$

where $\Delta\varepsilon_r$ is the change in ε_r over the same frequency range (Δf). Equation 1 has been applied to some of the experimental data in Figures 3, 4, 6, and 7, and the results are summarized in Table 2. It is sometimes difficult to obtain accurate values for either $\Delta\varepsilon_r$ or $\Delta\sigma$ so the numbers in Table 2 have considerable error bars.

For the samples other than the 0% H_2O, the values of $\Delta\sigma$ calculated by Equation 1 are roughly 1/3 to 1/2 the experimental values. It is reasonable that the values of $\Delta\sigma$ calculated by Equation 1 should be less than the experimental values because $\Delta\sigma$ near a given frequency f_c receives contributions from the $\Delta\varepsilon_r$'s at all other frequencies, not just

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6. M. M. Judy, "Separation of Electrode and Polarization Medium Impedances in Two-Terminal Measurements," Note 117, Electromagnetic Pulse Theoretical Notes, AFWL EMP1-9, April 20, 1967.

$\Delta\varepsilon_r$ near f_c. However, the contribution from $\Delta\varepsilon_r$ near f_c is the most important, and hence, Equation 1 is roughly correct. Thus the results in Table 1 are a reasonable check on the self-consistency of the data for these samples. For the 0% H_2O sample, the values of $\Delta\sigma$ calculated by Equation 1 are roughly a factor of two greater than the experimental values. Perhaps for low water content, $\Delta\sigma$ is determined by physics different from that implied by Equation 1.

Table 2

COMPARISON OF CALCULATED AND MEASURED $\Delta\sigma$

Soil Sample		f_c (Hz)	Δf_c (Hz)	Experimental $\Delta\varepsilon_r$	$\Delta\sigma$ Calculated by Eq. 1, (mho/m)	Experimental $\Delta\sigma$ (mho/m)
Fig. 3 and 4	0% H_2O	10^7	10^6	0.1	-5.5×10^{-5}	-2.5×10^{-5}
		10^5	10^4	0.3	-1.6×10^{-6}	-1×10^{-6}
		10^3	10^2	0.7	-3.8×10^{-8}	-5×10^{-8}
Fig. 3 and 4	5.1 cm	10^7	10^6	0.2	-1.1×10^{-4}	-3×10^{-4}
		10^6	10^5	0.3	-1.6×10^{-5}	-5×10^{-5}
		10^5	10^4	0.6	-3.3×10^{-6}	$-<1 \times 10^{-5}$
Fig. 3 and 4	1.1 cm	10^7	10^6	0.2	-1.1×10^{-4}	-2.5×10^{-4}
		10^6	10^5	0.5	-2.7×10^{-5}	-5×10^{-5}
		10^5	10^4	1.0	-5.5×10^{-6}	$\approx -2 \times 10^{-5}$
Fig. 6 and 7	2.9% H_2O	10^7	10^6	0.2	-1.1×10^{-4}	-1.2×10^{-4}
		10^6	10^5	0.3	-1.6×10^{-5}	-2.5×10^{-5}
		10^5	10^4	0.8	-4.4×10^{-6}	-8×10^{-6}
		10^4	10^3	1.5	-8.2×10^{-7}	$<-2 \times 10^6$
Fig. 11	5.8% H_2O	10^7	10^6	0.2	-1.1×10^{-4}	-2×10^{-4}
		10^6	10^5	0.3	-1.6×10^{-5}	$\lesssim -1 \times 10^{-4}$
		10^5	10^4	1.0	-5.5×10^{-6}	(?)

SECTION VI

SUMMARY

The following are the main conclusions from this work.

1. The present values of σ and ε_r are in rough agreement with the results of Scott for water contents from about 3 to 10% H_2O by volume.
2. Over this water-content range, the variation of σ (at 10^4 Hz) with water content is steeper than indicated by Scott's data.
3. This difference may be due to differences in the soil composition and density between our samples and those used by Scott for water contents around 1% H_2O by volume.
4. The curves of ε_r versus frequency for water contents from about 3 to 10% are somewhat flatter near 1 MHz than Scott's curves.
5. For the same low-frequency conductivity, our curves of ε_r versus frequency are in general agreement with Scott's data, in spite of the indicated differences in water content.
6. The model of Longmire and Smith that relates $\Delta\sigma$ versus frequency is roughly verified by the present data, at least for samples with water contents greater than a few percent.