SIGNIFICANCE OF THE MAGNITUDE OF DIELECTRIC DISPERSION IN SOIL TECHNOLOGY

K. Arulanandan, University of California, Davis; and
Raja Basu and R. J. Scharlin, Woodward Lundgren, Oakland, California

A description of the alternating current response characteristics of soils in the radio-frequency range (10^6 to 10^8 Hz) is given. The variation of dielectric constant as a function of frequency of alternating current, called electrical dispersion, for various clays is presented. The magnitude of dielectric dispersion, which is defined as the total amount of decrease in the measured dielectric constant, is shown to be dependent on structure-determining factors such as type and amount of clay, water content, pore fluid composition, and fabric. It is suggested that the value of the magnitude of dielectric dispersion, which takes into account both compositional and environmental factors of a clay-water-electrolyte system, can be used to characterize clays without destroying or separating the soil mass into different sizes.

•SIGNIFICANT progress in the area of soil technology has been somewhat limited because of the slow development of fresh approaches, new techniques, and equipment that could characterize clay-water-electrolyte systems without destroying the clay mass.

The alternating current electrical response characteristics of saturated clay-water-electrolyte systems have been studied in the low-frequency range (50 to 10^5 Hz) [1, 2, 3] and in the radio-frequency range (10^6 to 10^8 Hz) [4, 5, 6, 7] to develop a nondestructive method of characterizing soils.

This paper has as its purposes (a) the description of the alternating current response characteristics of soils in the radio-frequency range (10^6 to 10^8 Hz) and (b) the illustration of the influences of changes in structure-determining factors and fabric on magnitude of electrical dispersion and presentation of a new method for classifying soils.

RADIO-FREQUENCY ELECTRICAL DISPERSION OF CLAY-WATER-ELECTROLYTE SYSTEMS

When an alternating electric field is applied to a clay-water-electrolyte system, a response is produced that can be measured in terms of a resistance, R, and a capacitance, C. The measured value of the capacitance can be converted into a quantity known as the dielectric constant. This value is defined as C/C_o, in which C_o is the capacitance of a condenser with only a vacuum between the electrodes. The dielectric constant is actually a measure of the ability of the clay to store electrical potential energy under the influence of an electric field. From a knowledge of the dimensions of the sample, the dielectric constant can be calculated from the following relations:

$$\epsilon' \epsilon_a = \frac{Cd}{A} \tag{1}$$

where

> d = length of a specimen,
> A = cross-sectional area,
> ϵ_a = the dielectric constant of vacuum (8.85×10^{-14} farads/cm)

The dielectric constant of a dry silicate mineral is 4 and that of water is about 80. A mixture of soil and water should, therefore, have a dielectric constant between 4 and 80. When the dielectric constant of a clay-water-electrolyte system is measured with an alternating current in the radio-frequency range, it is found to be far in excess of the dielectric constant of components. This measured value, ϵ', referred to as the "apparent dielectric constant," reflects the heterogeneous nature of the path of the current and the electrical properties of the pore fluid and the clay mineral (4).

When the apparent dielectric constant, ϵ', of a liquid such as water or of an electrolyte is measured as a function of frequency, in the radio-frequency range, it is found that ϵ' does not vary (Fig. 1). The reason is that we are considering the electrical response characteristics of a one-component system. Water and salt are considered as a one-component system. In a one-component system, the current density, which is proportional to the ratio of conductivity to dielectric constant, does not vary from point to point. When we consider a two-component system (clay particles and solution), however, such as a saturated clay-water-electrolyte system, current density varies from point to point because the ratio of conductivity to dielectric constant is different for each of the two components. Charges therefore accumulate at the interface between the clay particle and the surrounding solution (9, 10, 11). Because this buildup of charges takes time, as the frequency is increased, there will be less time for the charges to accumulate at the interface, which in turn decreases the system's ability to store electrical potential energy and thus decreases the dielectric constant. When the frequency reaches a certain value, there will not be enough time for any charges to accumulate at the interface, and, at this point, the dielectric constant becomes independent of frequency. The value of the dielectric constant at this leveling-off frequency is defined as ϵ_∞. Figure 2 shows the change in ϵ' as a function of frequency for a two-component system (saturated illite Grundite). This change in ϵ' is generally referred to as electrical dispersion. The total amount of decrease in the measured dielectric constant is defined as the magnitude of dielectric dispersion, $\Delta\epsilon$. Several classes of materials exhibit this behavior (Fig. 3).

EXPERIMENTAL EQUIPMENT

The Cell

The design of the cell and its connections to the bridge terminal and the evaluation of the capacitance of the sample were similar to those used by Sachs and Spiegler (8). The cell is based on the principle of vectorial subtraction of impedances measured at different electrode distances. This procedure eliminates the influence of the transmission line, the electrodes themselves, and the surroundings of the cell in general.

The Meter

The measuring instrument used was an RX meter, type 250. It is essentially a Schering bridge, with oscillator, amplifier-detector, and null indicator designed to measure equivalent parallel conductance in the range of 0.0 to 0.067 mho, at frequencies of 0.5 to 250 MHz. All tests were performed at a constant room temperature of 22 C. Figure 4 shows the meter and cell.

RELATION BETWEEN MAGNITUDE OF ELECTRICAL DISPERSION AND PHYSICOCHEMICAL FACTORS

The sensitivity of magnitude of dielectric dispersion to variation in clay type, water content, amount of clay, amount and type of electrolyte, flocculated and dispersed saturated illite, method of compaction, and particle orientation was determined to investigate the significance of magnitude of dielectric dispersion to physicochemical properties.

Figure 1. Variation of dielectric constant with change in frequency for 0.01 N sodium-chloride solution.
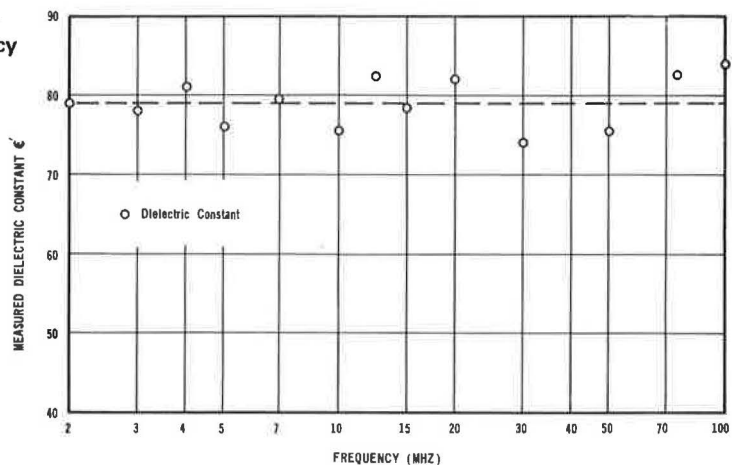

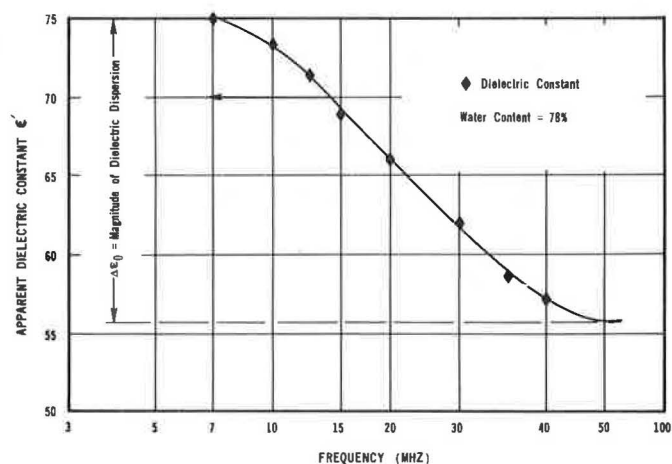**Figure 2. Dielectric dispersion characteristics of saturated illite Grundite.**

Figure 3. Variation of dielectric constant for solids, solid-liquid mixtures, and liquids in the radio-frequency range.
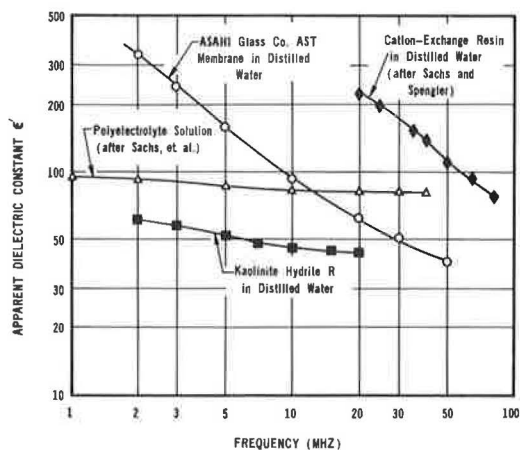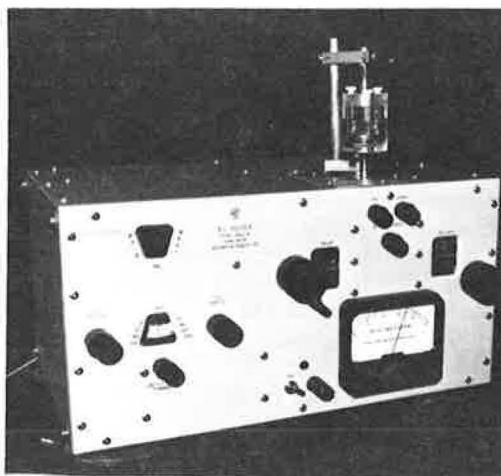

Figure 4. Measuring instrument.

Effect of Type of Clay on Magnitude of Dielectric Dispersion

Three basic clay minerals were studied: montmorillonite, illite, and kaolinite. Each was consolidated from a slurry under a pressure of 1 kg/cm^2, and electrical dispersion curves were then obtained. Figure 5 shows dielectric dispersion curves (in the radio-frequency range) for these three clay minerals. The curves show that the magnitude of the dielectric dispersion decreases for the three clay minerals in the following order: montmorillonite, illite, and kaolinite. This result can be interpreted in the following manner.

The dielectric constant of a medium reflects the magnitude of its polarizability, which is equal to the product of the number of charges per unit volume and the average displacement of particles. The number of charges per unit volume of particles is directly proportional to the number of unsatisfied surface bonding sites, the net electrical charge of the particle itself, and the specific surface area. The amplitude with which the particles will vibrate is directly proportional to the degree of association of the charge with particle surfaces when other factors remain unchanged, such as particle orientation, temperature, strength, and frequency of the electrical field.

We already know that each of the preceding four parameters decreases for the three clay minerals in the following order: montmorillonite, illite, and kaolinite. Hence, montmorillonite will show the greatest polarizability of these three basic clay minerals, and consequently the highest dielectric constant. Kaolinite will have the lowest one at the same frequency of applied electrical field when other factors, such as particle orientation and temperature, are kept constant. This difference would be prominent in the lower end of the radio-frequency spectrum. With increasing frequency, however, the time between alterations decreases and the polarization mechanism ceases to be effective, which means that the magnitude of polarizability will be minimum regardless of the type of clay and that therefore dielectric dispersion curves for all clay types will level off at the higher end of the radio-frequency spectrum. The fact that the dielectric constant decreases in the lower radio-frequency range in the previously given order, whereas all tend to level off at approximately the same level in the higher radio-frequency range, is the reason that the magnitude of dielectric dispersion also decreases in the same order (montmorillonite, illite, and kaolinite). This explains why the type of clay mineralogy is reflected in the nature of dielectric dispersion.

Effect of Amount of Clay on Dielectric Dispersion

Several samples of montmorillonite, illite, and kaolinite were mixed with different percentages of sand. Each was consolidated from a slurry under pressure of 1 kg/cm^2. A summary of the electrical dispersion characteristics obtained on illite and kaolinite sand mixtures is given in Table 1. With increasing sand content (decreasing clay content), the dielectric dispersion curve shifted downward, and the magnitude of dielectric dispersion decreased (Table 1). This may be interpreted in the following manner. With increasing sand content in a soil, the average specific surface area of the constituent soil particles decreases, reducing the number of charges associated with particles per unit volume, thus lowering the magnitude of dielectric dispersion. At the lower end of the radio frequency, of course, this phenomenon is prominent. At the higher end, the time available for charge distortion during any single current alteration decreases and may be insufficient for the polarization mechanism to operate, which means that the magnitude of polarizability will be minimum regardless of the percentage of clay content. Therefore, at the higher end of the radio-frequency spectrum, dielectric dispersion curves will level off and tend to merge together (Fig. 6). This explains why the dielectric dispersion curve shifts downward and the magnitude of dielectric dispersion decreases with decreasing amount of the clay fraction in a particular type of soil.

Therefore, adding sand to a soil changes the water content (after consolidation), which might affect the magnitude of dielectric dispersion. To investigate this, electrical dispersion tests were performed on several samples of a particular soil consolidated under different pressures to obtain different water contents (Table 2). The magnitude of dielectric dispersion of a soil proved independent of water content

(discussed further in the following section). Therefore, variation in water content does not explain the change in dielectric dispersion values for different clay minerals.

Effect of Water Content on Magnitude of Dielectric Dispersion

Samples of montmorillonite, illite, and kaolinite were brought to three different water contents by consolidating them under different pressures, and electrical dispersion curves were determined. With two of the soils, the entire dielectric dispersion curves shifted downward with decreasing water contents, whereas with montmorillonite they shifted upward (Fig. 7). The results of the magnitude of dielectric dispersion with changing water content have only a very little effect on the magnitude of dielectric dispersion.

Effect of Cation Type on Dielectric Dispersion

The main types of ions existing in natural soils are sodium, calcium, and magnesium ions. Their amount in soils can be expressed in terms of sodium-adsorption ratio (SAR), which is given by

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{++} + Mg^{++})}}$$

Used in the investigation was Yolo loam (a naturally silty soil commonly found in Yolo County, California). Several samples having different SAR's but the same electrolyte concentration were prepared and then consolidated under pressure of 1 kg/cm². The dielectric dispersion characteristics of the soil samples were determined, and the magnitude of dielectric dispersion $\Delta\epsilon_0$ is given in Table 3. They demonstrate that the dielectric dispersion curve is affected by SAR, which reflects the type and amount of exchangeable cations in the soil. The magnitude of dielectric dispersion increases with increasing SAR. The explanation may be as follows: Univalent sodium ions have weaker bonds with the clay particle surface than do bivalent magnesium or calcium ions. Therefore, when a field of alternating current is passed through a soil, average displacements are much greater for sodium ions than for magnesium or calcium ions. Hence, with increasing SAR (i.e., increasing amount of sodium ions or decreasing amount of magnesium or calcium ions) in the soil, the magnitude of polarizability increases, resulting in increased dielectric dispersion.

Effect of Electrolyte Concentration on Dielectric Dispersion

The dielectric dispersion characteristics of two samples of Yolo loam having the same SAR but different electrolyte concentrations were obtained, and the results are summarized in Table 4. With increasing electrolyte concentrations, the dielectric dispersion curve shifts downward, and the magnitude of dielectric dispersion is reduced slightly. This relation has been explained as follows. A high concentration of electrolyte reduces the double-layer thickness surrounding each clay particle. This reduction results in low interparticle repulsion, causing a tendency toward flocculation, i.e., edge-to-face arrangement of particles. This arrangement causes a relocation of charges associated with particle surfaces. There is a high concentration of surface charges around the junction between the edge of one particle and the face of another. Therefore, the average displacements of the surface charges are reduced. Because of this, the polarizabilities of the surface charges are also reduced, thus accounting for the reduced magnitude of dielectric dispersion.

Effect of Structure on Dielectric Dispersion

Two series of tests were carried out to investigate the effect of the structural arrangement of particles on dielectric dispersion characteristics.

Flocculated Illite and Dispersed Illite—One illite sample was flocculated by using an NaCl solution of comparatively high concentration (0.05 N) as electrolyte. Another illite sample was dispersed by using a dispersing agent (Calgon). Each was consolidated

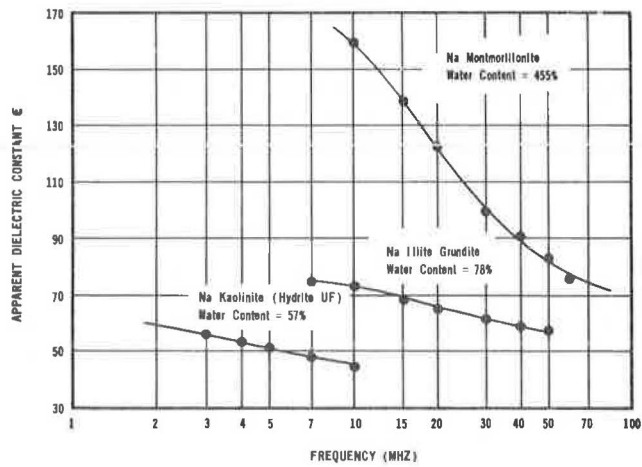**Figure 5. Effect of type of clay on dielectric dispersion.**

Table 1. Effect of clay content on dielectric dispersion.

Type of Soil	Water Content (percent)	Clay Content (percent)	Dielectric Dispersion
Sodium montmorillonite and sand	295	100	134
	230	83	110
	300	80	108
	255	70	94
	350	60	80
	182	55	72
Illite Grundite and sand	71.4	50	33
	40	47	30
	31.5	39	27
	25	34	17
	18.8	29	12
Kaolin UF and sand	70	100	14
	45	80	4
	39.3	60	5
	35.4	50	6
	28.7	40	4
	20.8	20	2

Figure 6. Effect of clay content on dielectric dispersion of sodium montmorillonite.

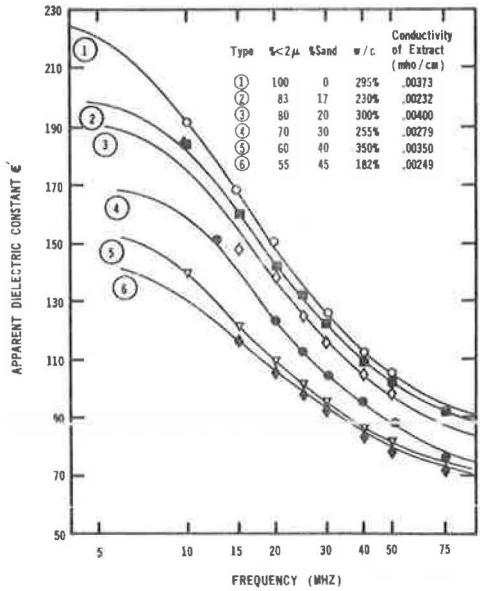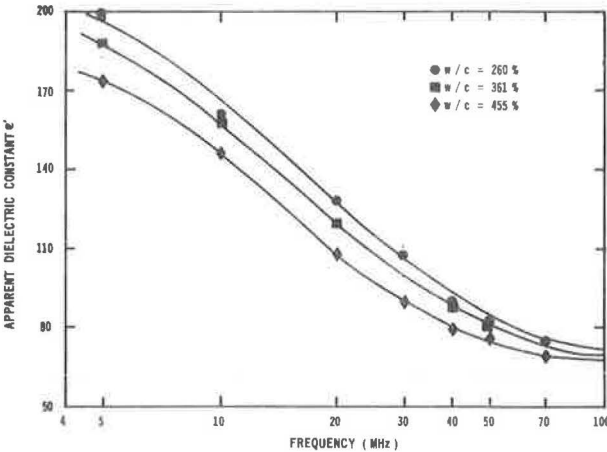**Table 2. Effect of water content on dielectric dispersion.**

Type of Soil	Water Content (percent)	Dielectric Dispersion
Montmorillonite	260	127
	361	128
	455	112
Illite Grundite	48.6	24
	52.0	26
	78.0	25
Kaolin UF	51.2	16.0
	61.0	17.5
	80.2	14.5

Figure 7. Effect of water content on dielectric dispersion of sodium montmorillonite.

under a pressure of $\frac{1}{2}$ kg/cm^2, and electrical dispersion tests were performed. The results (Fig. 8) show that a dispersed structure gives a higher dielectric dispersion than does a flocculated structure.

Yolo Loam Samples—Because Yolo loam is a structure-sensitive soil, as evidenced by the stress-strain curve shown in Figure 9, kneading compaction disperses the soil structure, whereas static compaction leaves the particles in a flocculated state (12). The two samples tested were not saturated but were good examples of soils having different structures but otherwise identical in all respects. Dielectric dispersion tests on these two samples (Fig. 10) demonstrate that kneading compaction (i.e., dispersed structure) gave rise to a higher dielectric dispersion than did static compaction (i.e., flocculated structure).

From these two series of tests, it is quite obvious that with increasing dispersion of particles, the dielectric dispersion curve shifts up and the magnitude of dielectric dispersion increases. The reason is that dispersion increases the specific surface area of particles and hence the number of bound charges per unit volume, which dictates the dielectric dispersion characteristics.

Effect of Particle Orientation on Dielectric Dispersion

Kaolinite Hydrite UF was consolidated under a pressure of 1 kg/cm^2. Two samples were taken from the consolidated soil, one perpendicular to the direction of consolidation (i.e., horizontal) and the other parallel to the direction of consolidation (i.e., vertical). Figure 11 shows that dielectric dispersion is higher when particles are aligned parallel to the direction of current. Clearly, particle orientation has an effect on the dielectric dispersion characteristics.

CONCLUSIONS

The results of this study give evidence that the radio-frequency dielectric dispersion characteristics of a saturated fine-grained soil are controlled by various compositional and environmental factors that determine the soil properties. A summary of the influences of these factors on the magnitude of dielectric dispersion is given in Table 5.

It can be noted that the magnitude of dielectric dispersion is mainly a measure of the clay mineral composition and percentage of clay content (Table 5). Consideration must also be given, however, to the second-order dependence of dielectric dispersion on water content, cation type, pore fluid concentration, structure, and particle orientation. The magnitude of dielectric dispersion may thus be of value in developing a soils classification method that takes into account both compositional and environmental factors and that can be used to characterize a soil without destroying or separating the soil mass into different sizes. The relation between the magnitude of dielectric dispersion and percentage of clay fraction is examined (Fig. 12) by plotting the results given in Table 1. Dielectric dispersion and percentage of clay fraction appear related linearly when increasing amounts of sand are added to a particular soil. Thus, three straight lines are obtained corresponding to the three basic clay minerals: montmorillonite, illite, and kaolinite. Figure 12 also shows the values of dielectric dispersion against clay fractions of 18 other natural soils investigated. The mineralogical composition, the percentage of clay content, water contents, and magnitude of dielectric dispersion for all experimental natural and artificial soils are given in Table 6. These soils fall under different zones according to their mineralogical compositions. These zones can be separated by the three lines corresponding to the three clay minerals, montmorillonite, illite, and kaolinite. For example, soil 1PB has a large amount of montmorillonite and illite (Table 6) and plots between the montmorillonite line and the illite line (Fig. 12). Similarly, other soils can also be placed appropriately in the classification table according to the amount and type of clay content.

ACKNOWLEDGMENTS

Table 3. Effect of sodium-adsorption ratio on dielectric dispersion of Yolo loam.

Electrolyte Concentration	Conductivity of Pore Fluid (mho/cm)	Sodium-Adsorption Ratio	Dielectric Dispersion
0.01 N	0.00160	8.5	33
0.01 N	0.00150	4.8	30
0.01 N	0.00110	2.1	26
0.10 N	0.00930	154	50
0.10 N	0.00980	23.2	50
0.10 N	0.01000	12.4	50

Table 4. Effect of electrolyte concentration on dielectric dispersion of Yolo loam.

Sodium-Adsorption Ratio	Electrolyte Concentration	Conductivity of Pore Fluid (mho/cm)	Dielectric Dispersion
1.3	0.01 N	0.00115	30
1.3	0.10 N	0.00850	28
9.0	0.01 N	0.00160	35
9.0	0.10 N	0.01000	30

Figure 8. Effect of structure on dielectric dispersion of illite Grundite.

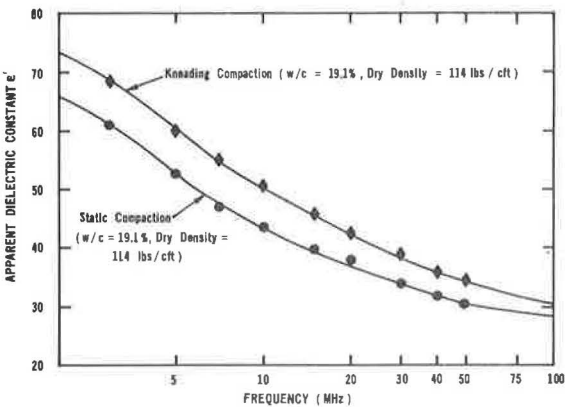**Figure 9. Effect of method of compaction on stress-strain relation of compacted Yolo loam.**

Figure 10. Effect of method of compaction on dielectric dispersion of Yolo loam.
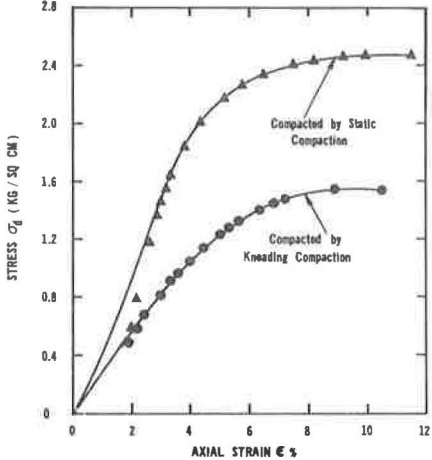

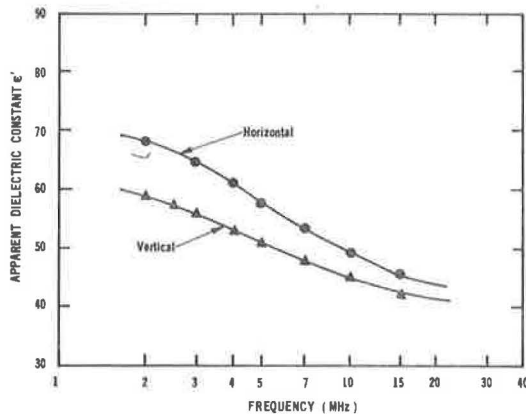**Figure 11. Dielectric dispersion of kaolinite Hydrite UF.**

Table 5. Effects of compositional and environmental factors on magnitude of dielectric dispersion.

Factor	Effect
Type of clay	Dielectric dispersion is different for different clay types. Of the three basic clay minerals, it significantly decreases in the following order: montmorillonite, illite, and kaolinite.
Clay content	Dielectric dispersion increases significantly with increasing clay content.
Water content	Water content has a very little effect on dielectric dispersion (in the radio-frequency range).
Cation type (SAR)	Dielectric dispersion increases slightly with increasing SAR.
Electrolyte concentration	With increasing electrolyte concentrations, dielectric dispersion decreases slightly.
Structure	With increasing dispersion of particles, dielectric dispersion increases slightly to moderately.
Particle orientation	Dielectric dispersion is slightly higher when current is flowing perpendicular to direction of consolidation pressure than when current is flowing parallel to the direction of consolidation pressure.

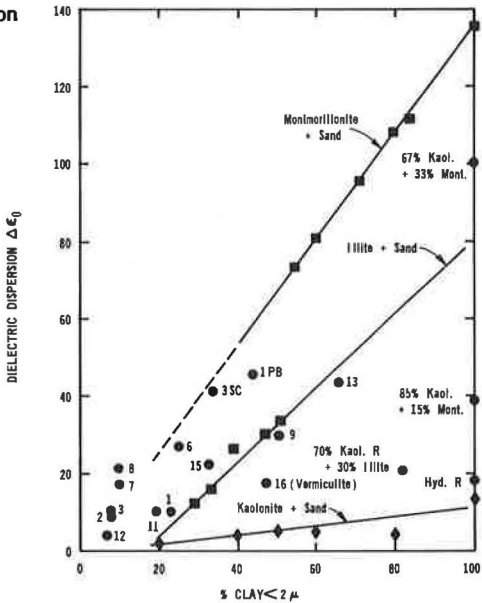**Figure 12. Relation between dielectric dispersion and percentage of clay fraction.**

Table 6. Composition of soils.

Type of Soil	Water Content (percent)	Dielectric Dispersion	Clay Content (percent)	Clay Mineralogy[a] (percent)			
				Montmorillonite	Mixed Layer	Illite	Kaolin
85 percent kaolin and 15 percent montmorillonite	157	39	100	—	—	—	—
70 percent kaolin and 30 percent illite	53.8	21	82	—	—	—	—
1	38.7	10	23	0	5	0	0
1PB	105.6	46	44	0	52	5	0
2	24.8	9	8	0	10	0	0
3	38.5	10	8	10	5	0	0
3SC	75	42	34	35	5	0	0
6	64	27	25	0	13	0	0
7	31.7	18	10	0	5	0	5
8	47	22	10	0	20	0	0
9	69	31	50	20	5	0	5
11	53	11	19	0	20	0	0
12	23.3	4	7	0	10	0	0
13	65.2	44	66	20	5	0	7
15	46.3	23	33	15	0	0	0
16 (vermiculite)	114	16	48	—	—	—	—
Hydrite R	65	18	100	—	—	—	—
67 percent kaolin and 33 percent montmorillonite	244	100	100	—	—	—	—

[a]The percentages of different clay minerals present in each soil are based on the total weight of the soil (data supplied by the California Division of Highways).

REFERENCES

1. Arulanandan, K. Electrical Response Characteristics of Clays and Their Relationships to Soil Structures. Univ. of California, Berkeley, PhD thesis, 1966.
2. Arulanandan, K., and Mitchell, J. K. Low Frequency Dielectric Dispersion of Clay-Water-Electrolyte Systems. Clay and Clay Minerals, Vol. 16, 1968, pp. 337-351.
3. Mitchell, J. K., and Arulanandan, K. Electrical Dispersion in Relation to Soil Structure. Jour. Soil Mech. and Found. Div., ASCE, Vol. 88, No. SM2, Proc. Paper 5853, March 1968, pp. 447-471.
4. Arulanandan, K., and Mitra, S. K. Soil Characterization by Use of Electrical Network. Proc. 4th Asilomar Conf. on Circuits and Systems, Nov. 1970, pp. 480-485.
5. Scharlin, R. A New Approach to Soil Classification. Univ. of California, Davis, MS thesis, June 1971.
6. Smith, S. S. Soil Characterization by Radio-Frequency Electrical Dispersion. Univ. of California, Davis, PhD dissertation, Nov. 1971.
7. Basu, R. Identification and Prediction of Swell of Expansive Earth Materials. Univ. of California, Davis, MS thesis, June 1972.
8. Sachs, S. B., and Spiegler, K. S. Radio-Frequency Measurements of Porous Conductive Plugs—Ion-Exchange Resin Systems. Jour. of Physical Chemistry, Vol. 68, 1964, pp. 1214-1222.
9. Maxwell, J. C. A Treatise on Electricity and Magnetism. Oxford Univ. Press, Article 314, 1973.
10. Wagner, K. W. Arch. Electrotechn., 2, 1914, p. 371.
11. Pauley, H., and Schwan, H. P. Über die Impedanzeiner Suspension Von Kugelformiten Teilchen unit einer Schale. Naturforsch., Vol. 125, 1959, pp. 125-131.
12. Seed, H. B., and Chan, C. K. Structure and Strength Characteristics of Compacted Clays. Jour. Soil Mech. and Found. Div., ASCE, 1959.