

# Electrical Resistivity of Soil-Sodium Chloride Systems

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A simple apparatus for the determination of the resistivity of soil systems is described. Correlations of the resistivity, density, sodium chloride content, and moisture content of various soils are shown. Soils containing halloysite, kaolinite and montmorillonite as the predominant clay mineral were used and compared with Ottawa sand. The variations in results are related to the physico-chemical properties of the soils.

- THE ELECTRICAL resistance of a material is defined as the opposition offered by that material to the flow of electric current. The resistance of a substance of a given length is represented by the ratio of the drop in electrical potential within that length to the intensity of electrical current passing through the substance.

The resistance of an electrical conductor opposes the flow of electricity in a manner somewhat analogous to the way friction opposes the flow of water in pipes. Electrical resistance ( $R$ ) is directly proportional to the length ( $L$ ) of a conductor and inversely proportional to the cross-sectional area ( $A$ ). The proportionality constant is known as the resistivity and is represented by  $\beta$ . Expressed as a mathematical equation:

$$R = \beta \frac{L}{A} \quad (1)$$

in which

$R$  = resistance of sample, in ohms;

$L$  = average path length, in centimeters;

$A$  = cross-sectional area of brine, in square centimeters; and

$\beta$  = resistivity of brine, in ohm-centimeters.

Resistivity means the capacity for resistance and is defined as the electrical resistance of a body of unit cross-section and of unit length. It is usually expressed in ohm-centimeters. Conductivity is the reciprocal of resistivity. The resistivity of natural soils is very high compared to that of metals; values have been found that range from 10 to 30,000 ohm-cm whereas copper has a resistivity of only  $1.72 \times 10^{-8}$  ohm-cm. The use of soil resistivity measurements have been studied as a means of determining the moisture content of soils (3, 8). The resistivity of a soil was found to be related to the dry density and the moisture content of the soil.

The application of resistivity in soil engineering requires further knowledge of the mechanism of the flow of current through soils. The study reported herein was undertaken to correlate the properties of soil-water-sodium chloride systems with the resistivity of such systems. The effects of various properties of the systems such as the dry density, moisture content, type of soil, cation exchange capacity, and the concentration of soluble salts were studied. The influence of factors on the resistivity was studied by varying the type of soil, the density, the moisture content, and the sodium chloride content.

## PREVIOUS WORK

The resistivity of soils was first measured by electrical means using four equally spaced electrodes driven into the earth in a straight line (9). The difference in potential between the two outer electrodes causes a passage of current through the soil. The resistivity of the soil and several factors are related as follows:

$$\beta = \frac{4\pi a R}{n} \quad (2)$$

in which

- $\beta$  = resistivity of soil;
- R = measured resistance;
- a = spacing between electrodes; and
- n = factor depending on depth of electrodes.

This equation is valid only when the portion of earth conducting the current is homogeneous. Increasing the spacing between the electrodes increases the quantity of soil through which the current flows, but the resistivity of the soil should remain constant. However, if the soil between the electrodes is composed of various strata, the average resistivity changes. This variation in the measured resistivity permits the location of layers with different conductivities and is related to variations in the physical properties of the soil or rock. If the differences in resistivity are very great, prospecting by electrical means leads to excellent results.

Leonardon (2) states the following:

Clays and unconsolidated clayey formations often possess resistivities as low as 10 to 30 ohms, clayey calcareous soft terrains show corresponding figures between 20 and 400 ohms, eruptive or metamorphic masses may have resistivities ranging from 200 to 2,000 ohms, and up according to their lack of porosity. As to sands, their resistivities will vary greatly according to their dryness and to the impurities contained therein (clay, organic waters).

This illustrates the large differences in resistivity from one soil or one rock formation to the other. Particularly noticeable is the comparatively low resistivity of clayey rocks. One study of shaly rocks made by Winsauer and McCardell (11) showed the influence on conductivity of the double layer on the clay surface. In that study, samples of shale saturated with a solution of known salt concentration were used. Soils containing clay minerals, especially those with clay minerals having high cation exchange capacities, should behave similarly.

A purely mathematical study by Owen (4) relates the resistivity of a fluid-filled porous body to the shape of the pores. However, Owen presents an hypothesis on the shape of the pores that is extremely restrictive, and probably not acceptable for soils. The mathematics indicate that a change of the geometric pattern, due to an increase in pressure, would lead to a reduction of the conductivity. This was verified by Wyble (12) in a study demonstrating the effect of pressure on the conductivity of sandstone. The results for sandstone may be very different from those related to soils.

TABLE 1  
SOIL SITE CHARACTERISTICS

Soil	Sampling Location	Geological Description	Soil Series	Horizon	Sampling Depth (in.)
AR-2	Ringgold Co., Iowa	Kansan age glacial till calcareous	Shelby Burchard	C	54-126
AR-5	Orange Co., Va.	Residual soil over diorite	Davidson	B	Unknown
AR-10	N. C.	Unknown	Unknown	C	Unknown
20-2	Harrison Co., Iowa	Friable Wisconsin loess	Hamburg	C	480
Ottawa	Ottawa, Ill. sand	-	-	-	-

The type of current that is used in geophysical prospecting is of great importance. Direct current causes electro-osmosis, so alternating current is usually used but has the disadvantage of causing self-induction. The variations of the current intensity in one path induce an electromotive force in the neighboring paths. The current thus induced tends to oppose variations in the magnetic flux. The use of alternating current will give a higher resistivity than if direct current could be used without causing electro-osmosis. Schlumberger (5) indicates that the use of alternating current is satisfactory if an alternating current of low frequency is used.

### MATERIALS AND EQUIPMENT

Five soil materials were used in this investigation. They were selected to represent a wide range in texture and predominant clay mineral (Tables 1, 2). The soil materials used are given in Table 3. The distilled water used throughout the investigation was tested and found to be non-conducting. The only salt used was C.P. sodium chloride obtained from the Fisher Scientific Company.

TABLE 2  
PROPERTIES OF SOIL

Property	Soil <sup>a</sup>				
	AR-2	AR-5	AR-10	20-2	Ottawa sand
<b>Textural composition<sup>b</sup> (%):</b>					
Gravel <sup>c</sup> (2 mm)	0	0	0	0	0
Sand (2-0.074 mm)	20.0	21.0	52.4	1.4	100
Silt (74-5 $\mu$ )	40.6	37.0	36.3	78.8	0
Clay (< 5 $\mu$ )	38.5	42.0	11.3	19.8	0
Clay (< 2 $\mu$ )	33.0	29.5	6.5	16.0	0
Passing No. 10 sieve	100.0	100.0	100.0	100.0	100
Passing No. 40 sieve	100.0	90.0	100.0	100.0	-
<b>Atterberg limits<sup>d</sup>:</b>					
Liquid limit	41.2	43.5	44.0	30.8	NP
Plastic limit	16.7	27.0	NP	24.6	NP
Plasticity index	24.5	16.5	NP	6.2	NP
<b>Chemical tests:</b>					
pHe	8.5	5.9	5.6	8.7	-
CEC (soil passing No. 10 sieve) <sup>e</sup>	17.5	11.0	3.1	13.4	-
Carbonates <sup>f</sup> (%)	7.4	0.65	0.1	10.17	-
Organic matter <sup>g</sup> (%)	0.06	2.62	0.04	0.17	-
Predominant clay mineral <sup>i</sup>	M	H	Mi-K	N	-
<b>Classification:</b>					
Textural <sup>j</sup>	Clay	Clay	Sandy loam	Silty loam	-
AASHO <sup>k</sup>	A-7-6(14)	A-7-6(12)	A-5(3)	A-4(8)	-

<sup>a</sup>Listed by Iowa Engineering Experiment Station soil sample number.

<sup>b</sup>ASTM Method D 422-54 T.

<sup>c</sup>Textural gradation tests were performed only on soil fraction passing No. 10 sieve.

<sup>d</sup>ASTM Methods D 423-54 T and D 424-54 T.

<sup>e</sup>Glass electrode method using suspension of 15 g of soil in 30 cc of distilled water.

<sup>f</sup>Ammonium acetate (pH=7) method on soil fraction < 2 mm (No. 10 sieve).

<sup>g</sup>Versenate method, total calcium expressed as  $\text{CaCO}_3$ .

<sup>h</sup>Potassium bichromate method.

<sup>i</sup>Identification by X-ray diffraction; M=montmorillonite, H=meta-halloysite,

Mi-K=mica-kaolinite.

<sup>j</sup>U.S. Bureau of Public Roads textural classification.

<sup>k</sup>AASHO Designation M 145-49.

TABLE 3  
SOIL MATERIALS USED

Sample Designation	Predominant Clay Mineral
Ottawa sand	Devoid of clay minerals
Sand AR-10	Kaolinite
Loess 20-2	Montmorillonite
Clay AR-5	Meta-halloysite
Clay AR-2	Montmorillonite

The assembled apparatus is shown in Figure 1 and the wiring diagram in Figure 2. The soil sample was placed in a lucite tube, and two graphite electrodes were placed in contact with the soil sample. The source of power forces current through both the soil sample and the resistors. The intensity was measured by an ammeter placed in series with the soil sample, the resistors, and the source of power. A voltmeter placed in parallel on the circuit determines the difference in voltage between the two faces of the sample. The intensity of current passing through the

voltmeter was found to be negligible. The apparatus measures the intensity of the current passing through the soil sample and the difference in voltage between the two faces of the sample. The resistance of the soil sample can be calculated from these values. The apparatus was checked when empty and with a space between the two graphite electrodes and found to permit no leakage of electrical current.

A 60-cycle, 110-volt alternating current was used to avoid electro-osmosis caused by direct current. Alternating current displaces ions alternately in one direction and then the other. It does not cause transportation of ions to the electrodes and therefore gives a reading that is independent of time.

A model 470 electronic volt-ohmmeter was used. This voltmeter, manufactured by

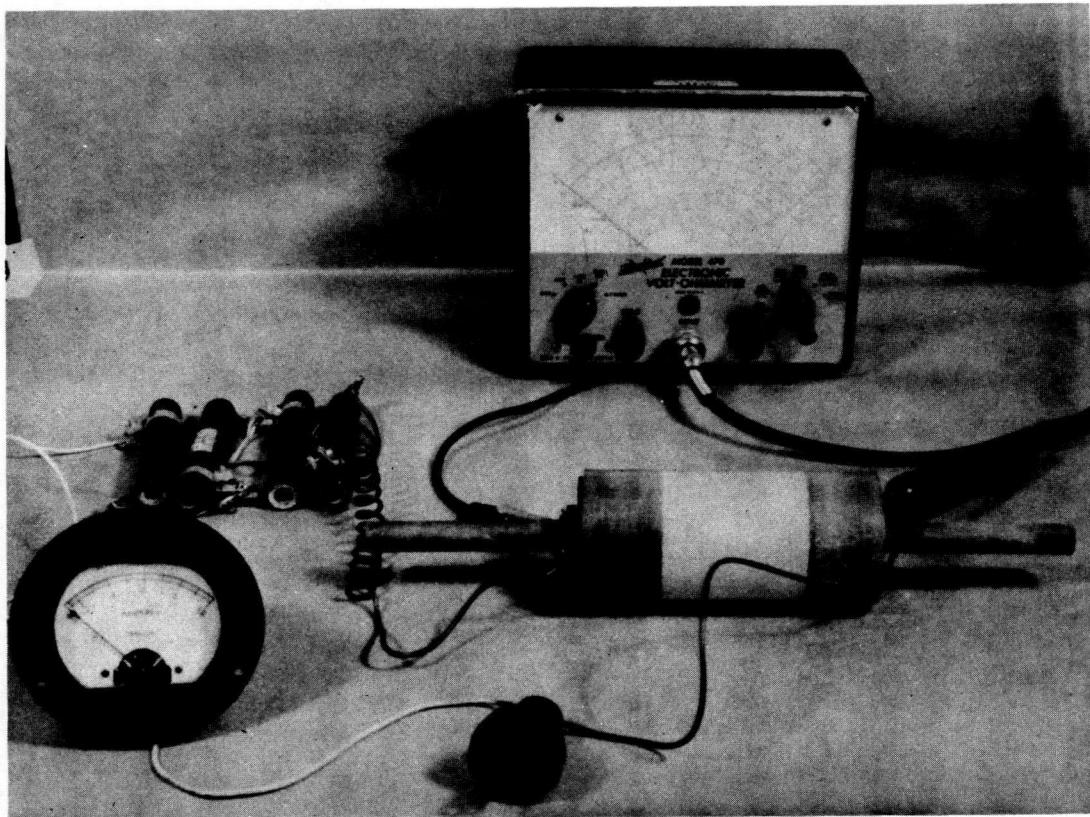


Figure 1. Laboratory apparatus.

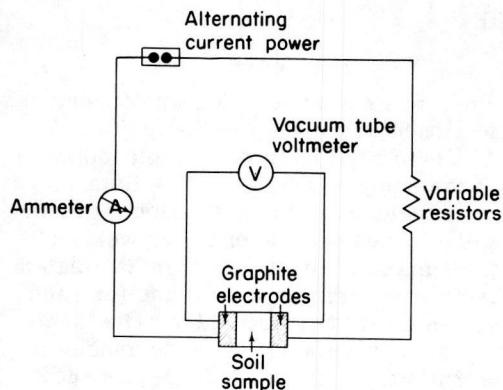


Figure 2. Wiring diagram.

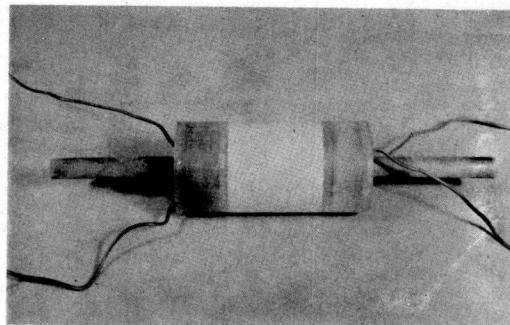


Figure 3. Lucite cylinder with the soil sample and graphite electrodes in place for resistance measurement.

the Hickok Electrical Instrument Company, can be used with alternating or direct current. The range of measurements is very wide, varying from a 1.5-volt scale to a 1,500-volt scale. The precision of the instrument is approximately 1 percent.

Four variable resistors were placed in series on the circuit; three resistors of 50-ohm and one of 10-ohm maximum resistance. All four resistors have a power of 50 watts, sufficient to withstand the maximum power that would pass through them; that is, when the soil sample has a resistance equal to zero.

The ammeter, manufactured by the Simpson Electric Company was designed for alternating current, with a scale varying from 0 to 1 amp. The variable resistors allow the reading of the ammeter to be kept within the narrow range of 0.3 to 1 amp where the precision of the reading is an optimum 1 percent.

Two-inch inside diameter lucite tubing (Fig. 3) was used to make testing cylinders because lucite is a non-conductor and the inside diameter fits a 2-in. diameter compacting hammer. A convenient working length was found to be 12.5 cm.

The electrodes were made of graphite and were designed to fit the lucite molds (Figs. 4 and 5). A small hole was drilled through each electrode to allow evacuation of any air that might be trapped between the soil sample and the electrode. Powdered graphite was used to insure a good contact between the sample and the graphite electrode.

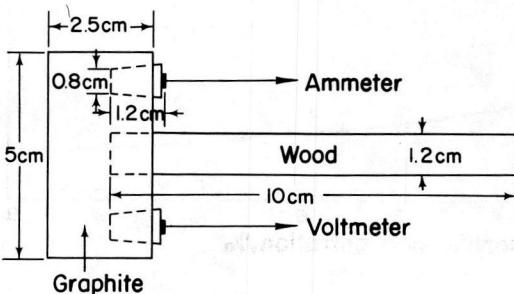


Figure 4. Details of a graphite electrode.

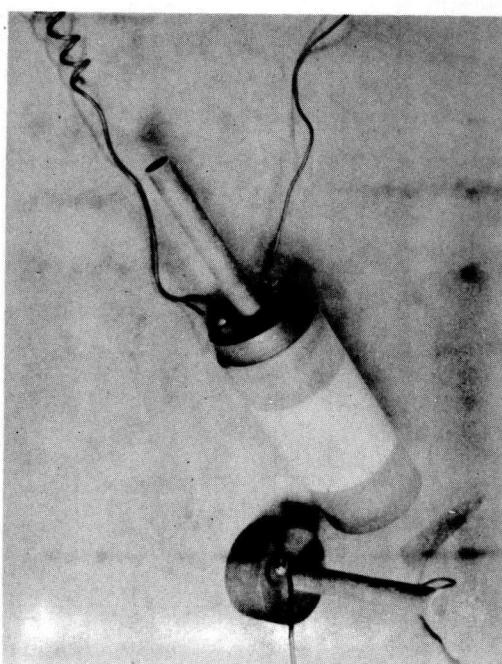


Figure 5. Soil sample in place in lucite cylinder.

## PROCEDURE

### Resistivity of the Brine

Sodium chloride was mixed with distilled water to make a brine of known concentration. One electrode, with the air evacuation hole closed was placed in the lucite cylinder and the brine was poured into the cylinder. The other electrode was placed so that no air was trapped between the electrode and the sample of brine. The distance between the two electrodes was measured and the current was passed through the brine sample. The voltage difference between the two electrodes was recorded as well as the intensity of the current. The resistance of the sample of brine was then calculated and converted to that of a sample 5 cm long. Five measurements were made for each salt concentration and the average value was taken as the resistance of the brine sample. Henceforth, the resistance of a sodium chloride solution implies resistance of a sample of brine 5 cm long. The following concentrations were tested: 0.6, 0.8, 1.2, 2.0, 4.0, 6.0, and 8.0 percent by weight. The values are plotted in Figure 6. The results obtained agree closely with the values observed by Kohlrausch and tabulated in the Handbook of Chemistry and Physics.

### Resistance of a Soil Sample

The following procedure was used to determine the resistivities of the various soil-salt brine systems:

1. A solution with a definite concentration of sodium chloride was made and used throughout the experiment.
2. A certain quantity of air-dried soil was weighed and enough brine to give the soil a moisture content of approximately 8 percent was added to the soil.
3. A thorough mix was obtained with a Hobart C 100 model mixer.
4. A small sample of the mixture was taken, placed in a moisture can, weighed, and placed in an oven for moisture content determination.

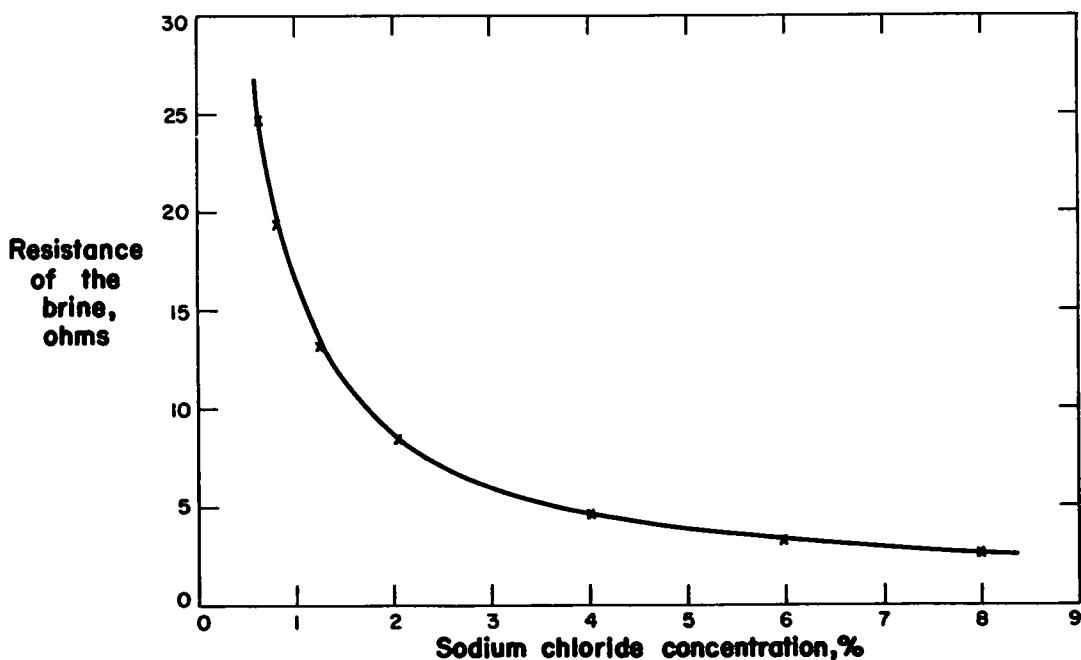


Figure 6. Curve of resistance of brine samples 5 cm in length and 5.1 cm in diameter, as a function of sodium chloride concentration, determined at 72 F.

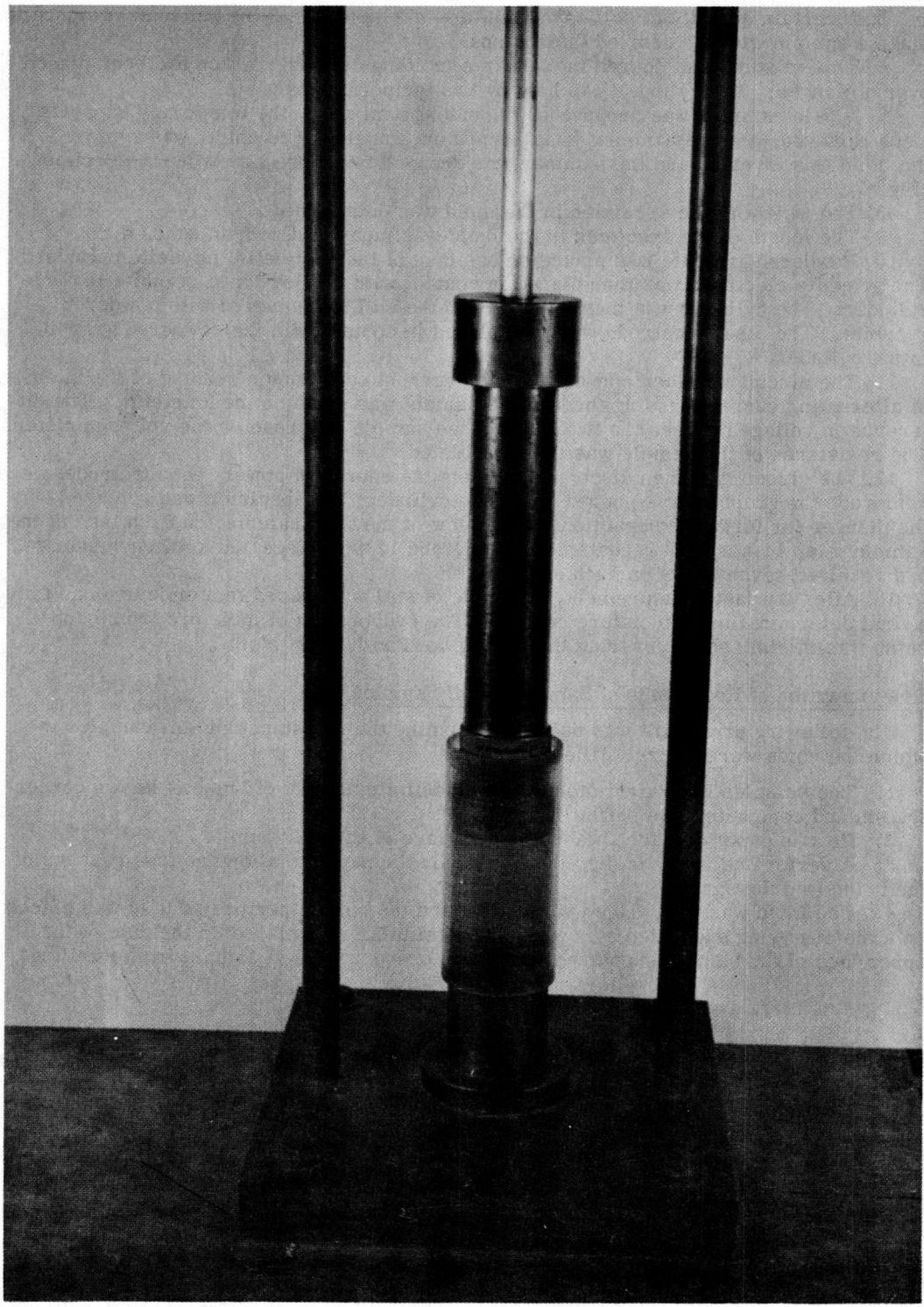


Figure 7. Soil sample in process of being molded in lucite cylinder.

5. A certain quantity of soil-brine mixture was taken from the batch and weighed to make a sample with the desired dimensions.

6. This mixture was poured into a lucite molding cylinder, which had been placed over a plunger. The cylinder was held by two temporary supports.

7. A 5-lb hammer was dropped 12 in. onto the mixture, the temporary supports were removed, and the hammer was dropped once again. The collar was removed, the mold was inverted and the hammer was dropped two more times on the specimen (Fig. 7).

8. The weight of the specimen in the mold was determined.

9. The length of the specimen in the mold was measured with an Ames dial.

10. Powdered graphite was placed on one face of the sample in the lucite cylinder. The graphite electrode was then placed in contact with the powdered graphite in the cylinder. The cylinder was then inverted and the soil was covered with powdered graphite. The other electrode was then placed in contact with the powdered graphite in the cylinder.

11. The circuit was then connected to the current outlet and a reading of the intensity of alternating current passing through the sample was made on the ammeter. The difference in voltage between the two faces of the sample was read on the volt-ohmmeter. The resistance of the sample was then calculated.

12. The circuit was then disconnected from the source of power, the electrodes were removed, the graphite was poured out of the cylinder, the specimen was replaced on the plunger for further compaction by one blow of the drop hammer on each face of the sample; step 11 was then repeated. Steps 11 and 12 were repeated until each sample had received seven blows on each end.

13. After the last measurement, a sample of soil was placed in a moisture can for a final determination of moisture content. The evaporation of moisture from each batch was minimized by covering the mixing bowl with a wet cloth.

#### Determination of Resistance of Saturated Soil Samples

The following procedure was used to determine the resistance of soil samples in which the voids were entirely filled with brine:

1. The samples were first molded with a definite amount of brine of known concentration and compacted to a definite density.

2. Porous paper was then placed on each face of the soil sample.

3. A perforated metallic disc was placed on the paper to allow the free passage of the brine into the sample.

4. The mold was then placed vertically, and the bottom perforated disc was placed on a metallic ring supported by a plunger. A similar ring placed on the disc of the upper face of the sample supported weights to prevent the soil sample from swelling.

TABLE 4  
RANGE OF MOISTURE CONTENT IN SOILS STUDIED

Soil	Range (%)	Comment
Soil 20-2	8-18	Above 18 percent moisture horizontal cracks appeared. Cracks contain air and create discontinuities in electrical paths. Resistance of such a sample has no significance in this study.
Soil Ar-2	9-16	Impossible to obtain a good mix above 16 percent.
Soil AR-10	10-19	Above 19 percent moisture the densities decreased, regardless of compactive effort.
Soil AR-5	11-24	Upper limit dictated by same effect observed for soil AR-10.

5. Brine was poured into the lucite cylinder.

6. The cylinder was then placed in a 100 percent humidity dessicator to prevent evaporation.

7. When the sample was saturated, the resistance was measured as explained previously.

8. The saturated sample was measured and weighed in the mold; the sample was then extruded and placed in an oven to determine the moisture content.

### Calculation of Results

**Moisture Content.** —Two determinations of the moisture content of each sample were made and were found to agree closely.

The average value of the two moisture contents was used in all correlations. The moisture contents studied for each soil range between two limits, the lower limit was taken as the lowest value for which the conductivity of the soil could be measured precisely. The higher value was chosen to be near the optimum moisture content for the least degree of compaction. Some of the specimens were saturated with brine after molding. The range of moisture content studied for each soil along with comments concerning the upper limit of moisture content is given in Table 4.

**Dry Density.** —The dry density of a specimen was calculated from its weight, volume, and moisture content. It was found to vary with the type of soil, the moisture content, and the compactive effort. The highest density was reached with a compactive effort of seven blows on each face of the sample at the corresponding optimum moisture content.

**Salt Concentration.** —The salt concentration was controlled by making solutions of 0, 1.2, 2, 4, and 6 percent. With the first soil investigated (20-2) 8 percent was used and found to be an unnecessarily high concentration, thereafter 6 percent was the maximum concentration used.

**Resistance of Soil Sample.** —All resistances were calculated on a 5-cm length basis from the resistance of a soil sample of known length to have a uniform basis for comparison. A preliminary investigation was made before obtaining the final results. In the preliminary work three samples were molded with the same soil moisture content, density, and salt concentration in the brine. The results showed very little difference in the resistance of samples with identical characteristics, and the measured values were therefore considered reliable. The maximum error in the calculated resistance can be shown to be approximately the summation of the percent error for each variable. If the precision of the voltmeter and the ammeter is 1 percent, and the maximum error in reading is 0.5 percent for the voltmeter, ammeter, and Ames dial, it can be shown that the maximum total error is  $1.5 + 1.5 + 0.5 = 3.5$  percent and the most probable error is

$$\sqrt{(1.5)^2 + (1.5)^2 + (0.5)^2} = 2.2 \text{ percent.}$$

### RESULTS

The data resulting from the experimental work are presented as graphs. All values of resistance are expressed in ohms; density, in grams of dry soil per cubic centimeter; and moisture content, in weight of water expressed as a percent of the weight of dry soil. Experimental points on all graphs were joined in a smooth curve.

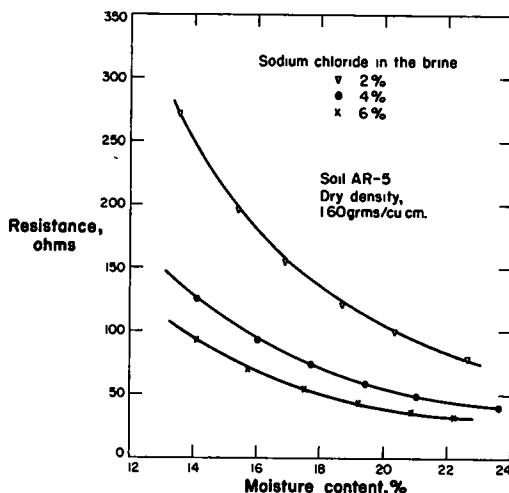


Figure 8. Curves of resistance of AR-5 samples as a function of moisture content for indicated sodium chloride concentrations.

### Factors on Which Resistance Is Dependent

Sundberg (7) states that the electrical conductivity of soil depends on the following factors:

1. Electrical conductivity of the minerals composing the soil.
2. Electrical conductivity of the liquid filling the pores.
3. Proportion of the volume of liquid filling the pores of the soil to the volume of solid soil material.
4. Shape of the pores.
5. Distribution of gas and liquids.
6. Temperature of the system.

To correlate the resistance of a soil sample with other soil properties as many of these factors as possible were eliminated.

Electrical Conductivity of Minerals Composing Soil. —The experimental data indicate that the minerals composing the soil cannot be considered conductors of electricity. Experiments performed at a low moisture content showed extremely high soil resistivities. No current flow could be detected by the ammeter when samples composed of soil and pure water were tested at moisture contents less than 4 percent. This indicates a negligible conductivity of the soil minerals compared with the conductivity of the liquid phase of the soil sample.

Temperature. —Because the resistivity of the brine is the factor most affected by temperature, the effect of temperature on the resistance of various brines was studied. The resistance of the brines was found to decrease almost linearly with temperature

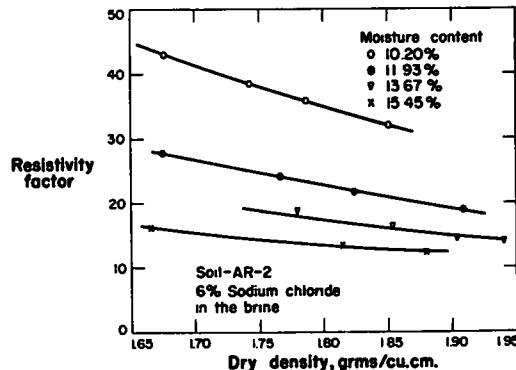
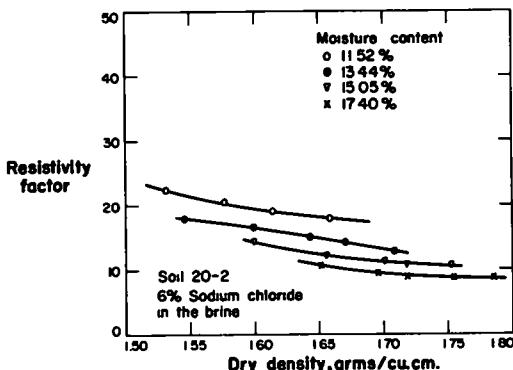
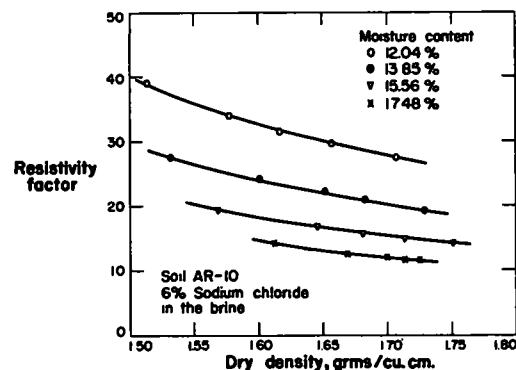
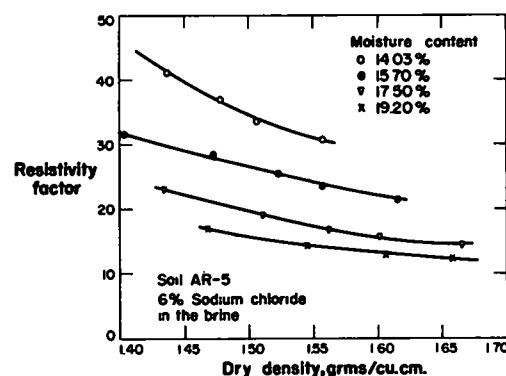


Figure 9. Resistivity factor curves as a function of dry density at different moisture contents for the indicated soils using a 6 percent brine.

in the range of laboratory temperatures (70 to 80 F). The decrease in brine resistance due to a temperature increase was determined to be about 1.5 percent per degree F regardless of brine concentration. The resistance of the brine was measured at 72 F, and readings from the soil samples were corrected to this temperature. The maximum correction necessary was 6 percent.

Electrical Conductivity of Liquid Filling Pores.—The percentage of salt in the brine contained in the soil had a profound influence on the resistance of a soil sample (Fig. 8). This was due primarily to the influence of the sodium chloride concentration on the resistance of the brine (Fig. 6).

To eliminate the influence of the sodium chloride concentration on the resistivity, a quantity introduced by Sundberg (7) called the resistivity factor was used. This term is defined as "the ratio of the resistivity of a porous rock completely saturated with brine to the resistivity of the brine itself." For convenience, the definition is modified so that the term means the ratio of the resistance of the soil-brine sample to the resistance of the brine; therefore, the resistivity factor has no dimensional units but is a number. The resistivity factor of a specimen is the same as if the resistance of the specimen were determined by using a brine of unit resistance. Then, according to Sundberg, the resistivity factor is dependant only on the following factors:

1. The proportion of the volume of liquid filling the pores of the soil to the volume of solid soil particles.
2. The shape of the pores.
3. The distribution of gas and liquid.

These factors in turn are primarily dependant on the physical properties of the soil-brine sample. The resistivity factor has been plotted for several soils as a function of moisture content and dry density.

#### Results from Ottawa Sand

Ottawa sand with a uniform particle size was used, and the dry density obtained in

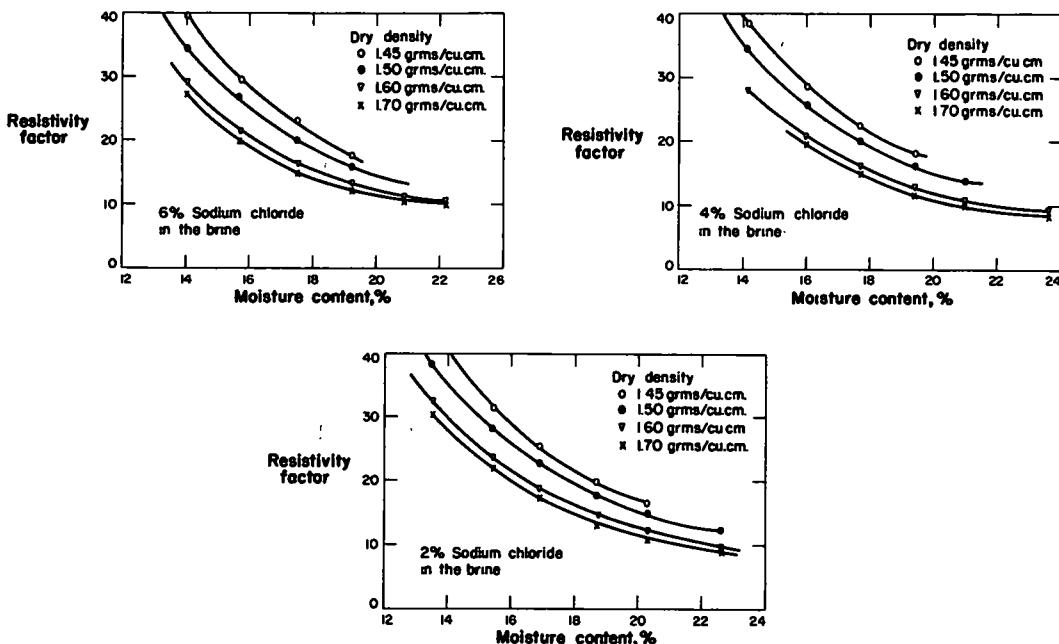


Figure 10. Resistivity factor as a function of moisture content of mixtures of AR-5 with indicated sodium chloride concentrations for indicated densities.

every sample was nearly the same—no moisture density relationship could be found. The resistivity factor of three samples of saturated Ottawa sand was measured for each salt concentration and was found to vary between 4.35 and 4.55. A value of 4.45 was taken as representative of Ottawa sand. Because the sample was saturated, the resistivity factor depends only on the shape and relative position of the individual sand grains.

#### Determination of Average Length of Pore Channels of Ottawa Sand

Winsauer et al. (9) present a discussion of the concept of tortuosity in a paper concerning the resistivity of brine saturated sands. Tortuosity of the pores within a rock was defined as the ratio of the length of the pore channels traversed by an electric current, flowing from one to another of two parallel planes within a brine saturated rock, to the distance between the planes. This concept is developed as follows.

The brine-filled channels, which lead from one face to the other of the sample, are extremely curved and complex. This lengthens the path followed by the current and increases the electrical resistance of the sample. The resistance of the sample is given by Eq. 1.

If the sample were all brine and no sand, the equation would be

$$R' = \beta \frac{L'}{A'} \quad (3a)$$

in which

$R'$  = resistance of brine sample in ohms;

$L'$  = distance in centimeters from face of sample to other; and

$A'$  = cross-section area in square centimeters.

The resistivity factor is then

$$\frac{R}{R'} = \frac{L}{L'} \cdot \frac{A'}{A} \quad (3b)$$

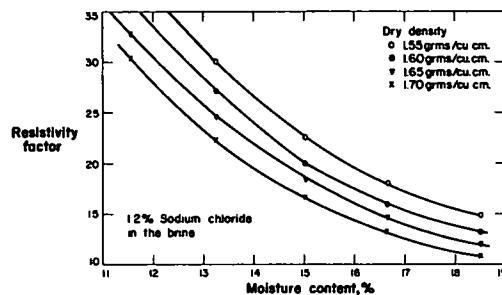
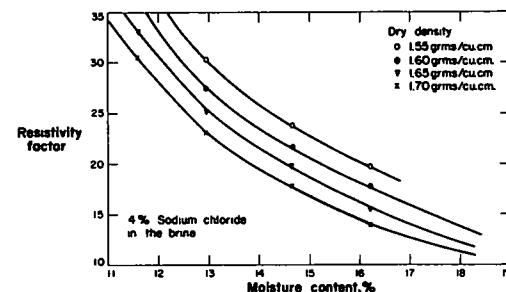
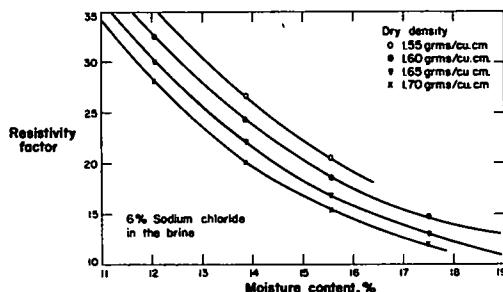


Figure 11. Resistivity factor as a function of moisture content of mixtures of AR-10 soil with indicated sodium chloride concentrations for indicated densities.

in which  $A/A'$  represents the porosity, which was found to be 0.334 for Ottawa sand. This makes  $L/L' = 1.49$  which means the average length of the flow path of the current is 1.49 times the length of the sample. This agrees reasonably well with the value of 1.37 as measured for Ottawa sand in a tortuosity cell by Winsauer et al. The discrepancy is probably due to differences in specimen density and average particle size.

### Moisture Content, Dry Density, and Resistivity Factor

Curves have been plotted (Figs. 10, 11, 12, and 13) for different densities, showing the resistivity as function of the moisture content. All of these curves indicate that the resistivity factor decreases as the moisture increases. When the moisture content is low, the resistivity factor is very high. As the moisture content increases the rate of decrease in resistivity becomes less and less.

Curves plotted for each soil giving the resistivity factor as function of the dry density for a given moisture content are shown in Figure 9. As the dry density increases for a given moisture content, the resistivity factor decreases. When the density is low for a given soil, the resistivity factor is high. As the density increases, the rate of decrease of the resistivity factor is less and less until the curve is nearly parallel to the density axis and the resistivity factor remains practically constant regardless of further density increases.

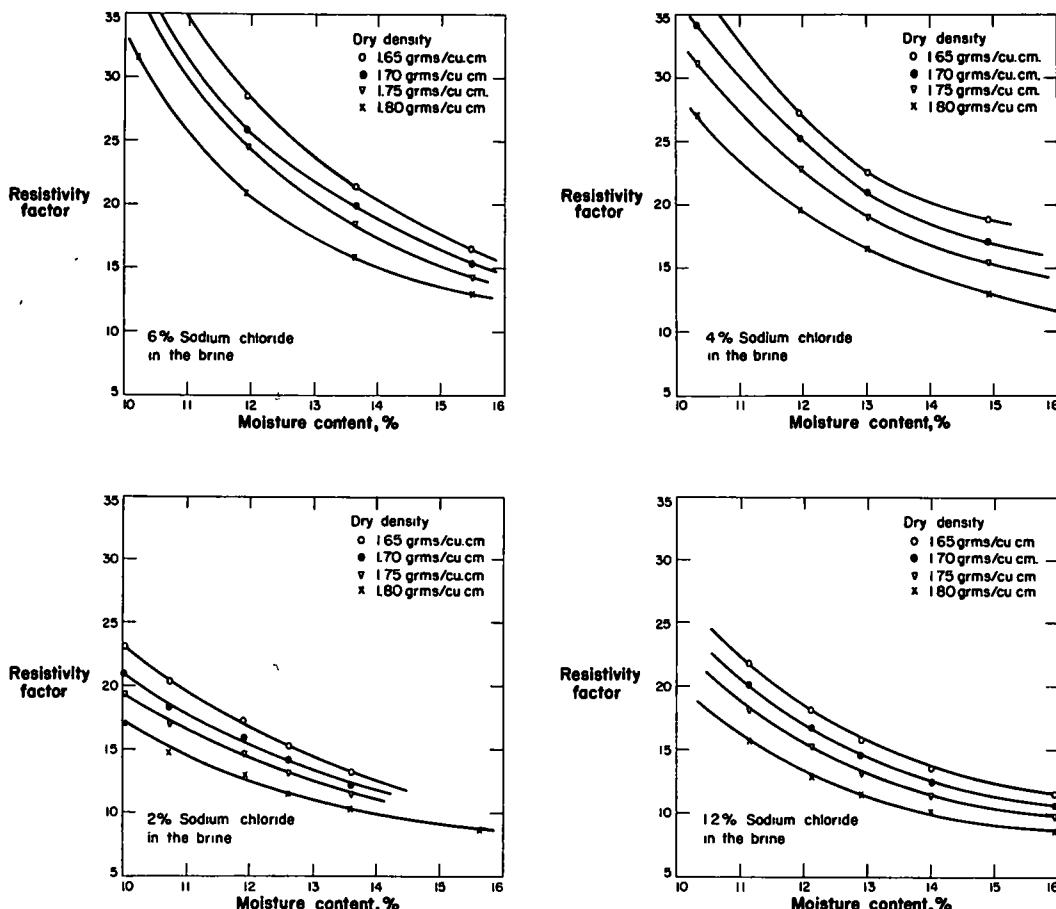


Figure 12. Resistivity factor as a function of moisture content of mixtures of AR-2 with indicated sodium chloride concentrations for indicated densities.

At any moisture content there are three phases present in the sample—solid, liquid, and gaseous. The liquid phase will surround the solid soil particles, and the gas will be surrounded with liquid.

An increase of dry density at constant moisture content or an increase of moisture at a fixed density corresponds to replacement of gas by solid and brine and the total liquid cross-sectional area normal to the passage of current will increase as the dry density or moisture content increases. Thus the resistivity factor will diminish as the dry density or the moisture content increases.

The reduction of the resistivity factor when the dry density increases is then not related so much to the increased density as to the increased amount of pore space occupied by the liquid volume in the sample even though the moisture content is held constant. A comparison of the resistivity factor of samples made from soils AR-5 and AR-10, using a constant volume of brine for each sample, shows that the samples with the highest dry densities had a slightly lower resistance. The difference was much larger for soils 20-2 and AR-2, particularly for AR-2.

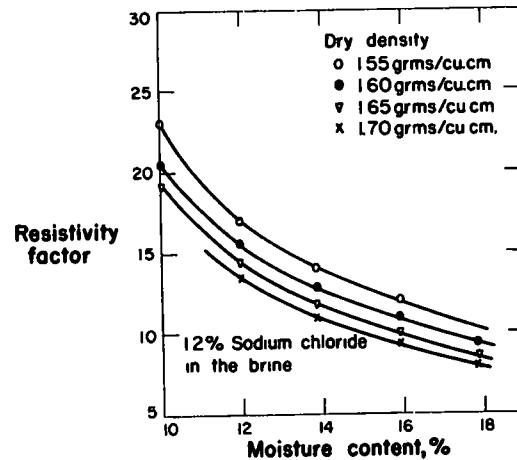
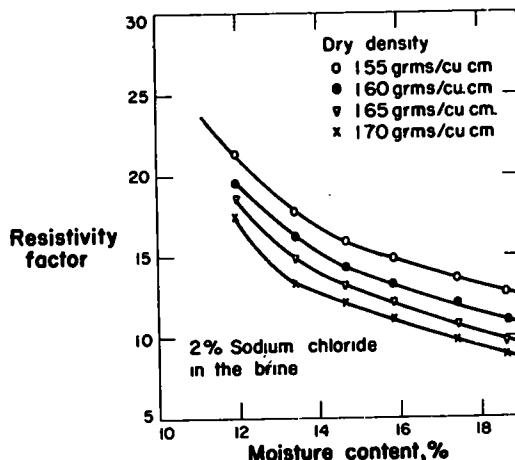
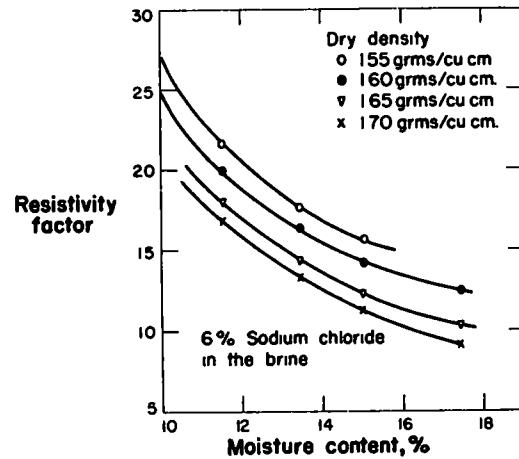
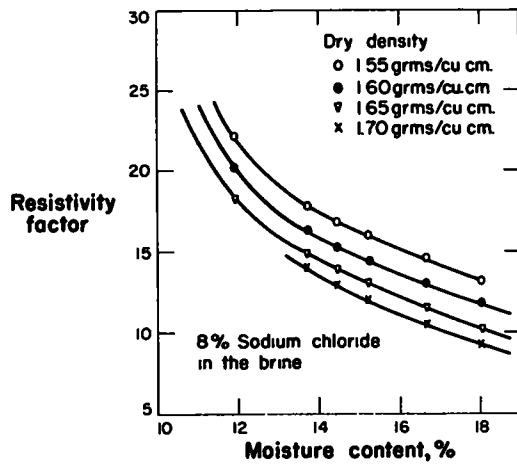


Figure 13. Resistivity factor as a function of moisture content, of mixtures of 20-2 soil with indicated sodium chloride concentrations for indicated densities.

### Comparison of Curves Obtained at Different Salt Concentrations

Soils AR-10 and AR-5.—The curves of resistivity factor vs moisture content for equal density are identical regardless of the concentration of the brine (Figs. 10, 11). This shows that the salt content in the capillary pores is only determined by the salt content of the brine, and that there are very few free ions on the surface of the soil particles and few natural soluble salts in the soil. Both soils contain a small quantity of calcium carbonate which has a very low solubility (0.0014 g per 100 g of water) and cannot be dissolved in sufficient quantity to modify the salt content appreciably and therefore the conductivity of the brine. This was verified by testing a mixture of the soil and pure water. The resistivity of the mixture was very high and could not be measured.

These two soils contain appreciable quantities of clay; AR-10 contains 11.3 percent clay-size material which is mostly kaolinite, the soil has a cation exchange capacity of 3.1 meq per 100 g, and AR-5 contains 42 percent of clay-size material which is mostly meta-halloysite, the soil has a cation exchange capacity of 11.0 meq per 100 g.

The cation swarm surrounding both meta-halloysite and kaolinite is held by charges resulting from broken bonds. Thus the exchangeable cations are held mainly around the edges of the flakes and elongate units. The edges of the clay particles, where there is a weak swarm of ions with a certain degree of freedom, will be regions of relatively high conductivity. The remainder of the clay surface and water will contain very few free ions and in these regions the conductivity will be low.

Tests were also run on samples saturated with brine. The values obtained for the resistivity factor at saturation were found to be close to the values obtained by extrapolation of the curves obtained from unsaturated samples.

Soils AR-2 and 20-2.—Figures 12 and 13 show that the resistivity factor vs moisture content curves for equal density do not coincide when the salt concentration of the brine varies. The resistivity factor decreases as the salt concentration decreases. This indicates that some factor independant of the brine influences the conductivity.

The soils were tested for naturally occurring salts by leaching and subsequent evaporation of the leachate. Each soil was shaken with distilled water for sufficient time to dissolve any soluble salts and was then separated from the solution by several filtrations. The resulting solution was evaporated to dryness; and because no detectable residue was found, the soils were assumed to be free of soluble salts.

The predominant clay mineral for both soils is montmorillonite; AR-2 contains 38 percent clay-size material, the soil has a cation exchange capacity of 17.5 meq per 100 g of soil, and 20-2 contains 19.8 percent clay-size material, the soil has a cation exchange capacity of 13.4 meq per 100 g of soil.

The cation exchange capacity of these montmorillonitic soils is mainly due to the lattice substitutions in the clay mineral so that most of the cations are held on the

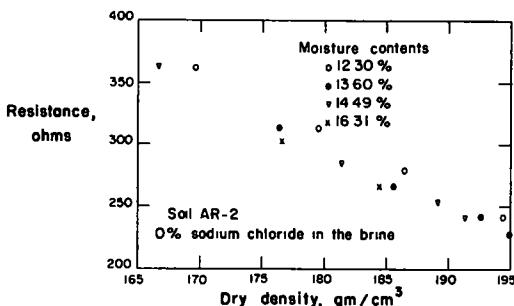


Figure 14. Resistance of samples of AR-2 soil mixed with pure water as a function of dry density for indicated moisture contents.

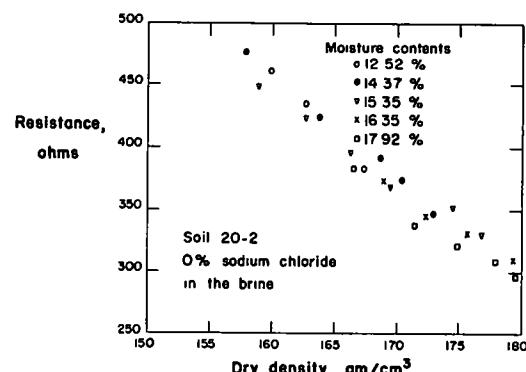


Figure 15. Resistance of samples of 20-2 soil mixed with pure water as a function of dry density for indicated moisture contents.

plane surfaces. About 80 percent of the cation exchange sites are thought to be on basal planes and only 20 percent due to broken bonds on the edges.

The surfaces of the clay, when coated with a solution, becomes enclosed by an ion swarm in which the cations are held in close proximity to the clay surface. The cations and water forming the diffuse ion layer have some degree of freedom and suggest a conducting path for the current along the clay surface. The influence of this added conductivity seems to be relatively greater at the lower salt concentrations. This observation is consistent with the diffuse double layer theory which states that the thickness of the diffuse layer is inversely dependent on the ion concentration of the surrounding solution. Comparison of the curves of 20-2 and AR-2 indicates that the reduction of the resistivity factor when the salt concentration decreases is more accentuated for AR-2 than for 20-2. This is to be expected since the clay content is higher in AR-2 than in 20-2.

The curves representing the resistivity factor vs density for equal moisture content are plotted for a salt concentration equal to zero (pure water) (Figs. 14 and 15). The data indicate that considerable conductivity is due to the ions on the clay surface. After a certain minimum moisture content is reached the curves for any higher moisture contents are very nearly identical. This occurs because the part of the moisture that conveys most of the current is near the clay surface and contains the ion swarm of the clay, and further, does not include all of the capillary water. If the dry density remains unchanged and the moisture content is increased, the conductivity increases until the ion swarm reaches its maximum expansion, then the conductivity remains approximately constant with further moisture increase. The resistivity diminishes as the dry density increases because the total clay surface increases per unit volume of soil and therefore

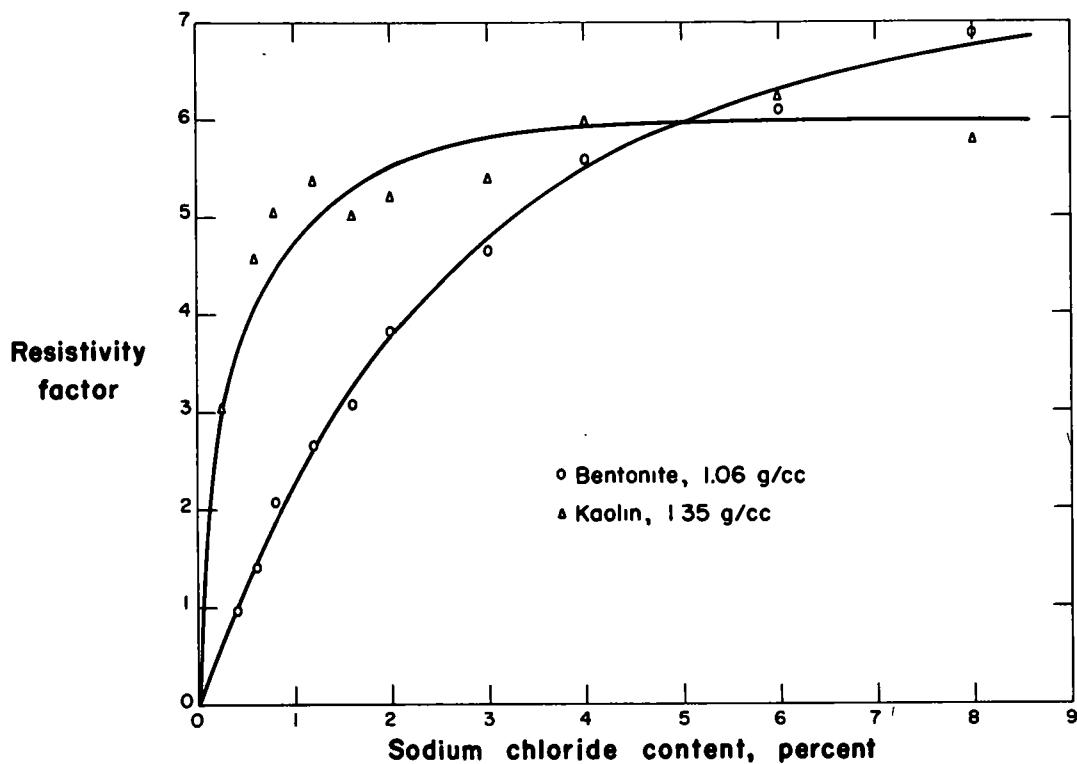


Figure 16. Bentonite and kaolin (pure clays) resistivity factor curves as a function of sodium chloride content. All points were taken from samples of constant density and constant moisture content.

the number of flow-paths for the current also increases. This explains the previous observation that the resistivity factor decreases for an identical volume of water as the dry density increases. The increased quantities of ions introduced with the added clay also contribute. AR-10 and AR-5 show a decrease in resistivity that is much smaller.

### Conductivities of Bentonite and Kaolin Clays

The resistivity factors of samples made from mixtures of sodium bentonite or kaolin and brines of various sodium chloride percentages are plotted as a function of the sodium chloride concentration in Figure 16. All bentonite samples were molded at 57 percent moisture and a dry density of 1.06 g per cc and all kaolin samples at 34 percent moisture and a dry density of 1.35 g per cc. The curves show that the resistivity factor increases with increasing sodium chloride concentration. The rate of increase in resistivity factor on the other hand, decreases with increasing sodium chloride concentration. The rate of increase in resistivity factor on the other hand, decreases with increasing sodium chloride concentration and rapidly reaches zero for kaolin and probably approaches zero for bentonite. Both curves were extrapolated to the origin because samples treated with pure water had negligible resistances compared to the resistance of water.

The initial portion of the curves show the greatest rate of increase in resistivity factor. Here the effect of the ion swarm on the conductivity is paramount. At higher NaCl concentrations the thickness of the ion swarm is reduced and its effect on conductivity eventually becomes negligible as compared to the conductivity of the solution. The curves in Figure 16 show that the effect of the ion swarm on the conductivity persists up to a salt content of at least 8 percent for bentonite, for kaolin the effect of the ion swarm is not as great and becomes negligible near a salt concentration of 3 or 4 percent.

### Over-all Comparison

Curves of resistivity factor as a function of moisture content for the four different soils compacted to 1.70 g per cc using salt solutions of 6 and 1.2 percent are shown in Figure 17. This figure shows that, when curves of the same brine concentration at a constant water content are considered, the soils can be categorized by descending values of resistivity factor as follows: AR-5, AR-10, AR-2, 20-2. Further consideration of the curves and the properties of the soils suggests that the conductivity of soil-water-sodium chloride systems is dependent on the density of the system, shape of the particles, geometric arrangement of the particles, the water content, the amount of salt present, the gradation of the soil (here, the most important item is probably the amount of clay), and the type of clay minerals in the soil.

AR-5 and AR-10 contain 42.0 and 11.3 percent, respectively, of clay-size material with meta-halloysite and kaolinite identified as the predominant clay mineral. Both of these clay minerals are associated with a weak ion swarm and have a low cation exchange capacity of about the same value. The soil (AR-5) containing the greatest amount of clay-size material offers the greatest resistance of the two. Apparently, the exchangeable cations do not play an important part in creating electrical flow paths for these types of clay minerals. If the number of exchange sites were important the soil containing

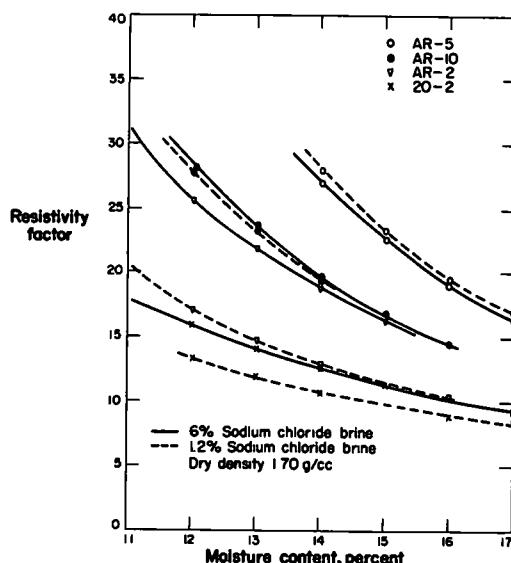


Figure 17. Comparison of the curves of resistivity factor as a function of moisture content for four soils investigated.

the most exchange sites would offer the least resistance. AR-5 has 42.0 percent clay against 11.3 percent clay for AR-10, yet AR-10 offers the least resistance. Here, the density, shape and arrangement of particles, the water content and the amount of salt are the controlling factors of conductivity.

AR-2 and 20-2 both contain montmorillonite clay minerals with 38.5 and 19.8 percent clay-size material, respectively. The cation swarm surrounding the clay minerals of these soils is due to isomorphous substitution as well as to broken bonds, and the ion swarms cover the entire clay mineral grain. The conductivity of both of these soils appears to be less affected by the amount of water and more by the amount of salt than that of either of the other soils. Apparently, the ion swarms in montmorillonitic soils are important conducting paths.

Figure 17 shows that the resistivity factor decreases for the soils AR-2 and 20-2 when the sodium chloride concentration in the brine decreases. The decrease of the resistivity factor is greater for the soil AR-2 than for 20-2.

An interpretation of this phenomenon may be given as follows: the conductivity of a given montmorillonitic soil, at a given dry density and moisture content depends primarily on the sodium chloride concentration of the brine and the presence of cation swarms which have some degree of freedom in the neighborhood of the surfaces of the clay particles. The conductivity of a specimen of either AR-2 or 20-2 is then a function of the sodium chloride concentration ( $x$ ) of the brine and the surface potential of the clay minerals which causes the ion swarm to exist. The magnitude of the ion swarm is also dependent on the salt concentration if the clay mineral is constant as in this case. These can be stated mathematically as follows: Conductivity of the specimen =  $G(x)$ . The conductivity of the brine is also dependent on the salt concentration; therefore, conductivity of the brine =  $f(x)$ . The resistivity factor ( $F_R$ ) is by definition the ratio of the resistance of the sample to the resistance of the brine, or in terms of conductivity:

$$F_R = \frac{f(x)}{G(x)} \quad (4)$$

The function  $G(x)$  is thought to be a sum of several functions of  $x$ , such as

$$G(x) = k f(x) + \Phi(x) \quad (5)$$

in which the value  $k f(x)$  represents the contribution of the electrolyte and the constant  $k$  depends on the geometry of the system.  $\Phi(x)$  represents several effects but mainly those due to the ion swarm. Assuming this relationship to be correct, there must be some value of concentration above which the function  $\Phi(x)$  is no longer important. Then  $F_R$  must approach some limiting value such that

$$\lim_{x \rightarrow x_c} F_R = \lim_{x \rightarrow x_c} \frac{f(x)}{G(x)} = \frac{f(x_c)}{k f(x_c)} = \frac{1}{k} \quad (6)$$

in which  $x_c$  represents a critical concentration above which the unique limiting value ( $1/k$ ) of  $F_R$  exists. This theoretical consideration is supported by the data shown in Figure 16 where the limit is readily apparent. Figure 17 also shows this, but not as obviously as Figure 16.

When the values of  $x$  are small, the function  $\Phi(x)$  is an important part of  $G(x)$  and influences the magnitude of  $F_R$ . This may be seen in both figures but is most apparent in Figure 16 where the resistivity factor is shown to undergo considerable change with a small increase in salt content in the lower ranges of concentration.

The following conclusions can be drawn from this mathematical study:

1. As the sodium chloride concentration increases the resistivity factor reaches a value that is independent of the effect of the ion swarm (asymptotic to  $1/k$ ).
2. If a soil has a high cation exchange capacity, which usually indicates a clay mineral with a heavy ion swarm, the point of noticeable decrease of resistivity factor as the concentration of sodium chloride decreases occurs at a higher brine concentration than for a soil with a lower value of the cation exchange capacity.

3. At the same sodium chloride concentration, the difference in resistivity factor from the maximum resistivity factor will be greater for a soil with a high cation exchange capacity than for a soil with a low cation exchange capacity.

These considerations help to explain the greater decrease in resistivity factor, when the sodium chloride decreases from 6 to 1.2 percent in the case of the soil AR-2 than for 20-2, and also why the decrease of resistivity factor for 20-2 was noticeable at a sodium chloride concentration of 1.2 percent whereas for AR-2 the decrease was noticeable at 2 percent.

### Soil Conductivity and Corrosion

Studies by Scott (6) indicate that the loss in weight of underground metallic objects due to corrosion is linearly related to the in situ soil conductivity. The data also show that the corrosive properties of a soil are especially destructive when the resistivity of the soil is less than 1,000 ohm-cm. Such a soil is particularly corrosive if direct current leaks into the ground from some power source such as the third rail for electric trains.

The resistivity of a mixture of soil and pure water can be easily and rapidly measured in the laboratory and could possibly serve as a basis for classification of soils according to corrosiveness. For instance, for AR-5 (meta-halloysite) and AR-10 (kaolinite) the possibility of corrosion due to electrochemical attack is not critical because the conductivity is unmeasureable. For 20-2 with a density of 1.60 g per cc, Figure 15 shows a resistance of 450 ohms that is practically independent of the moisture content and the resistivity of the soil is 1,800 ohm-cm which is not considered critical. However, for a density of 1.80 g per cc, the resistivity of the soil is 1,200 ohm-cm which is near the critical value. For AR-2 with a density of 1.90 g per cc and a moisture content greater than 12 percent, the resistance is 250 ohms, the resistivity is 1,000 ohm-cm, and the possibility of corrosion is critical.

The conductivity of top soil depends mainly on the density, moisture content, type of soil, the clay content, type of clay, and cation exchange capacity because the soil is generally leached and free of soluble salts. The data indicate that montmorillonite has a higher conductivity than meta-halloysite or kaolinite. A metallic object placed in a montmorillonitic soil would be more likely to be corroded through electrochemical attack than if it were placed in a soil containing meta-halloysite or kaolinite clay minerals.

### SUMMARY AND CONCLUSIONS

The values of resistivity were measured as a function of the type of soil, the dry density, the moisture content, and the sodium chloride content of the brine. Five soils were used in the investigation—Ottawa sand, a sandy soil containing kandite, a silty soil containing montmorillonite, a clay soil containing meta-halloysite, and a clay soil containing montmorillonite. The following conclusions are based on the data obtained from these five soils:

1. The soil minerals, per se, are non-conductors of electricity.
2. The resistivity of soil-brine systems decreases with an increase in density or moisture content.
3. The resistivity is inversely related to the salt content of the brine, except for soils containing montmorillonite. In these soils, the ion swarms due to isomorphous substitutions produce a high conductivity which is particularly noticeable at low salt concentrations.
4. The resistivity factor is a convenient form of representing the resistivity.
5. The change in resistivity from one soil to another, at identical moisture content, dry density, and salt concentration is due primarily to the differences in the characteristics of the paths followed by the electric current in passing from one electrode to the other.
6. Correlation of the resistivity with the properties of a soil containing a known salt, permits the determination of the salt content of the soil through resistivity.

7. The conductivity of soil is a factor in the rate of corrosion of buried metals. A corrosivity classification of soils, based on conductivity, would probably only hold for corrosion due to electrochemical attack caused by stray currents.

8. Correlation of the resistivity with the density of a salt-free soil should permit the rapid field determination of the dry density of a similar soil through simple conductivity determinations.

9. Rapid tentative identification of clay mineral types may be possible from electrical resistivity measurements.

#### ACKNOWLEDGMENTS

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#### REFERENCES

1. Hamilton, H. L., "Effects of Soil Corrosion on Cast-Iron Pipes." Am. Water Works Assoc. Jour., 52:638-650 (1960).
2. Leonardson, E.G., "Electrical Exploration Applied to Geological Problems in Civil Engineering." Am. Inst. of Min. and Mte. Eng. Trans, Geophysical Prospecting, 1932:99-113 (1932).
3. Lossing, V. T., "Measurement of Soil Moisture Content by Means of Electrical Resistivity." M.S. thesis, Iowa State Univ. of Science and Tech., Ames (1948).
4. Owen, J. E., "The Resistivity of a Fluid Filled Porous Body." Jour. Pet. Technol., 4:169-176 (July 1952).
5. Schlumberger, C., and Schlumberger, H., "Depth of Investigation Attainable by Potential Methods of Electrical Exploration." Am. Inst. of Min. and Met. Eng. Trans, Geophysical Prospecting, 1932:127-193 (1932).
6. Scott, O. H., "Distribution of Soil Conductivity and Its Relation to Underground Corrosion." Am. Water Works Assoc. Jour., 52:378-392 (1960).
7. Sandberg, N., "Effect of Impregnating Waters on Electrical Conductivity of Soils and Rocks." Am. Inst. of Min. and Met. Eng. Trans. Geophysical Prospecting, 1932:367-391 (1932).
8. Taylor, O.S., "A Portable Four-Electrode Probe for Measuring Soil Moisture." Ph. D. thesis, Iowa State Univ. of Science and Technol., Ames (1950).
9. Wenner, F., "A Method of Measuring Earth Resistivity." U.S. Bureau of Standards Bull. 15, 469-478 (1915-16).
10. Winsauer, W.O., Shearin, H.M., Jr., Wasson, P.H., and Williams, M., "Resistivity of Brine Saturated Sands in Relation to Pore Geometry." Am. Assoc. Pet. Geol. Bull. 36, 253-277 (1952).
11. Winsauer, W.O., and McCardell, W.H., "Ionic Double Layer Conductivity in Reservoir Rock." Jour. Pet. Technol., 5:129-134 (May 1953).
12. Wyble, D.O., "Effect of Applied Pressure on the Conductivity, Porosity and Permeability of Sandstones." Jour. Pet. Technol. 10:57-59 (Nov. 1958).