



## Project Summary

# An Investigation of Electrical Properties of Porous Media

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The problem of ground-water contamination has generated a need for detailed information on ground-water quality. The information derived from well drilling and sampling is limited, especially for delineating a ground-water contamination plume. DC electrical geophysical methods are increasingly used to help delineate contaminated ground water, but these methods provide only resistivity data. Because simple resistivity is affected by many different parameters, it is often impossible to develop a unique interpretation of the data. Complex resistivity (CR) supplies considerably more information about the saturated porous medium, thus introducing the possibility of reducing the number of unknown parameters affecting the electrical response of the porous medium.

The CR method provides two frequency dependent curves: impedance amplitude (related to resistivity) and phase shift (related to capacitive effects). Although CR offers much more information than a single resistivity measurement, there is not much known about how the CR responses are affected by pore geometry, pore fluid chemistry and clay content.

In this study, a laboratory measurement system is set up to allow systematic variation of parameters of interest, in order to determine their effect on amplitude and phase data. The laboratory apparatus consists of a sample holder, appropriate electrodes, and a data collection and analysis system. Experiments were conducted to vary grain size, concentration of NaCl and clay content.

Results indicate that grain size has little to no effect on amplitude or phase at any frequency for clay-free samples.

Phase-shift becomes increasingly negative over the range of frequencies investigated for a clay-bearing sample (3% clay content). The amplitude also becomes increasingly smaller with increased frequency for a clay-bearing sample.

Comparison of amplitude versus salinity for the clay and nonclay samples show that it may be possible to develop a modified version of Archie's Law for low salinity samples that contain clay.

*This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).*

### Introduction

Geophysical techniques are commonly used in investigations of the character and extent of the ground-water resource. This is especially true with respect to electrical methods. In general, these techniques rely on detecting the electrical response of subsurface units and then correlating this response with other geologic information so that estimates of hydrogeologic parameters can be made.

Traditional DC resistivity techniques used in conjunction with other methods usually provide adequate information about ground-water levels. However, DC methods are inadequate for many problems in which the contaminant plume location, distribution, and chemical nature are of interest because so many unknown parameters are generally involved in determining the DC resistivity. (For instance, a relatively low

resistivity value can be indicative of high salinity and/or high moisture content.)

Complex resistivity (CR) investigations conceptually could reduce the unknowns and therefore the ambiguity inherent in traditional DC methods. This potential advantage of CR exists because two sets of numbers, impedance and phase shift, for a suite of frequencies are generated for a particular porous medium, instead of a single value of resistivity obtained with DC techniques. With this additional information, it may be possible to obtain actual concentration values and/or type of chemical species present in a contaminated ground-water system.

This study is an effort to characterize the complex, frequency dependent electrical response of a saturated porous medium when certain parameters are varied. The parameters to be varied in these experiments are grain size, salinity and clay content.

### Procedure

To determine the complex impedance of the sample, the voltage waveforms across a known resistance ( $V_r$ ) and across the sample ( $V_s$ ) are digitized. By measuring the voltage drop across the known resistance ( $R_r$ ), the current can be determined utilizing Ohm's law. To characterize the sample impedance independent of sample geometry, it is necessary to multiply by the sample length ( $L$ ) and divide by the sample cross section ( $A$ ). This is referred to as the intrinsic impedance of the material.

To obtain the complex electrical response of the sample, a sine wave was used as an input and the digitized voltages were recorded and analyzed for up to 10 harmonics. This was repeated until the frequency range of interest was covered. Measurement of voltage waveforms across the sample and resistor were facilitated by digital recording.

The basic electrical measurement system used in this study is shown in Figure 1. To determine complex impedance, it is necessary to provide a current of the desired frequency in the sample. This is done by connecting a function generator to the current electrodes in the sample holder.

A function generator was employed as the voltage source. A decade resistor box was constructed which contains values from 10 ohm to  $1 \times 10^6$  ohms. Because the current density had to be kept low to ensure a linear electrical response, the resulting voltage drops

were too small to be accurately determined using the A/D converter. This was especially pronounced for samples with low impedances and at low frequencies. To overcome this problem, a preamp was used.

After the voltage waveforms are amplified, they are digitized and recorded with a resolution of 0.002 volts. The A/D converter is interfaced to a computer that controls the sampling and recording.

An important feature of the system is the sample holder (Figure 2) and its four electrode arrangement. The unit consists of two plexiglass reservoirs that are connected by a cylindrical plexiglass sample tube. The sample is held in place by plexiglass plates. The cylinder and sample can be removed from the reservoirs without disturbing the sample.

The sample was saturated by filling the fluid reservoirs. Saturation was considered to be complete when the reservoir level remained constant and the pore fluid conductivity, temperature, and pH were constant in both reservoirs.

### Results

Four different porous medium samples were prepared. The first three porous medium samples were pure glass beads of different grain sizes. The size distribution within each sample varied slightly, but the variation was limited enough so that each sample could be considered uniform in size.

The fourth sample was prepared as a clay-bearing porous medium containing 3% Na-Montmorillonite by weight mixed uniformly with large (2.2-2.8 mm) glass beads. A number of different

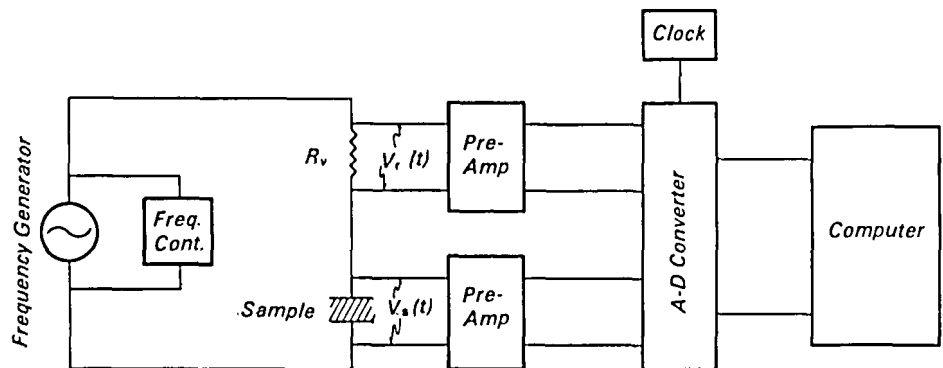


Figure 1. Experimental setup.

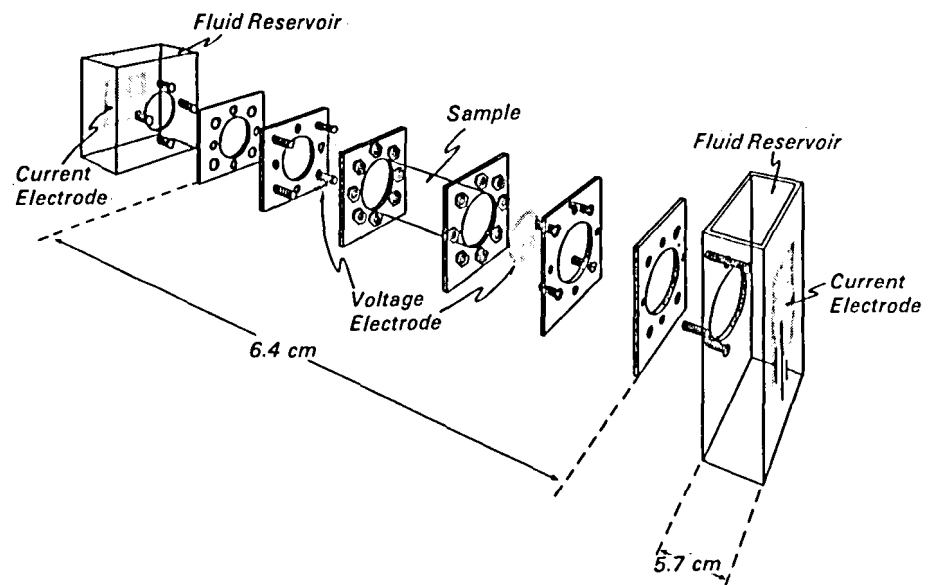


Figure 2. Sample holder.

experiments were run on each sample, varying the salinity concentrations, as shown in Table 1.

Induction effects were observed at frequencies greater than 100 Hz in low salinity samples (<0.001 molarity). The phase increase at higher frequencies was expected because the calibration showed similar phase increases. These phase increases are caused by inductive coupling within the equipment and should not be attributed to true sample response.

Small differences in amplitude occurred in the three clay free samples above 1000 Hz but are within the expected errors of the experiment. It may be concluded that there is no effect of grain size on the phase shift in clay-free samples. This is an expected result, since the phase shift should always be zero in a clay-free sample.

Figure 3 compares the phase shift response of two samples of the same grain size, one of which contained 3% clay. The results are shown for runs of three different salinities. The clean samples have essentially zero phase shift, whereas the clay samples have negative shifts.

Figure 4 relates amplitude to salinity for samples of the same pore size. Because the effect of frequency on amplitude is small, only one frequency was used (10 Hz). The clean sample plots as a straight line on the log-log plot, in agreement with Archie's Law. The clay-bearing sample also plots as a straight line, but with a smaller slope. Run CG4 falls above the straight line, however it is believed that about one-half of the clay was lost from the sample between run CG3 and CG4, thus causing the shift. The smaller slope associated with CG4 implies that a new form of Archie's Law can be developed for porous media containing clay with pore fluid of low salinity. This form of Archie's Law would have the form:

$$\rho_B = a\phi^{-m}\rho_f^n$$

where:

- a = empirical constant
- $\phi$  = porosity
- m = cementation factor
- $\rho_B$  = bulk (formation) resistivity
- $\rho_f$  = fluid resistivity
- n = constant which depends on the formation clay content

The data from these results suggest that the fluid resistivity has an exponent

**Table 1.** Summary of the Samples Used

Experiment Run	Glass Bead dia. (mm)	% Na-Mont by Weight	Molarity of NaCl Sat. Sol.
GB1	2.8-2.0	0	0.0001
GB2	2.8-2.0	0	0.0005
GB3	2.8-2.0	0	0.001
GB4	2.8-2.0	0	0.005
GB5	2.8-2.0	0	0.01
GB6	2.8-2.0	0	0.05
GB7	2.8-2.0	0	0.1
GB8	2.8-2.0	0	0.5
GB9	0.85-0.60	0	0.0005
GB10	0.85-0.60	0	0.001
GB11	0.85-0.60	0	0.005
GB12	0.85-0.60	0	0.01
GB13	0.85-0.60	0	0.005
GB14	0.85-0.60	0	0.1
GB15	0.15-0.106	0	0.0005
GB16	0.15-0.106	0	0.001
GB18	0.15-0.106	0	0.01
GB19	0.15-0.106	0	0.05
GB20	0.15-0.106	0	0.1
CG1	2.8-2.0	3.0	0.1
CG2	2.8-2.0	3.0	0.05
CG3	2.8-2.0	3.0	0.01
CG4	2.8-2.0	3.0	0.005
CG5	2.8-2.0	3.0	0.001
CG6	2.8-2.0	3.0	0.0005

greater than one for clay-bearing samples. Because there were only three valid data points, no attempt was made to calculate a value for n.

Another significant result is that the samples have nearly identical response when the pore fluid has 0.1 molarity NaCl. Unfortunately, there are no data beyond where the curves meet, so it is impossible to determine what will happen at higher NaCl concentrations. It is generally assumed that clay-containing formations will have a lower resistivity than clean formations due to the additional surface conductance on the clay.

These results indicate that salinity may influence this effect.

## Conclusions

Amplitude/phase data are not affected by variation in grain size for clay-free samples. This result implies that hydraulic conductivity cannot be determined by amplitude/phase data because hydraulic conductivity is a function of porosity and grain size.

Clay-free samples have zero phase shift over the range of frequency measurement, whereas the clay-bearing sample showed increasingly negative

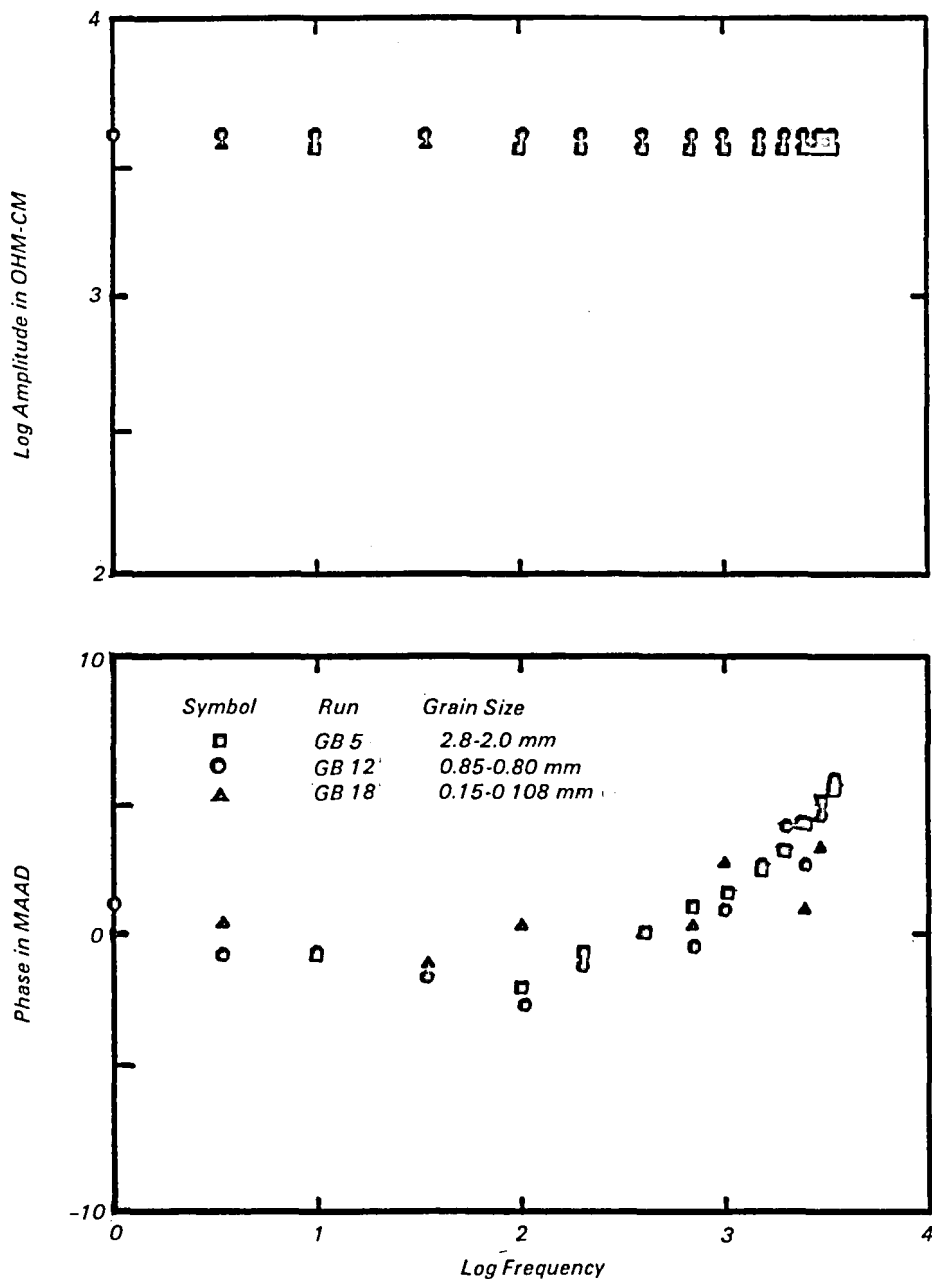


Figure 3. Effect of grain size on phase and amplitude (without clay).

phase shifts from about 10 Hz through 3500 Hz. The amount of clay in the sample was only 3%, which is an indication that CR measurements may be quite sensitive to clay content and therefore useful for detecting changes in hydraulic conductivity that are due to the presence of clay. Downhole CR data would be more useful than surface CR for clay-content determination for two reasons: a) the vertical changes in hydraulic conductivity are very useful in

determining contaminant migration in ground water, and b) surface measurements cannot provide the detailed resolution necessary to delineate thin but important changes in hydraulic conductivity.

The results of this study show that the presence of clay has a large effect on the frequency dependent electrical properties of a saturated porous medium. Most well log interpretation strategies that have been used in hydro-

logic investigations ignore or avoid this problem, thus making the interpretations subject to significant error. The electrical effects of clay on a saturated porous medium need to be understood so that clay content and variation can be determined. Amplitude/phase data taken over a range of frequencies show promise for enabling these determinations. Further quantitative laboratory work needs to be done to understand more fully the relationships between amplitude/phase information and clay content.

Clay content information can be derived from nuclear logging techniques. However, to apply this information in interpreting the electrical response requires an indirect relationship involving the cation exchange capacity of the clay. A model accounting for the effect of clay on amplitude that is based on phase information may be more direct. An additional advantage of CR over techniques using active sources is the elimination of the logistical problems associated with the radioactive source. The potential advantages to downhole CR over other methods may lend further weight to the recommendation to develop a better understanding of the relationship between amplitude/phase information and clay content.

The insensitivity of amplitude and phase to grain size variation provides a strong indication that further research in this area will not be necessary. It does not seem likely that hydraulic conductivity variations resulting purely from grain size variations will be detectable with downhole CR methods. Information on grain size variation is very important for the determination of hydraulic conductivity variations, and it is recommended that other downhole methods be examined to determine their potential in this area.

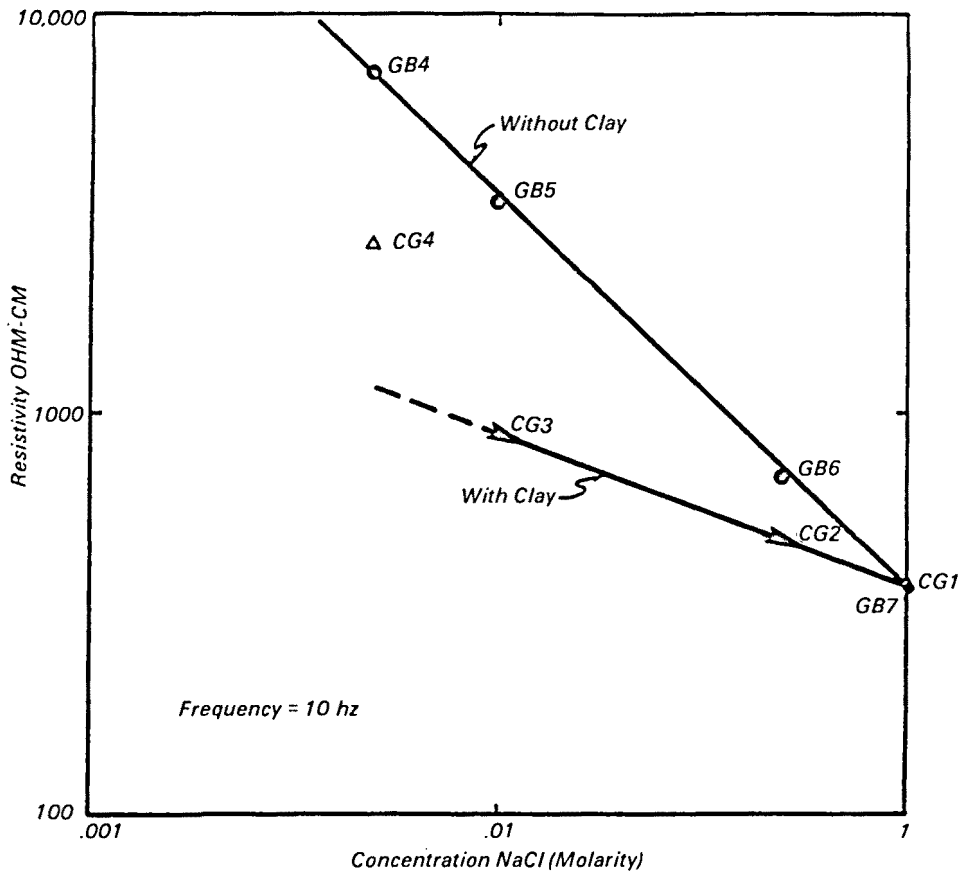


Figure 4. Effect of clay content on the impedance vs. salinity relationship.