SPECTRAL INDUCED POLARIZATION MEASUREMENTS ON UNSATURATED, UNCONSOLIDATED SEDIMENTS

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Abstract

Understanding the Spectral Induced Polarization (SIP) response to saturation is required to improve application of this geophysical technique in the vadose zone. SIP measurements (0.1-1000 Hz) were conducted on three unconsolidated sediments during evaporative drying. Sample grain size distribution was determined from laser particle size diffraction measurements. The dependence of the real and imaginary conductivity components on frequency and degree of saturation was determined. Both conductivity components exhibit an Archie-type power law dependence on saturation. However, the imaginary conductivity is less dependent on saturation. We find that, for each sample, the low frequency imaginary (surface) conductivity saturation exponent is approximately about half the low frequency real (bulk) conductivity exponent. The dependence of the imaginary conductivity exponent on frequency independent. For a coarse sample, the imaginary conductivity saturation dependence decreases above 10 Hz. This is tentatively related to the difference in the size of polarizable pores within each sample.

Introduction

Measurements of Spectral Induced Polarization (SIP), or complex conductivity, are used to determine the bulk and frequency dependent surface electrical properties of subsurface materials. The surface conductivity measured with SIP is dependent upon specific surface and cation exchange capacity (CEC), as well as surface charge density and surface ionic mobility (Vinegar and Waxman, 1984; Revil and Glover, 1998; Lesmes and Frye, 2001). The sensitivity of SIP to surface properties has generated interest in the method for lithologic discrimination (particularly clay content) (Iliceto et al., 1982), hydraulic conductivity estimation (Börner et al, 1996) and surface electrochemical reactions caused by hydrocarbon contamination (Olhoeft, 1985).

There have been multiple SIP studies conducted on saturated rock and sediments, yet little attempt has been made to quantify the influence of degree of saturation on complex conductivity, particularly in unconsolidated materials. Such studies are required to evaluate the applicability of SIP in the near-surface, vadose zone. In this paper, we present a simple model to describe the dependence of the complex conductivity components on degree of saturation. Making accurate SIP measurements on unsaturated unconsolidated materials is non-trivial. Therefore, we also discuss the apparatus used to obtain the data reported here.

Theory

The intrinsic conductive and capacitive properties of earth materials can be represented by a complex electrical conductivity (σ^*), a complex resistivity (ρ^*), or a complex permittivity (ϵ^*),

$$\sigma^* = \frac{1}{\rho^*} = i\omega\varepsilon^*,\tag{1}$$

where ω is the angular frequency and $i = \sqrt{-1}$. For example, measured complex electrical parameters can be expressed in terms of a conductivity magnitude ($|\sigma|$) and phase ($|\phi|$), or by real (σ) and imaginary (σ ') components,

$$\sigma^* = |\sigma| e^{i\phi} = \sigma' + i\sigma'' \,. \tag{2}$$

The real component (σ) represents conduction currents that are in-phase with the applied electric field. The imaginary component (σ'') represents displacement currents that are 90° out-of-phase with the applied electric field.

Theoretically based effective medium theories can be used to model the complex electrical properties of porous media. These models are formulated in terms of the intrinsic electrical properties of the mixture and the shape of the embedded particles (Sen et al., 1981; Mendelson and Cohen, 1982). Three-phase mixing models that account for the electrical properties of the surface phase are required to predict the dispersions that are observed in the permittivity and conductivity responses of water saturated samples (Bussian, 1983; Knight and Endres, 1990; Samstag and Morgan, 1991).

A more simplistic approach, which has been used previously, is to model the bulk conductivity (σ_{bulk}) and surface conductivity (σ_{surf}^*) mechanisms as parallel conduction paths (Wyllie and Southwick, 1954; Marshall and Madden, 1959; Waxman and Smits, 1968; Clavier et al., 1984; Vinegar and Waxman, 1984; Lesmes and Frye, 2001). At low frequencies (i.e. less than 1000 Hz), where IP phenomena are typically measured in the field, we assume,

$$\omega \varepsilon_{\text{bulk}} \ll \sigma^{"}_{\text{surf}}(\omega), \tag{3}$$

where ε_{bulk} is assumed to be equal to the high frequency dielectric permittivity (ε_{∞}) and σ''_{surf} is the imaginary component of the surface conductivity. Following Lesmes and Frye (2001) the low-frequency complex conductivity model for the sample response is then,

$$\sigma^* = [\sigma_{\text{bulk}} + \sigma'_{\text{surf}}(\omega)] + i\sigma''_{\text{surf}}(\omega), \qquad (4)$$

where σ_{surf} is the real component of the surface conductivity. The bulk conductivity σ_{bulk} is independent of frequency and can be derived from the low frequency conductivity response of the Hanai-Bruggeman (HB) effective medium theory (Sen et al., 1981),

$$\sigma_{\text{bulk}} = \frac{1}{F} \sigma_w = \sigma_w \phi^m, \tag{5}$$

where σ_w is the solution conductivity, ϕ is the porosity, and *m* is the cementation index which is a function of the effective grain shape. The quadrature conductivity is only a function of the surface conductivity, whereas the in-phase conductivity is a function of both the bulk and surface conductivity mechanisms,

$$\sigma''(\omega) = \sigma''_{surf}(\omega), \tag{6}$$

and,

$$\sigma'(\omega) = \sigma'_{bulk} + \sigma'_{surf}(\omega).$$

An equivalent circuit for the complex conductivity can be seen in Figure 1.



Figure 1. Simple circuit diagram of the parameters of the complex conductivity component (σ^*).

The σ_{surf}^* is a frequency dependent component that is a complicated function of the scale of the surface area, ionic charge density and the ionic mobility (Vinegar and Waxman, 1984; Revil and Glover, 1998; Lesmes and Frye, 2001). The ionic charge density and ionic mobility will depend on fluid chemistry. Although σ_{surf}' is a relatively understudied component of σ^* , one assumption is that the bulk conductivity and surface conductivity mechanisms both follow the same tortuous path and are both related to an electrical formation factor (Vinegar and Waxman, 1984; Börner et al., 1996). In this sense, Börner et al. (1996) related the surface conductivity to the formation factor (*F*), specific surface to porosity ratio (*S*_{por}), and an undefined function of fluid chemistry (σ_w) such that:

$$\sigma' = \sigma_{bulk} + \sigma'_{surf} = \frac{1}{F} \left(\sigma_w + f(\sigma_w) S_{por} \right)$$
(8)

$$\sigma'' = \sigma''_{surf} = \frac{1}{F} f(\sigma_w) lS_{por}$$
⁽⁹⁾

where l is the ratio of the surface conductivity to the imaginary component and independent of fluid composition and distribution. Vinegar and Waxman (1984) adopted a similar approach but noted that the formation factor for the quadrature conductivity path was best given by the inphase formation factor scaled by porosity.

The formation factor is dependent upon the degree of saturation. A decrease in saturation effectively increases the tortuosity of the real and quadrature conductivity paths, thus decreasing σ' and σ'' . Equations (8) and (9) can be generalized for unsaturated sediments:

$$\sigma_{us}' = \frac{1}{F} S_w^n \left(\sigma_w + f(\sigma_w) S_{por} \right)$$
(10)

$$\sigma_{us}'' = \frac{1}{F} S_w^p f(\sigma_w) l S_{por}$$
⁽¹¹⁾

where S_w is the degree of saturation at some point, and *n* and *p* describes the dependence of the real and imaginary components on saturation respectfully. For a coarse grained sample in the absence of significant clay content, $\sigma_{\text{bulk}} >> \sigma'_{\text{surf}}$ such that,

(7)

$$\sigma'_{us} \approx \frac{1}{F} \sigma_w S_w^n \,. \tag{12}$$

In this study we only investigate the variance of the parameters n and p for sandy unconsolidated sediments. For any given sediment sample (constant F, S_{por} , and σ_w) we can write the dependence of the ratio of unsaturated to saturated conductivity component (S) on saturation as,

$$S' = \frac{\sigma'_{us}}{\sigma'_{sat}} \approx \frac{\sigma'_{bulk(us)}}{\sigma'_{bulk(sat)}} = S_w^n$$

$$S'' = \frac{\sigma''_{surf(us)}}{\sigma''_{surf(sat)}} = S_w^p$$
(13)
(14)

Instrumentation

Frequency domain Spectral Induced Polarization (SIP) measurements were made from 0.1-1000 Hertz using a NI 4551 Dynamic Signal Analyzer (DSA) (Figure 2). Stainless steel coiled current electrodes were placed on either end of the sample, which was saturated with a 0.01 molar NaCl solution. Non-polarizing electrodes (Ag-AgCl) are used to measure the phase shift (ϕ) and conductivity magnitude($|\sigma|$) across the sample relative to a reference resistor. The



Figure 2. Schematic of sampler apparatus and circuit setup for obtaining phase angle and magnitude responses.

sample container is made of clear Polyvinyl Chloride Tubing (PVC), which produces no spurious phase response. An AD620 pre-amplifier is used to increase the input impedance to ~ $10^9 \Omega$ on the sample channel, eliminating any spurious response from the instrumentation.

In Figure 2 the Ag-AgCl electrodes are positioned outside of the current path. This is done to avoid potential electrodes in the current path, which cause spurious phase shifts (Lesmes, 1993; Vanhala and Soininen, 1995). Slight misorientation of the non-polarizing electrodes from perpendicular to current flow causes a voltage gradient across the electrode and an anomalous phase shift as seen in Figure 3. These tests were run on a 16 Ohm m water sample, which should have no measurable phase response between 0.1-1000 Hz. Increasing the angle from perpendicular increases the spurious phase shifts up to a maximum of ≈ 42 (mRads). Even with the electrodes perfectly perpendicular to the current pathway, a slight spurious inductive effect occurs at high frequencies. Measurements on unsaturated samples thus require good electrical contact without placement of large electrodes in the sample itself. This was accomplished by using specially made porous glass tubes and inserting them to the edge of the sample. The porous tubes were filled with fluid of the same chemistry as the in-situ fluid, saturating the porous frit, thus making a contact path for the non-polarizing electrodes outside of the current path. The phase response with M and N out of the current pathway (OCP) is a zero phase response with a minor capacitive effect (~ 4 mRad at 1000 Hz) at the high frequencies (yellow triangles in Fig. 3). The remaining high frequency phase error is due to the wiring and can be calibrated and reduced if necessary.



Figure 3. Phase responses for different angle positioning of M and N electrodes in 16 Ohm m water placed in the current pathway, compared with the response of the electrodes outside the current pathway (OCP). The true response for the sample is effectively 0 mRad over the measured frequency range.

A Coulter LS200 particle size analyzer was used to determine the grain size distribution (GSD) of three sandy samples. For this study the physical characteristics of the samples are summarized by an effective grain size and a spread of the grain sizes in Table 1. Effective grain size (D_{10}) is the grain diameter for which 10% of the sample is finer. The spread of the GSD curve in phi units is:

$$\varphi_{PHI} = Log_2 \left(\frac{D_{90} - D_{10}}{2} \right)$$
(15)

where D_{90} is the grain diameter for which 90% of the sample is finer.

Sample	d ₁₀ (mm)	PD _{Phi}
A	0.047	1.3
В	0.302	1.0
D	0.749	0.6
Error	± 0.002	± 0.1

Fable 1.	Summary	of Sample	Characteristics
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Results

SIP Acquisition Procedure

The three samples were saturated with a 0.01 molar NaCl solution and weighed to obtain total wet weight. SIP measurements were made from 0.1-1000 Hz at 40 logarithmic intervals. Samples were then partially dried by evaporation, after which the degree of saturation from weighing and SIP measurements were again obtained. This procedure was repeated until the sample weight could no longer be reduced. The soil was finally extruded from the sampler and oven dried to obtain the total dry weight. Porosity and degree of saturation (S_w) were calculated for each saturation interval.

SIP Dependence on Saturation

In Fig. 4 σ'' is frequency dependent, whereas σ' is effectively frequency independent. In this paper we concentrate on the nature of the low frequency σ'' dependence on S_w , i.e. within the frequency range of field IP measurements (typically ≈ 0.1 -10 Hz). Figure 5 illustrates the power law dependence of the ratio of unsaturated to saturated conductivity components (S' and S'') on S_w . As expected both decrease with decreasing S_w . Note that S is not 1 at S_w equal to 1 as our saturation procedure could not provide 100 % absolute saturation.



Figure 4. The dependence of σ' and σ'' upon S_w and frequency (a) sample A (b) sample B.

For all samples S'' is clearly less dependent upon S_w than S'. The linear correlation coefficient (R²) is greater than 0.9, (95% confidence interval) in each case. The values for the saturation components and associated errors are given in Table 2. We find that p < n and that p appears $\approx 0.5 n$.



Table 2. Summary of the model parameters obtained from equations13 and 14. For each regression $R^2 > 0.9$ (95% confidence interval).

∆ S'**○** S''

Sample	п	p
A	1.01 ± 0.11	0.41 ± 0.07
В	0.98 ± 0.04	0.42 ± 0.05
D	1.28 ± 0.09	0.61 ± 0.06

Discussion

The reduced dependence of S'' on $S_{w_{x}}$ relative to S' on $S_{w_{x}}$ corresponds to the findings of Vinegar and Waxman (1984) for oil-saturated sandstones. For their sandstone samples, $p \approx 1$ and $n \approx 2$ i.e. $p \approx 0.5 n$, which is congruent with our findings on unconsolidated materials listed in Table 2. However, results in Fig. 4 indicate that p is also dependent on frequency although nis effectively frequency independent. The quadrature saturation exponent p is plotted versus frequency for two samples (A and B) in Fig. 6. Sample A is fine grained with a wide grain size distribution and Sample B is coarse grained with a narrower grain size range (Table 1). The p value for the fine-grained sample is relatively constant across the range of frequencies. In contrast, p for the coarse-grained sample is only constant below10 Hz, with σ'' becomes less saturation dependent above 10 Hz. Lesmes and Morgan (2001) correlate the frequency of the polarization in sediments with the inverse square of the grain radius. We expect that grain size and saturated pore size are correlated. In the coarse sample, finer grain sizes are absent and most of the water is contained in relatively large pores. The frequency insensitivity above 10 Hz may then relate to the absence of draining fine pores within the sample. The saturation dependence of σ'' across the entire measured frequency range of the fine sample may similarly reflect the broader grain size distribution and the presence of small pore sizes. More work on the frequency dependent SIP response to saturation is required to validate these concepts.



Conclusion

Figure 6. The relationship of saturation exponent p to the range of frequencies.

A simple IP model was developed to describe the surface conductivity dependence on degree of saturation. We find that imaginary conductivity is less dependent on S_w than real conductivity (which for our sample is effectively bulk conductivity) and both exhibit a power law relation to S_w . The imaginary saturation exponent *p* appears related to *n* by $p \approx 0.5 n$, which

agrees with Vinegar and Waxman (1984) findings for oil-bearing sands. However the imaginary saturation exponent is frequency dependent, the degree to which depends on material type.

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References

- 1. Archie, G.E. (1942), "The electrical resistivity log as an aid in determining some reservoir characteristics", *Trans. Am. Inst. Min. Metall. Pet. Eng.*, 146, pp. 54-62.
- 2. Börner, F. D., Schopper, J. R. and A. Weller (1996), "Evaluation of transport and storage properties in the soil and groundwater zone from induced polarization measurements", *Geophys. Prosp.*, 44, pp. 583-602.
- 3. Bussian, A. E. (1983), "Electrical conductance in a porous medium", *Geophysics*, 48, pp. 1258-1268.
- 4. Clavier, C. G., Coates, G. and Dumanoir (1984), "Theoretical and experimental basis for the dual-water model for the interpretation of shaly sands", *Soc. Pet. Eng. J.*, 9, pp. 341-351.
- 5. Iliceto, V., Santarato G., and Veronese, S. (1982), "An approach to the identification of fine sediments by induced polarization laboratory measurements", *Geophysical Prospecting*, 30, pp. 331-347.
- 6. Knight, R. J. and A. Endres (1990), "A new concept in modeling the dielectric response of sandstones, 60Hz to 4MHz: Defining a wetted rock and bulk water system", *Geophysics*, 55, pp. 586-594.
- 7. Lesmes, D. P. (1993), "Electrical-impedance spectroscopy of sedimentary rocks", *Dissertation*, 164 pp.
- 8. Lesmes, D. P., and K. M. Frye (2001), "The influence of pore fluid chemistry on the complex conductivity an induced-polarization responses of Berea sandstone", *J. Geophy. Res.*, 106, B3, pp. 4079-4090.
- 9. Marshall, D. J. and T. R. Madden (1959), "Induced polarization: A study of its causes", *Geophysics*, 24, pp. 780-816.
- 10. Mendelson, K. S., and M. H. Cohen (1982), "The effect of grain anisotropy on the electrical properties of sedimentary rocks", *Geophysics*, 47, pp. 257-263.
- 11. Olhoeft, G. R. (1985), "Low-frequency electrical properties", *Geophysics*, 50, pp. 2492-2503.
- 12. Revil, A., and P. W. J. Glover (1998), "Nature of surface electrical conductivity in natural sands, sandstones, and clays", *Geophys. Res. Lett.*, 25, pp. 691-694.
- 13. Samstag, F. J. and F. D. Morgan (1991), "Induced polarization of shaly sands: Salinity domain modeling by double embedding of the effective medium theory", *Geophysics*, 56, pp. 1749-1756.

- 14. Sen, P. N., Scala, C. and Cohen, M. H. (1981), "A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads", *Geophysics*, 46, pp. 781-795.
- 15. Vanhala, H. and H. Soininen (1995), "Laboratory technique for measurement of spectral induced polarization response soil samples", *Geophys. Prosp.*, 43, pp. 655-676.
- 16. Vinegar, H. J., and M. H. Waxman (1984), "Induced polarization of shaly sands", *Geophysics*, 49, pp. 1267-1287.
- 17. Waxman, M. H. and L. J. M. Smits (1968), Electrical conductivities in oil-bearing shaly sands, *Soc. Pet. Eng. J.*, 243, pp. 107-122.
- 18. Wyllie, M. R. and P. F. Southwick (1954), an experimental investigation of the SP and resistivity phenomena in dirty sands, *J. Pet. Technol.*, 6, pp. 44-57.