Contribution of Stern layer and membrane polarization to spectral induced polarization of variably saturated sandy soils

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1. Introduction and motivations

- Most existing process-based models of induced polarization (IP) consider either membrane (e.g. Titov et al., 2002) or grain (EDL) polarization (e.g. Revil and Florsch, 2010), but not both mechanisms together.
- Experiments have however shown that both the grain size distribution and the characteristics of the pore space influence SIP (spectral induced polarization) response of granular materials. Possibly this suggests that both types of polarization play a role.
- Furthermore, theoretical and experimental works on micro/nanofluidic devices demonstrated that membrane polarization occurs in real systems (see for example Mani et al., 2009).
- The aim of this work is to develop a mechanistic model for SIP that incorporates both grain and membrane polarization and uses a non-linear mixing rule to describe effect of the pore-space configuration of the solid and fluid phases.

2. Methodology

- The (frequency-dependendent) bulk conductivity in variably saturated conditions is computed using the Hashin-Shtrikman Average (HSA) model of Brovelli and Cassiani (2010, 2011) (the * denotes compex variables),

$$\sigma_b^*(\omega) = HSA\left(\sigma_w^*(\omega), \sigma_s^*(\omega), \phi, s_w, m, n\right) = \frac{3-\phi}{2}\phi^{m-1}\sigma^*_{HSU} + \frac{\phi-3}{2}\phi^{m-1}\sigma^*_{HSL},$$

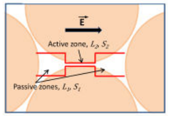
$$\sigma^*_{HSU}\left(\sigma_p^*, \sigma_s^*, \phi\right) = \sigma_s^* + \frac{1-\phi}{\left(\sigma_p^* - \sigma_s^*\right)^{-1} + \frac{\phi}{3\sigma_s^*}} \qquad \sigma^*_{HSL}\left(\sigma_p^*, \sigma_s^*, \phi\right) = \sigma_p^* + \frac{\phi}{\left(\sigma_s^* - \sigma_p^*\right)^{-1} + \frac{1-\phi}{3\sigma_p^*}}$$

- σ_{HSU} and σ_{HSU} are the upper and lower H-S bounds, σ_p is the conductivity of the pore-space (a function of water electrical conductivity and saturation), σ_w and σ_s are the electrical conductivities of the water and solid phases.
- m is Archie's cementation exponent, ϕ is porosity and S_w water saturation.
- Maxwell-Wagner polarization and high frequency noise are considered using a Cole-Cole model

3. Polarization mechanisms

- Membrane polarization is modelled using a modified form the SNP model (Titov et al., 2002), with a convolution integral over the pore-throat distribution $f_p(L,a)$

$$\sigma_w^*(\omega) = \sigma_w^0 \left[1 - \int_0^\infty\int_0^\infty f_p(L,a)\eta_0(L,a)\left(1 - \frac{1-\exp\left(-2\sqrt{i\omega\tau_p(L)}\right)}{2\sqrt{i\omega\tau_p(L)}}\right) dL\,da\right]^{-1}$$



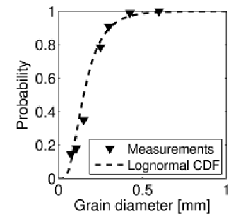
Chargeability $\eta_0 = \frac{4\alpha L_2 \Delta t^{\pm}}{2\pi\left(a_1^2 + a_2^2\right)\left(L_1^{-1} + \xi_2^{-1}L_2^{-1}\right)}$, and time constant τ_p

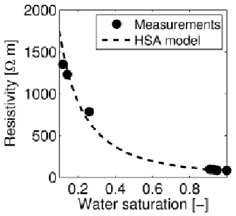
- Stern layer polarization is modelled following Revil and Florsch, (2010),

$$\sigma_s^{*S}(\omega) = 4E_h\left(\Sigma^{s'} + i\Sigma^{s''}\right) \quad \Sigma^{s'}(\omega) = \Sigma^S\left(1 - \int_0^\infty \frac{g(\tau)}{1+\omega^2\tau^2}d\tau\right) \quad \Sigma^{s''}(\omega) = \Sigma^S\int_0^\infty \frac{g(\tau)\omega\tau}{1+\omega^2\tau^2}d\tau$$

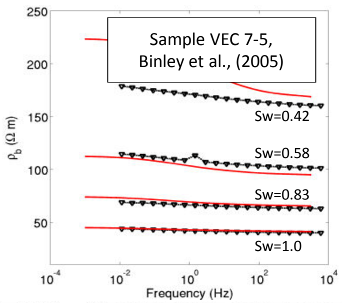
- Σ is the surface conductance of the Stern layer , $g(\tau)$ is the distribution of relaxation times, which is computed from the grain size distribution, E_h is related to the first moment of the grain size distribution.

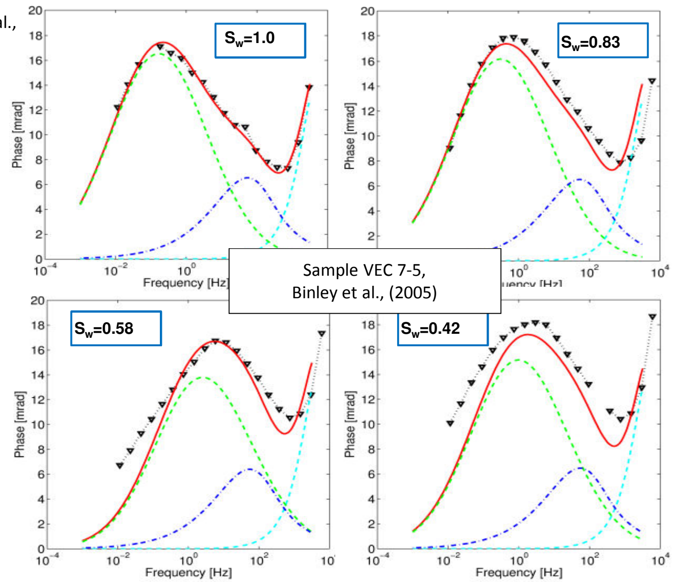
4. Model application and preliminary results

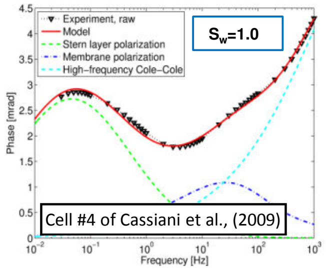




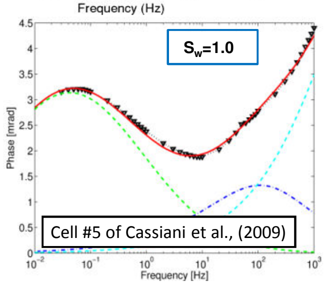
- Experiments from Binley et al., (2005) and Cassiani et al., (2009) were used to test the model.
- Available data on the grain- and pore-size distributions were used to constrain model parameters.
- Archie's cementation and saturation exponents were calibrated on the data in the DC limit







Cell #4 of Cassiani et al., (2009)



Cell #5 of Cassiani et al., (2009)

Parameter	Binley et al., (2005)	Cassiani et al., (2009)
Archie's m and n	1.5; 1.6	1.75; 2.24
Grain size distribution	1.5×10^{-4} 1.4×10^{-5} m	1.45×10^{-4} 1.0×10^{-5} m
Pore-throat distribution	7×10^{-7} 1.25×10^{-7} m	6.9×10^{-7} 1.25×10^{-7} m
Surface conductance (ω=0Hz)	3.6×10^{-8} S	2.1×10^{-8} S

5. Discussion

- The model fits reasonably well measurements at high water saturation (Sw>0.5), whereas in drier conditions the comparison is less satisfactory.
- The ability of the model to reproduce the patterns observed in the experimental data suggests that the observed SIP results from a combination of grain and membrane polarization.
- Frequently, however, Maxwell-Wagner polarization and noise at high frequency (ω>100Hz) hide the contribution of membrane polarization.
- In our model, the relaxation time is controlled by the characteristic length of the pores (membrane polarization) and of the grains, the diffusion coefficient and a tortuosity factor computed from Archie's cementation factor and water saturation.
- As the grain diameters are normally greater than the characteristic length of pore-throats, Stern (grain) polarization occurs at lower frequencies than membrane polarization.
- According to our model, as water saturation decreases, the contribution of surface conductivity (i.e of Stern layer polarization) increases and becomes dominant, while membrane polarization remains constant.

6. References and acknowledgements

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