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Numerical Investigation of Parameters Affecting Seismoelectric Coupling Coefficient in Partially-Saturated Porous Media

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Abstract

We conducted a numerical investigation on the effects of brine concentration, water saturation, and frequency of seismic wave on the seismoelectric coupling response in a two-phase saturated porous media. The numerical model was formulated based on Pride's theoretically developed seismoelectric coupling coefficient that accounts for the conversion of seismic wave to electromagnetic wave. The results show that in oil-water system brine concentration has significant influence on the coupling coefficient at higher water saturation. When water saturation is less than about 0.2, the effect of brine concentration and seismic frequency on the coupling coefficient is insignificant.

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The general characteristics is that at the given water saturation, there is a critical frequency beyond which frequency does not have much impact on the seismoelectric coupling coefficient. When the water saturation is 0.2, such critical frequency is about 100 kHz. The value of the critical frequency increases as water saturation increases suggesting that it is a function of water saturation. In general, the seismoelectric response is stronger at higher water saturation, lower brine concentration and lower seismic frequency.

Keywords: Seismoelectric, Saturation, Porous medium, Oil

1 Introduction

Solid surface minerals, in contact with electrolyte solution such as brine, essentially develop electrical charges on the solid surface due to amphoteric reactions [6]. Subsequently, the surface charges are counter balanced by electrical charges of the electrolyte solution in the Stern layer; where other electrical charges remain in a so-called diffuse layer. Subsequently, this leads to formation of the electrical double layer (EDL) that is shown in Fig. 1. When a seismic wave propagates through fluid-containing porous media it induces relative fluid-to-solid motions at the microscale, where such motions result in a relative-to-solid surface motion of electrical charges in the double layer. This, in turn, triggers conversion of mechanical to electromagnetic energy, also known as the seismoelectric conversion. Furthermore, this transient electrokinetic phenomenon of seismoelectric effects can be observed at the macroscale using dipole receivers placed on the ground surface [9] or installed in wellbores [3].

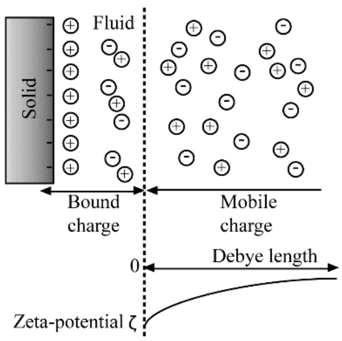

Fig. 1 Electrical Double Layer

The electrokinetic conversions make up the foundation of the seismoelectric method, which combines the sensitivity of electrical methods to subsurface hydrological properties with high resolution of seismic surveys. The distinctive characteristic of this method is the detection of subsurface interfaces prompted by contrasts in rock properties and in fluid electrical properties, such as porosity and permeability, water saturation and electrical conductivity, respectively [7]. Recent field experiments have shown promising results of using the seismoelectric method to investigate hydrocarbon and hydraulic reservoirs. Moreover, it has also been highlighted that the interpretation of amplitudes of converted signals can be used for imaging the geometry of a reservoir [11].

The seismoelectric method has a long history [4, 5], however the first principal comprehensive theory of the method was developed by Pride in the early ‘90s [8]. Ever since, his canonical groundwork has led to numerous breakthroughs. Despite the advances made to understand the complex physics that govern the conversion, theoretical calculations of coefficients affecting the seismoelectric phenomenon are difficult because of a large number of parameters, such as porosity, permeability, rock and fluid properties and so forth [15]. In spite of that, results obtained from such studies can provide some insight on what is anticipated before conducting an actual laboratory and/or field experiment. Therefore, we intend to conduct a theoretical investigation to study the impact of water saturation, brine concentration and seismic frequency on seismoelectric coupling in fully- and partially-saturated conditions prior to performing a laboratory experiment.

2 Methodology

Seismoelectric coupling is directly dependent on reservoir rock properties, fluid density and fluid conductivity, and the electric double layer [7]. For instance, zeta-potential, as a key element of the EDL, is directly dependent on brine concentration, and this in turn, has a substantial effect upon the magnitude of the seismoelectric amplitudes [15]. Additionally, recent studies revealed that seismoelectric effects are also greatly affected by changing fluid saturations in a porous medium [2, 10]. Therefore, the methodology of our study begins with determining the magnitude of zeta-potential using an empirically derived model. Moreover, we assume that water is the wetting phase of the porous medium, and thus varying water saturation does not affect neither the EDL nor zeta-potential. Thereafter, we expand Pride’s equation of seismoelectric coupling coefficient for fully- and partially-saturated porous media saturated with oil and water as a function of seismic frequency and brine concentration.

2.1 Zeta-potential model

The zeta-potential is the electrical potential on the slipping plane within the double layer [12]. A number of researchers conducted experiments to measure zeta-potential for brine-saturated porous media, and thus they state that the magnitude of zeta-potential reduces with increasing salinity [12]. Since the measurement of zeta-potential in fluid-saturated porous media is complex, it can be estimated by using empirically derived Eq.1 below. Researchers report various equation coefficients and validity limits, because measurements were obtained from different equipment configurations, brine compositions and porous media. For this reason, a care must be taken before using one’s correlation.

$$\zeta = a\log_{10}C_f + b \tag{1}$$

Vinogradov, et al. [12] conducted a number of experiments to measure the magnitude of zeta-potential for a wide range of brine concentration. They compared their results with other published data, where the values of measured zeta-potential in mVolt were plotted on a semi-log plot with the x-axis representing the concentration with units of mol/l. Subsequently, they proposed the model shown in Eq. 2. In this study, we adopted their model with an assumption that the brine composition consists solely of sodium chloride (NaCl) and is valid for concentrations less than 0.4 mol/l.

$$\zeta = 19.02\log_{10}C_f - 9.67 \tag{2}$$

2.2 Pride's Model for Partially-Saturated Conditions

Pride [8] developed a complete set of equations that characterizes the coupling between seismic and electromagnetic wave propagation by combining Biot's poroelasticity theory and Maxwell's equations via frequency-dependent seismoelectric coupling shown in Eq. 3 [7]. The coupling equation is considered to be quite complex, since it takes into account multiple variables that affect both seismic and electromagnetic fields.

$$L(\omega) = L_0\left[1 - i\frac{\omega}{\omega_c}\frac{m}{4}\left(1 - 2\frac{\tilde{d}}{\Lambda}\right)^2\left(1 - i^{3/2}\tilde{d}\sqrt{\frac{\omega\rho_f}{\eta_f}}\right)^2\right]^{-1/2} \tag{3}$$

where L_0 is the low-frequency electrokinetic coupling, m is a dimensionless number, $\tilde{d}$ is the Debye length, Λ is a geometry term of the porous material, ω_c is the transition angular frequency, and ω is the angular frequency.
Subsequently, the coupling can be calculated with an additional set of equations shown below in Eq. 4 to Eq. 8.

$$L_0 = -\frac{\phi}{\alpha_\infty}\frac{\varepsilon_f\zeta}{\eta_f}\left(1 - 2\frac{\tilde{d}}{\Lambda}\right) \tag{4}$$

where

$$\tilde{d} = \left[\frac{\varepsilon_f\varepsilon_\circ k_B T}{2e^2z^2N_A}\right]^{1/2} \tag{5}$$

$$\omega_c = \frac{\phi\eta_f}{\alpha_\infty k_0\rho_f} \tag{6}$$

$$m = \frac{\phi \Lambda^2}{\alpha_\infty k_0} \tag{7}$$

$$\omega = 2\pi f \tag{8}$$

Due to complexity of Pride's coupling coefficient, Walker, et al. [13] proposed to use a simplified version of the equation assuming that the Debye length can be neglected when compared to the characteristic pore size. Moreover, they modified the following parameters:

$$m = 8\left(\frac{\Lambda}{r_{eff}}\right)^2 \tag{9}$$

where r_{eff} is effective pore radius. The transition angular frequency is given by equation 10.

$$\omega_c = \frac{8\eta_f}{\rho_f r_{eff}^2} \tag{10}$$

And thus, the simplified Pride's electrokinetic equation for fully-saturated porous medium becomes

$$L(\omega) = L_0\left[1 - 2i\frac{\omega}{\omega_c}\left(\frac{\Lambda}{r_{eff}}\right)^2\right]^{-1/2} \tag{11}$$

where

$$L_0 = -\frac{1}{F}\frac{\varepsilon_f \varepsilon_o \zeta}{\eta_f} \tag{12}$$

Early theoretical developments accounted for seismoelectric effects that occur only in fully-saturated conditions [4, 8]. However, the practical potential of using the seismoelectric method is realized when it takes into account both fully- and partially-saturated conditions in porous media. Therefore, for our theoretical study, we adopted the simplified version of Pride's seismoelectric coupling coefficient modified by Walker, et al. [13] and extended it for partially-saturated conditions with water and oil saturating the porous medium. The calculations were performed in the frequency range of 10 kHz–150 kHz. Brine concentration was varied from 0.001 mol/l to 0.1 mol/l. Water saturation was varied from 0.1 to 1.0. The remaining parameters used in our calculations are listed in Table 1 shown below.

Table1 Parameters used in the calculations

	Notation	Value	Unit
Water density	ρ_w	1000	kg/m^3
Oil density (Baronia)	ρ_o	818	kg/m^3
Water dynamic viscosity	η_w	0.000894	$Pa*s$
Oil dynamic viscosity	η_o	0.00282	$Pa*s$
Vacuum permittivity	ε_0	8.854188	F/m
Water dielectric constant	ε_w	78.4	–
Oil dielectric constant	ε_o	2.10	–
Porosity	ϕ	19.9	%
Tortuosity	α_∞	4	m^2
Boltzmann's constant	k_B	$1.3806551E-23$	J/K
Temperature	T	298.15	^0K
Charge of an electron	e	$1.602177E-19$	$Coulumb$
Ionic valence (NaCl)	z	1	–
Avogadro's number	N_A	$6.022E26$	$ions/m^3$
Formation factor	F	18.28	–
Effective pore radius	r_{eff}	80	μm
Pore geometry length	Λ	0.000008	m

3 Results and Discussion

Effect of brine concentration on the seismoelectric coupling coefficient L was studied numerically. Fig. 2a shows the variation of the coupling coefficient at various water saturation values when frequency was fixed at 100 kHz. The results show that the effect of brine concentration is prominent at high water saturation. In general, the coupling coefficient shows a declining trend as brine concentration increases. However, the rate of decline is slightly lower at low water saturation. When the saturation is increased from 0.2 to 0.6 at brine concentration 0.001 mol/l, the coupling coefficient increased from 0.125 nV/Pa to 0.425 nV/Pa, respectively. This is about 340 % increase in seismoelectric coupling coefficient. In comparison, when water saturation is increased from 0.2 to 0.6 at brine concentration 0.1 mol/l, the coupling coefficient increased from 0.054 nV/Pa to 0.182 nV/Pa, which is about 337% increase. Fig. 2b shows the effect of brine concentration at constant water saturation of 0.4 at three different frequencies. There is a general declining trend when brine concentration increases at fixed water saturation. When low and high frequencies are compared, the coupling coefficient is higher at lower frequencies. This observation suggests that at lower frequency excitations, the relaxation time and effect of nonlinearities are lower which results in less dissipation.

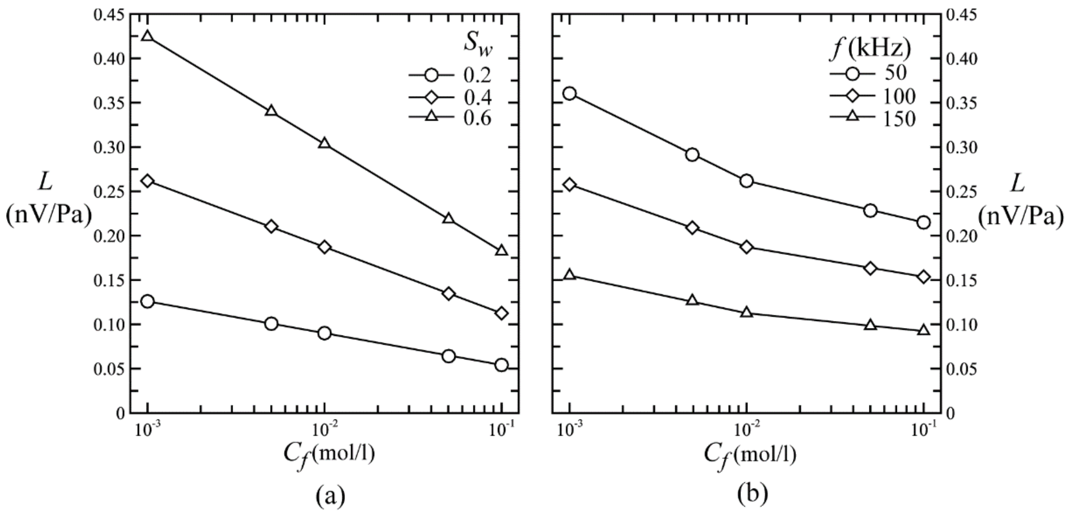

Fig. 2 Effect of brine concentration on coupling coefficient. (a) f = 100 kHz, (b) S_w = 0.4

Figure 3a shows effect of water saturation on the coupling coefficient at various frequencies. Brine concentration was fixed at 0.1 mol/l. At higher water saturations, the contrast between the coupling coefficients at different frequencies is larger. When the frequency is increased from 50 kHz to 150 kHz in the fully saturated case, the value of the coupling coefficient is reduced by 57 %, i.e. from 0.51 nV/Pa to 0.29 nV/Pa. On the contrary, when water saturation is low, the contrast between the coupling coefficient at various values of frequency is rather insignificant. Our results are consistent with previous studies such as Bordes, et al. [1] and Strahser, et al. [10]. Fig. 3b shows effect of water saturation on the coupling coefficient at various brine concentrations when the frequency is fixed at 100 kHz. The result exhibits similar trend that is shown in Fig. 3a. At water saturation less than 0.2, brine concentration does not seem to have significant effect. However, at higher water saturations, the seismoelectric coupling is sensitive to brine concentration. The response is higher at lower brine concentration.

Warden, et al. [14] highlights that the seismoelectric signal properties vary with water saturation, because the content of aqueous phase affects seismic velocity and seismic attenuation, electrical conductivity of a fluid-containing porous medium, and propagation and diffusion of electromagnetic waves. On the contrary, in a porous medium saturated with gas and water, water saturation has entirely different effect on the seismoelectric coupling, Bordes, et al. [2].

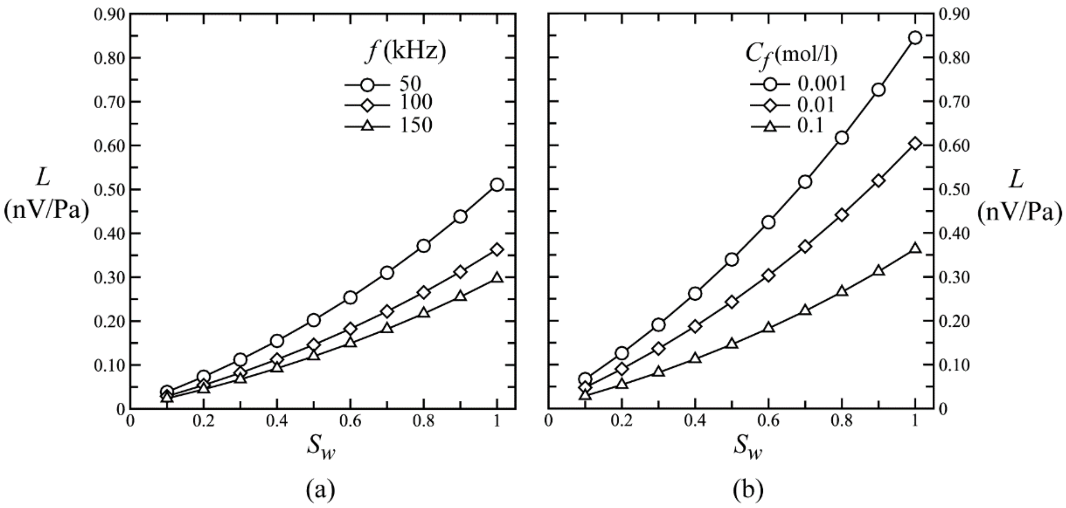

Fig. 3 Effect of water saturation on coupling coefficient. (a) C_f = 0.1 mol/l, (b) f = 100 kHz.

Effect of seismic frequency on the seismoelectric coupling coefficient at various water saturation is present in Fig.4a. Brine concentration is fixed at 0.1 mol/l. Although the general trend is that the seismoelectric coupling coefficient decreases as frequency increases, it seems that for a particular water saturation there is a critical frequency beyond which the effect of frequency is insignificant. When the water saturation is 0.2, this critical frequency is about 100 kHz. The critical frequency shifts to the right when water saturation increases. Fig. 4b shows the effect of frequency when water saturation is fixed at 0.4 and brine concentration is varied. The seismoelectric coupling coefficient is higher at lower frequencies. As frequency increases, the coupling coefficient declines. However, the rate of decline is becoming lower at higher frequencies. The declining trend of the coupling coefficient as frequency increases might be related to the nonlinearities that occur at high frequency. Also, high frequency affects relaxation time which in turn feeds into the nonlinearities producing higher dissipation. As such, the seismoelectric coupling becomes lower at higher frequencies.

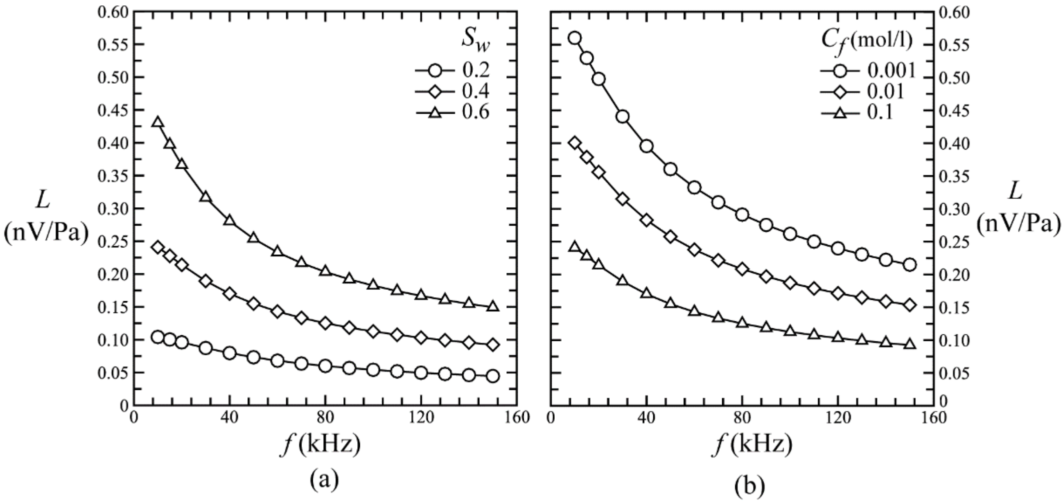

Fig. 4 Effect of frequency on coupling coefficient. (a) C_f = 0.1 mol/l, (b) S_w = 0.4

4 Conclusion

In this paper, we extended Pride's theoretical seismoelectric coupling ratio to a partially-saturated medium, where the coupling was formulated as a function of water saturation, brine salinity and frequency of seismic wave. The resulting model is applied to a porous media saturated with oil and water. Our results show that there is a general declining trend in the seismoelectric coupling coefficient when brine concentration is increased at fixed water saturation. When lower and higher frequencies are compared at fixed water saturation, the coupling coefficient is higher at lower frequencies. This observation suggests that at lower frequencies, the relaxation time and effect of nonlinearities are lower, which results in less dissipation. As such, more mechanical energy can be converted to electromagnetic energy as the seismic wave propagates through the medium as manifested by the characteristics of the coupling coefficient as shown in our study. At water saturation less than 0.2, brine concentration and seismic frequency do not seem to have significant effect on the coupling coefficient. However, at higher water saturations, the seismoelectric coupling is sensitive to both brine concentration and frequency. The general characteristics is that at the given water saturation, there seem to be a critical frequency beyond which frequency does not seem to have much impact on the seismoelectric coupling coefficient. When the water saturation is 0.2, such critical frequency is about 100 kHz. When water saturation increases, the critical frequency also increases.

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