electronics

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Seismoelectric Effect of Oil-Wetted Porous Media Containing Two-Phase Flow

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Abstract: In oil reservoirs, if oil mainly has wettability in the solid phase, such as in carbonate reservoirs, the medium is oil-wetted. For oil-wetted porous media containing an oil and water two-phase flow, there are electric double layers at both the oil–solid interface and the oil–water interface, which can stimulate the seismoelectric effect. To date, most of the studies on the seismoelectric effects of porous media have mainly focused on water-wetted porous media, however, there are few reported studies on cases of oil-wetted porous media, especially on oil-wetted porous media containing an oil–water two-phase flow. In this paper, we adopted the oil-wetted pore model, in which oil and water are assumed to be immiscible, and each phase is continuous and distributed in parallel. We also considered the influence of the electric double layer at both the oil–solid interface and the oil–water interface on the seismoelectric effect. It was concluded that the seismoelectric effect of oil-wetted porous media containing a two-phase flow is mainly caused by the electric double layer at the oil–water interface, while the effect of the electric double layer at the oil–solid interface can be ignored. We regarded the two-phase flow as an equivalent fluid, and then we derived a governing equation of the seismoelectric effect and proposed the flux-averaging method to derive the electrokinetic coupling coefficients under the excitation of a steady acoustic field and a time-harmonic acoustic field. We also investigated the effects of formation parameters, namely, water saturation, pore size, water viscosity and porosity, on the seismoelectric effect, which can provide a theoretical reference for the study of seismoelectric logging in oil-wetted porous formations containing a two-phase flow.

Keywords: oil-wetted porous media; two-phase flow; seismoelectric effect; flux-averaging method; electrokinetic coupling coefficient

Citation: Zhao, Y.; Sun, X.; Nie, Z. Seismoelectric Effect of Oil-Wetted Porous Media Containing Two-Phase Flow. *Electronics* **2023**, *12*, 346. https://doi.org/10.3390/electronics12020346

Academic Editor: Elias Stathatos

Received: 22 November 2022
Revised: 27 December 2022
Accepted: 5 January 2023
Published: 9 January 2023

1. Introduction

The theory of the seismoelectric effect of porous media is a fundamental basis for seismoelectric logging, so research on this topic plays an important role in the exploration of oil and gas reservoirs. For some oil-bearing reservoirs, such as carbonate reservoirs, oil mainly has wettability in the solid phase, and these types of porous media are oil-wetted [1]. During the logging process, the transition zone of these formations is often oil-wetted porous media containing an oil–water two-phase flow, so it is necessary to study the seismoelectric effect of such two-phase flow oil-wetted porous media. Some studies have shown that the type I seismoelectric effect affects the conductivity of soil, and then it affects the transformation, existing state and availability of soil nutrients. For oil-wetted soil containing a multiphase flow, the seismoelectric effect on conductivity is greater. It is also of great significance to study the seismoelectric effect of oil-wetted porous media containing a two-phase flow for the detection of organic pollutants in soil. The seismoelectric effect of water-wetted pores is mainly caused by the electric double layer at the solid–liquid interface, while that of oil-wetted porous media is different. The seismoelectric effect of oil-saturated porous media is mainly caused by the electric double layer at the oil–solid interface [2,3]. For oil-wetted pores with a two-phase flow of oil and water, electric double layers exist at both the oil–solid interface and the oil–water interface, and the seismoelectric effect is mainly caused by the electric double layer at the oil–water interface [2,3], so the wettability characteristic of porous media plays a decisive role in the seismoelectric effect.

The research on the seismoelectric effect of water-wetted porous media is quite mature. In 1944, Frenkel proposed a coupling equation for the seismoelectric effect of porous media [4]. However, this theory has some drawbacks, because it ignores the effect of the solid phase and suggests that the streaming potential is only generated by the longitudinal wave of the acoustic field. In 1953, Packard proposed a microscopic model of the electromagnetic fields induced by acoustic fields in capillary pores [5]. In 1989, Pride deduced the streaming potential coupling coefficient of capillary pores [6]. In 1991, Pride studied the seismoelectric coupling effect of slit-like pores in a time-harmonic case and investigated the energy dissipation caused by the seismoelectric effect [7]. In 1994, Pride combined the Biot theory with Maxell's equations and deduced the coupling equations of the acoustic and electric fields in water-saturated porous media [8], which provided a theoretical basis for the study of the seismoelectric effect. A lot of studies have also been carried out on the seismoelectric effect of water-wetted pores with a two-phase flow. In 1994, Wurmstich studied the streaming potential coupling coefficient of porous media containing gas and water [9]. Wurmstich suggested that bubbles would reduce the conductivity of the pore fluid and, thus, produce an amplification factor for the streaming potential coupling coefficient. In 2007, Revil and Linde considered the seismoelectric wave field to be a quasi-static field, and they derived the streaming potential coupling coefficient [10,11]. From 2010 to 2015, Allègre conducted periodic drainage experiments on rock formations, measured the streaming potential generated by the seismoelectric effect and deduced the empirical formula of the streaming potential coupling coefficient of unsaturated porous media according to the experimental results [12–14]. Seepage characteristics are also very important for the seismoelectric effect, as they provide a theoretical basis for the study of its acoustic field characteristics. Li and Ma et al. investigated the pore structures and hydraulic properties of a broken rock mass using NMR technology and non-Darcy models [15]. Ma et al. established a one-dimensional radial three-phase flow model to investigate the hydraulic characteristics of fault rock during a water–silt inrush [16]. Ma et al. carried out 1D radial seepage experiments under various grain size distributions and water pressures to investigate hydraulic properties under 1D radial grain migration [17]. Some studies have been carried out on the seismoelectric effect of oil-wetted porous media. From 2001 to 2006, Alkafeef studied the electric double layer at the oil–solid interface in oil-saturated pores, calculated the streaming potential coupling coefficient in capillary pores, measured the streaming potential generated by oil flowing through rock samples and calculated the shear potential generated by the electric double layer at the oil–solid interface according to the measurement results [18–20]. From 2008 to 2010, Jackson used the unequal diameter capillary model to deduce the electrokinetic coupling coefficient of a multiphase oil-wetted porous medium and investigated the influence of water saturation on the seismoelectric effect [2,3]. However, Jackson only investigated the effect of the electric double layer at the oil–water interface on the seismoelectric effect and did not give a reason for ignoring its influence on the oil–solid interface. Moreover, he adopted the multiphase flow capillary model proposed by Dullien, Hui and Dijke [21–23], assumed that the wetted phase occupied small capillaries, that the non-wetted phase occupied large capillaries and that there was a film of wetted phase in the large capillaries. Furthermore, this model is too simple and does not conform to actual models of two-phase flow in oil-wetted pores, so the conclusion is not reliable.

The existing studies on the seismoelectric effect of porous media mainly focus on water-wetted porous media [4–14], while there are few studies on the seismoelectric effect of oil-wetted porous media containing an oil–water two-phase flow. Based on the above, we used the capillary model [24] and adopted the multiphase flow model [10,11], in which oil and water are assumed to be immiscible, continuous and distributed in parallel, which makes it a more suitable option than that used by Jackson. Then, we deduced the basic governing equation of the seismoelectric effect of oil-wetted porous media containing a two-phase flow, and we investigated the effects of the electric double layer at the oil–solid interface and the oil–water interface on the seismoelectric effect at the same time. It was proved that the seismoelectric effect is mainly caused by the electric double layer at the oil–water interface. We proposed the flux-averaging method to determine the effective net residual charge density, and we further obtained the streaming potential coupling coefficient under the action of a steady acoustic field and the streaming current coupling coefficient under the action of a time-harmonic acoustic field. We also studied the influences of formation parameters, namely, water saturation, pore size, water viscosity and porosity, on the seismoelectric effect. We also analyzed the change in the electrokinetic coupling coefficient of ideal oil-wetted soil containing a two-phase flow with soil particle size. These studies can provide a reference for the theoretical study of the seismoelectric exploration of oil-wetted porous formations containing oil and water.

2. Methods

In order to study the principle of the seismoelectric effect of oil-wetted porous media containing a two-phase flow, we adopt the parallel capillary bundle model devised by Ishido [24]. Because the porous medium studied in this work is homogeneous and isotropic, we assume that all pores have the same radius R and that there are n_0 pores per unit volume of the porous medium.

The parameters used in this paper are shown in Table 1.

Table 1. Model parameters.

Model Parameters	
ϕ	Porosity
k	Static permeability
σ	Conductivity of oil-wetted porous media containing two-phase flow
σ_f	Aqueous-phase conductivity
σ_r	Relative conductivity
k_w	Water permeability
k_{wr}	Relative permeability of water phase
s_w	Water saturation
s_{w0}	Residual water saturation
s_{o0}	Residual oil saturation
ς	Shear potential
ε	Dielectric constant
ψ	Electrostatic potential of electric double layer
d	Debye length
c	Salinity
k_b	Boltzmann constant
e	Electron charge
η_f	Effective viscosity of two-phase flow
η_w	Water-phase viscosity
η_o	Oil-phase viscosity

Some of the formation parameters can be expressed as follows:

Porosity:

$$\phi = n_0 \pi R^2. \tag{1}$$

Using Warden's model [25] of a multiphase flow, the two-phase flow can be regarded as an equivalent fluid, and the static permeability of the equivalent fluid can be determined as follows:

$$k = (n_0 \pi R^4)/8. \tag{2}$$

For the capillary bundle model used in this work, pore size has the following relationship with porosity and permeability:

$$R = \sqrt{8k/\phi}. \tag{3}$$

According to Archie's law [26,27], the conductivity of oil-wetted porous media containing a two-phase flow is as follows:

$$\sigma = \sigma_f \cdot \sigma_r = \sigma_f \cdot s_w^n. \tag{4}$$

Here, $n = 2$, s_w denotes the water saturation, σ_f denotes the water conductivity, and σ_r denotes the relative conductivity of the porous media relative to water.

The water permeability [28] is as follows:

$$k_w(s_w) = k_{wr}(s_w) \cdot k. \tag{5}$$

where k_{wr} denotes the relative permeability of the water phase:

$$k_{wr}(s_w) = (s_e)^2. \tag{6}$$

$s_e = \frac{s_w - s_{w0}}{1 - s_{w0} - s_{o0}}$, where s_{w0} denotes the residual water saturation, s_{o0} denotes the residual oil saturation, and $s_{w0} = s_{o0} = 0.1$.

The microscopic model of the two-phase flow adopted in this paper is similar to the model devised by Revil and Linde [10,11]: oil and water are incompatible with each other, and each phase is continuous and parallel-stratified, with the difference being that the oil phase is in contact with the solid phase.

According to the research by Stachurski, there is an electric double layer at the interface of oil and water [29], the interface is negatively charged, and there are net residual positive charges in the aqueous solution. When $pH = 7$, the shear potential of the oil–water interface ranges from -25 mv to -80 mv.

According to the experiment performed by Alkafeef [20] using the same rock sample, when an organic solution flows through it, the streaming current generated is at the level of 0.1 nA, and when a water solution flows through it, the streaming current is at the level of µA, and the difference between the two is 4 orders of magnitude. Furthermore, the electric double layer at the oil–solid interface has little effect on the seismoelectric effect.

According to Sherwood's research [30], the streaming current in the pore is as follows:

$$I_w = -2\pi R\varepsilon\zeta(dv/dy)\big|_{y=0}. \tag{7}$$

For petroleum, the relative permittivity is 20, the viscosity is 0.1 Pa · s, and the shear potential at the oil–solid interface is about -0.1 mv [20]. For an aqueous solution, the relative permittivity is 81, and the viscosity is 0.001 Pa · s. The shear potential at the oil–water interface is in the order of -10 mv. We can deduce that the streaming current generated by the electric double layer at the oil–water interface is 3 to 4 orders of magnitude larger than that generated by the electric double layer at the oil–solid interface. So, we can draw the conclusion that the seismoelectric effect of oil-wetted porous media containing water and oil is mainly caused by the oil–water interface and that the influence of the oil–solid interface is negligible.

2.1. Seismoelectric Effect under Steady Conditions

When the acoustic field in an oil-wetted porous medium containing water and oil is a steady field, the electric field excited by the seismoelectric effect is also a steady electric field. At this time, the streaming current and the conduction current in the porous medium are equal in magnitude and run in opposite directions.

The current in the pore satisfies the Nernst–Planck Equation [31]:

$$\mathbf{J}_w = \mathbf{J}_{ws} + \mathbf{J}_{wc}. \tag{8}$$

where $\mathbf{J}_{ws} = Q_w \mathbf{v}_{wo}$ denotes the streaming current, Q_w denotes the net residual charge density generated by the electric double layer at the oil–water interface, and $\mathbf{v}_{wo}$ denotes the velocity of the water phase relative to that at the oil–water interface. $\mathbf{J}_{wc} = \sigma_w \mathbf{e}_w$ denotes the conduction current, where σ_w denotes the pore fluid conductivity, and $\mathbf{e}_w$ is the electric field in the pore fluid.

Then, the volume average of the conduction current can be written as follows:

$$\mathbf{J}_c = \sigma \mathbf{E}. \tag{9}$$

where $\mathbf{J}_c = (\mathbf{J}_{wc})$, $\sigma = (\sigma_w)$, and $\mathbf{E} = (\mathbf{e}_w)$, with the brackets indicating the volume average.

The flux average of Q_w can be defined relative to v_{wo}:

$$Q^{eff} = \int_{v_f} Q_w v_{wo} dV / \int_{v_f} v_{wo} dV, \tag{10}$$

The expression of the streaming current of porous media has the following form:

$$\mathbf{J}_s = Q^{eff} \cdot \mathbf{V}_{wo}. \tag{11}$$

where $\mathbf{V}_{wo}$ denotes the macroscopic velocity of the water phase relative to that of the oil phase, and Q^{eff} denotes the effective net residual charge density corresponding to the electric double layer at the oil–water interface.

According to Warden's research [25], the effective fluid seepage velocity in the pore is as follows:

$$\mathbf{V}_{fs} = -k/\eta_f \cdot \nabla P. \tag{12}$$

Then, the velocity of the water phase relative to that of the solid phase can be determined as follows:

$$\mathbf{V}_{ws} = -k_w/\eta_f \cdot \nabla P. \tag{13}$$

where $\eta_f(s_w) = \eta_o(\eta_w/\eta_o)^{s_w} = \eta_w(\eta_o/\eta_w)^{1-s_w}$.

The velocity of the oil phase relative to that of the solid phase [32] in the pore is as follows:

$$v_{os}(r) = \Delta P/4\eta_o \cdot (R^2 - r^2). \tag{14}$$

The velocity of the water phase relative to that of the oil phase near the oil–water interface in the pore is as follows:

$$v_{wo}(r) = \Delta P/4\eta_w \cdot (R_c^2 - r^2). \tag{15}$$

The velocity of the water phase relative to that of the solid phase in the pore is as follows:

$$v_{ws}(r) = \Delta P/4\eta_w \cdot (R_c^2 - r^2) + \Delta P/4\eta_o \cdot (R^2 - R_c^2). \tag{16}$$

where ρ_o denotes the density of the oil, ρ_w denotes the density of the water, R_c denotes the water-phase radius, and R denotes the radius of the pore. v_{wo} and v_{ws} are integrated in the range of $[0, R_c]$ in the pore, and when divided, the obtained value is as follows:

$$l = 2s_w\eta_o/[2s_w\eta_o + 3\eta_w(1 - s_w)]. \tag{17}$$

So, the following can be deduced:

$$\mathbf{V}_{wo} = l\mathbf{V}_{ws} = -k_w l/\eta_f \cdot \nabla P. \tag{18}$$

The net residual charge density generated by the electric double layer at the oil–water interface [33] can be expressed as follows:

$$Q_w = eN_+ \exp(-Z_{+1}e^{-y_1/d}) - eN_- \exp(-Z_{-1}e^{-y_1/d}). \tag{19}$$

where $d = \sqrt{\varepsilon k_b T/(2e^2 N_l)}$, $y_1 = R_c - r$, $z_+ = 1$, $z_- = -1$, $N_+ = N_- = cN_0$, $Z_{l1} = ez_l\varsigma_1/(k_b T)$, and r denotes the radial position in the pore.

For the capillary pore model, the effective net residual charge density can be obtained using the flux-averaging method through Equation (10).

In the steady case, the streaming current and the conduction current are equal in size and run in opposite directions.

By expressing the electric field in terms of the streaming potential, $\mathbf{E} = -\nabla\phi$, and by substituting the definition of the streaming potential coupling coefficient, $C_Q = \nabla\phi/\nabla P$, we obtain the following equation:

$$C_Q = lQ^{eff}k_w/(\eta_f\sigma). \tag{20}$$

In summary, the governing equation of the seismoelectric effect of oil-wetted porous media containing water and oil under the action of a steady acoustic field can be finally obtained:

$$\nabla\phi = C_Q\nabla P. \tag{21}$$

2.2. *Seismoelectric Effect under Time-Harmonic Conditions*

When the acoustic field in the oil-wetted porous media containing water and oil is time-harmonic, the electric field excited by the seismoelectric effect is also time-harmonic. At this time, the amplitude of the streaming current and the conduction current are not equal.

Similar to the steady case, the streaming current in the pore is as follows:

$$\mathbf{J}_{ws} = Q_w\mathbf{v}_{wo}. \tag{22}$$

As in the steady case, the flux average of Q_w can be defined relative to $\mathbf{v}_{wo}$.:

$$Q^{eff} = \int_{v_f} Q_w v_{wo} dV \Big/ \int_{v_f} v_{wo} dV. \tag{23}$$

Then, the streaming current of the oil-wetted porous media containing a two-phase flow can be determined as follows:

$$\mathbf{J}_s = Q^{eff} \cdot \mathbf{V}_{wo}. \tag{24}$$

where $\mathbf{V}_{wo}$ denotes the macroscopic velocity of the water phase relative to that of the oil phase. Q^{eff} denotes the effective net residual charge density corresponding to the electric double layer at the oil–water interface.

Then, the macroscopic velocity of the water phase relative to that of the solid phase can be determined as follows:

$$\mathbf{V}_{ws} = -k_w/\eta_f \cdot (-\nabla P + i\omega\rho_f v_s). \tag{25}$$

The velocity of the oil phase relative to that of the solid phase in the pore [34] is as follows:

$$v_{os} = -\frac{(-\nabla P + i\omega\rho_f v_s)}{i\xi_o^2\eta_o}[1 - \frac{I_0(i^{1/2}\xi_o r)}{I_0(i^{1/2}\xi_o R)}]. \tag{26}$$

The velocity of the oil–water interface in the pore is as follows:

$$U = -\frac{(-\nabla P + i\omega\rho_f v_s)}{i\xi^2\eta}[1 - \frac{I_0(i^{1/2}\xi R_c)}{I_0(i^{1/2}\xi R)}]. \tag{27}$$

The velocity of the water phase relative to that of the oil phase near the oil–water interface in the pore is as follows:

$$v_{wo} = -\frac{(-\nabla P + i\omega\rho_f v_s)}{i\xi_w^2\eta_w}[\frac{I_0(i^{1/2}\xi R_c) - I_0(i^{1/2}\xi_w r)}{I_0(i^{1/2}\xi_w R)}]. \quad (28)$$

where $\xi_o = \sqrt{\omega\rho_o/\eta_o}$, and $\xi_w = \sqrt{\omega\rho_w/\eta_w}$. The velocity of the water phase relative to that of the solid phase in the pore can be determined as follows:

$$v_{ws} = v_{wo} + U. \quad (29)$$

As in the steady field case, v_{wo} and v_{ws} are integrated in the range of $[0, R_c]$ in the pore, and when divided, the obtained value is as follows:

$$l = 2s_w\eta_o/[2s_w\eta_o + 3\eta_w(1 - s_w)]. \quad (30)$$

So, we have the following:

$$\mathbf{V}_{wo} = l\mathbf{V}_{ws} = -k_w l/\eta_f \cdot (-\nabla p + i\omega\rho_f v_s). \quad (31)$$

In the time-harmonic case, the distribution of the net residual charge in the pore is the same as that in the steady case. For the capillary model, the effective net residual charge density in oil-wetted porous media containing a two-phase flow can be calculated using Equation (23).

The expression of the streaming current in porous media can be obtained as follows:

$$\mathbf{J}_s = k_w Q^{eff} l/\eta_f \cdot (-\nabla P + i\omega\rho_f v_s). \quad (32)$$

We can deduce the streaming current coupling coefficient of the oil-wetted porous media containing water and oil as follows:

$$L_Q = Q^{eff} k_w l/\eta_f. \quad (33)$$

In summary, under the action of the time-harmonic acoustic field, the governing equation of the seismoelectric effect of the oil-wetted porous media containing water and oil can finally be obtained as follows:

$$\mathbf{J}_s = L_Q(-\nabla P + i\omega\rho_f v_s). \quad (34)$$

2.3. Verification of the Validity of the Flux-Averaging Method

In this section, based on the definitions of the volume-averaging method and the flux-averaging method, we verified that the streaming currents obtained using the flux-averaging method and the volume-averaging method are equal.

The solution of the streaming current using the Pride theory is obtained by identifying the overall volume average of $\mathbf{J}_{ws} = Q_{ws}\mathbf{v}_{ws}$. While for oil-wetted porous media containing a two-phase flow, it is necessary to consider the velocity of the water phase relative to that of the oil phase near the oil–water interface in the pore; this model is more complicated, and it is difficult to directly determine the volume average of the local streaming current. In this paper, the net residual charge and the relative velocity in the pore are treated separately, $\mathbf{v}_{wo}$ is the volume average, Q_w is the flux average relative to $\mathbf{v}_{wo}$, and then the two are multiplied to obtain the streaming current. The flux average is similar to the weighted average of Q_w relative to $\mathbf{v}_{wo}$. The equivalence of the flux-averaging method with the volume-averaging method used in the Pride theory [8] is demonstrated below.

The volume average of the velocity of the water relative to that of the oil is as follows:

$$\mathbf{V}_{wo} = \int_v \mathbf{v}_{wo} dV/v. \quad (35)$$

where v is the volume-averaged reference volume.

The volume average of the streaming current is as follows:

$$\mathbf{J}_s = \int_{v_f} Q_w v_{wo} dV / v = (Q_w \mathbf{v}_{wo}). \tag{36}$$

By multiplying Q^{eff} and $\mathbf{V}_{wo}$, we obtain the following:

$$Q^{eff}\mathbf{V}_{wo} = \frac{\int_{v_f} Q_w v_{wo} dV}{\int_{v_f} v_{wo} dV} \frac{\int_{v_f} v_{wo} dV}{v} = \frac{\int_{v_f} Q_w v_{wo} dV}{v}. \tag{37}$$

So, the following can be obtained:

$$Q^{eff}\mathbf{V}_{wo} = \mathbf{J}_s. \tag{38}$$

It is proved that the product of the effective net residual charge density and the velocity of the water relative to that at the oil–water interface is equal to the streaming current. Therefore, the feasibility of this proposed method can be proved.

3. Simulation and Discussion

3.1. The Streaming Potential Coupling Coefficient

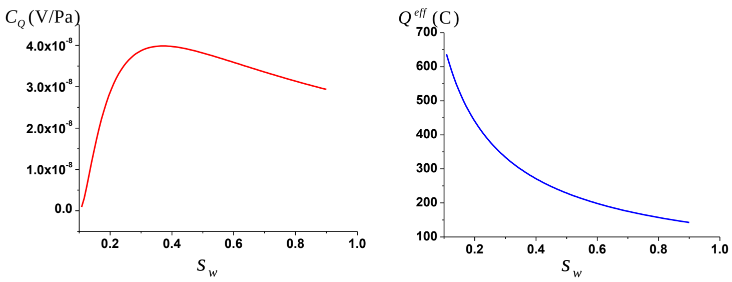
In this subsection, we use the parallel capillary bundle model to study the influences of formation parameters, namely, water saturation, pore size, porosity and water viscosity, on the streaming potential coupling coefficient of the steady seismoelectric effect of oil-wetted porous media containing oil and water.

In Figure 1, we investigate the effect of water saturation on the steady seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 1a shows the influence of water saturation on the streaming potential coupling coefficient. Figure 1b shows the effect of water saturation on the effective net residual charge density. It can be seen in the figure that, with a decrease in the water saturation, the streaming potential coupling coefficient first increases and then decreases, and that, with a decrease in the water saturation, the effective net residual charge density gradually increases. According to Equation (20), the coupling coefficient of the streaming potential is directly proportional to the net residual charge density, water permeability and l, and it is inversely proportional to conductivity. With a decrease in the water saturation, the effective net residual charge density and l increase, but the water permeability decreases. According to Equation (6), the relationship between water permeability and water saturation is quadratic, and the influence of water permeability is greater, causing the $lQ^{eff}k_w$ term to decrease with a decrease in the water saturation. However, according to Equation (4), the conductivity decreases with a decrease in the water saturation. When the saturation is large, the influence of conductivity is large, causing the streaming potential coupling coefficient to increase with the decrease in the water saturation. When the water saturation decreases to a certain extent, the influence of conductivity is weakened, leading to a decrease in the streaming potential coupling coefficient with the decrease in the water saturation.

In Figure 2, we study the effect of pore size on the steady seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 2a shows the influence of pore size on the streaming potential coupling coefficient. Figure 2b shows the effect of pore size on the effective net residual charge density. With an increase in the pore size, the streaming potential coupling coefficient gradually increases, and the effective net residual charge density gradually decreases. When the pore radius becomes larger, the effective net residual charge density becomes smaller, whereas, according to Equations (2) and (6), the corresponding water phase permeability increases (a quadratic relationship with pore size). The effect of the water phase permeability is greater, so the coupling coefficient increases with an increase in the pore size.

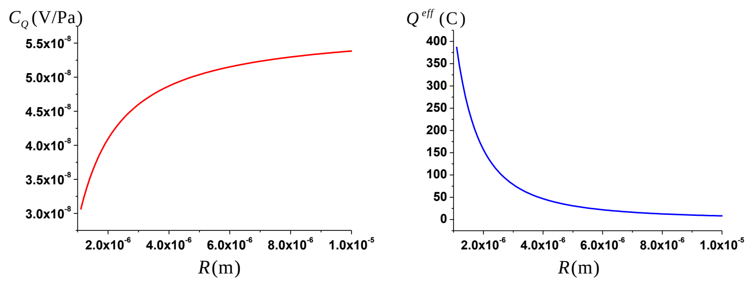
For ideal soil, when the conditions of particle distribution and porosity are the same, the larger the soil particle size, the larger the corresponding pore model size. The effect of soil particles on the seismoelectric effect can be analyzed through the influence of pore size. It can be seen in Figure 2 that, for ideal soil with the same porosity, the larger the soil particle size, the greater the streaming potential coupling coefficient.

In Figure 3, we investigate the effect of porosity on the steady seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 3a shows the influence of porosity on the streaming potential coupling coefficient. Figure 3b shows the effect of porosity on the effective net residual charge density. The streaming potential coupling coefficient is proportional to porosity, and the effective net residual charge density is not affected by porosity. When the porosity becomes larger, the number of pores becomes larger, the volume of the pore liquid becomes larger, and the coupling ability between the acoustic field and the electric field becomes stronger, resulting in an increase in the coupling coefficient.



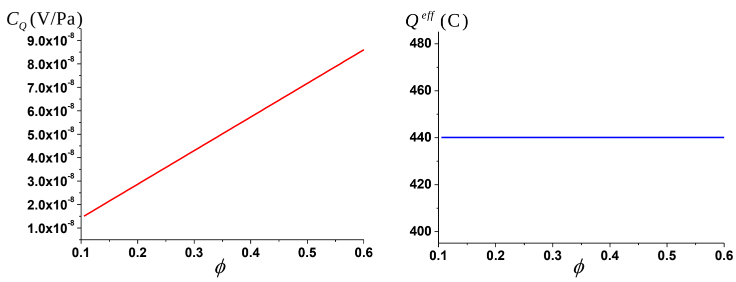
(**a**) (**b**)

Figure 1. Effect of water saturation (steady case): (**a**) streaming potential coupling coefficient; (**b**) effective net residual charge density.



(**a**) (**b**)

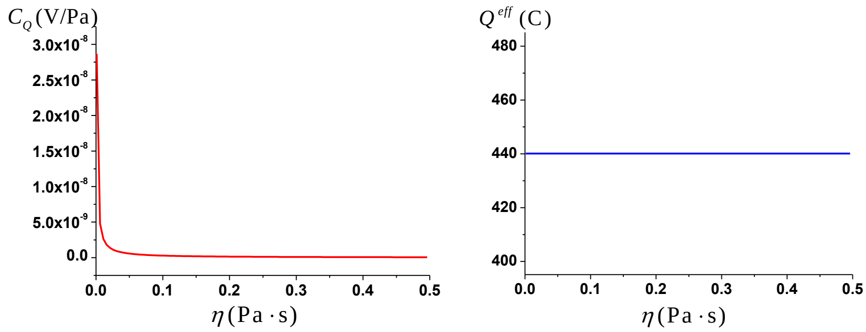
Figure 2. Effect of pore size (steady case): (**a**) streaming potential coupling coefficient; (**b**) effective net residual charge density.



(**a**) (**b**)

Figure 3. Effect of porosity (steady case): (**a**) streaming potential coupling coefficient; (**b**) effective net residual charge density.

In Figure 4, we study the effect of water viscosity on the steady seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 4a shows the influence of water viscosity on the streaming potential coupling coefficient. Figure 4b shows the effect of water viscosity on the effective net residual charge density. As the viscosity of the water increases, the streaming potential coupling coefficient gradually decreases, and the effective net residual charge density remains unchanged. When calculating the effective net residual charge density, the viscosities in the numerator and denominator will cancel each other out, and the effective net residual charge density is not affected by the water viscosity. According to Equation (13), when the viscosity of the water becomes greater, the seepage velocity of the water becomes lower, and the acoustoelectric conversion efficiency becomes lower, resulting in a decrease in the coupling coefficient.



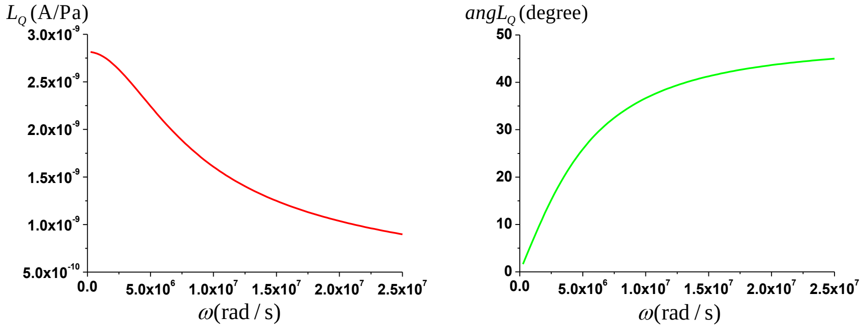
(**a**) (**b**)

Figure 4. Effect of water viscosity (steady case): (**a**) streaming potential coupling coefficient; (**b**) effective net residual charge density.

3.2. The Streaming Current Coupling Coefficient

We also carried out a numerical simulation of the streaming current coupling coefficient in the time-harmonic case, and the influences of the formation parameters, namely, water saturation, pore radius, porosity and water viscosity, were investigated.

In Figure 5, we examine the variations in the amplitude and phase of the streaming current coupling coefficient with frequency in oil-wetted porous media containing a two-phase flow in the time-harmonic case. Figure 5a shows the influence of the angular frequency on the amplitude of the streaming current coupling coefficient. Figure 5b shows the effect of the angular frequency on the phase of the streaming current coupling coefficient. As the frequency increases, the amplitude of the streaming current coupling coefficient gradually decreases, and the phase gradually increases, finally becoming a constant value ($\pi/4$).



(**a**) (**b**)

Figure 5. Variation with frequency (time-harmonic case): (**a**) amplitude; (**b**) phase.

In Figure 6, we study the effect of water saturation on the time-harmonic seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 6a shows the influence of water saturation on the streaming current coupling coefficient. Figure 6b shows the effect of water saturation on the effective net residual charge density. It can be seen in the figure that, with a decrease in the water saturation, the streaming current coupling coefficient gradually decreases, and the effective net residual charge density gradually increases. According to Equation (33), the coupling coefficient of the streaming current is directly proportional to the net residual charge density, water permeability and l. With a decrease in the water saturation, the effective net residual charge density and l increase, but the water permeability decreases. According to Equation (6), the relationship between water permeability and water saturation is quadratic, and the influence of water permeability is greater, causing the $lQ^{eff}k_w$ term to decrease with a decrease in the water saturation, as well as the coupling coefficient.

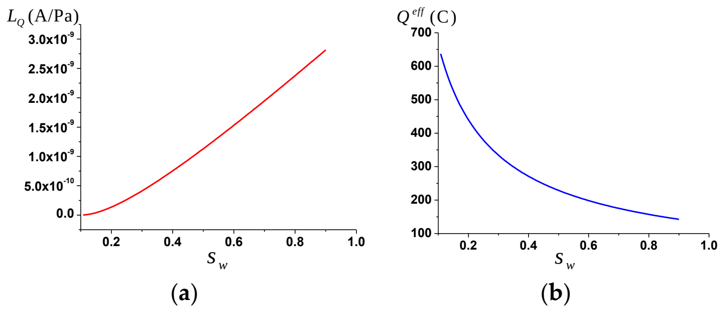


Figure 6. Effect of water saturation (time-harmonic case): (**a**) streaming current coupling coefficient; (**b**) effective net residual charge density.

Comparing Figures 1 and 6, with a decrease in the water saturation, the coupling coefficient of the streaming potential first increases and then decreases, and there is a peak point: $s_w = 0.35$. In contrast, the coupling coefficient of the streaming current decreases monotonously with a decrease in the water saturation. By comparing Equations (20) and (33), ignoring the influence of frequency, we obtain the following: $C_Q \approx L_Q/\sigma$. Compared with the streaming current coupling coefficient, the existence of conductivity causes the streaming potential coupling coefficient to change non-monotonically with water saturation. Moreover, conductivity is determined by salinity, so the peak point of the streaming potential coupling coefficient can reflect the salinity of the pore fluid.

In Figure 7, we study the effect of pore size on the time-harmonic seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 7a shows the influence of pore size on the streaming current coupling coefficient. Figure 7b shows the effect of pore size on the effective net residual charge density. With an increase in the pore size, the streaming current coupling coefficient gradually increases, and the effective net residual charge density gradually decreases. When the pore radius becomes larger, the effective net residual charge density becomes smaller, whereas, according to Equations (2) and (6), the corresponding water phase permeability increases (a quadratic relationship with pore size), resulting in a larger coupling coefficient.

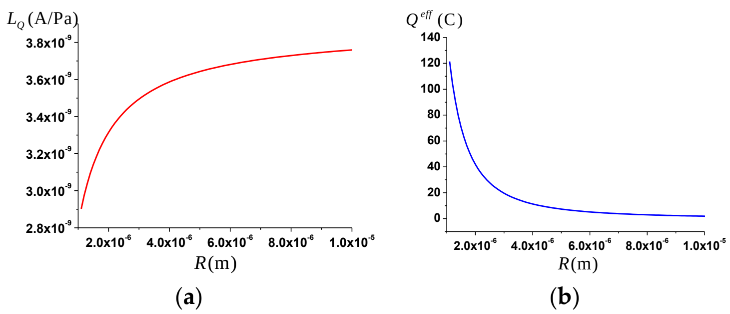


Figure 7. Effect of pore size (time-harmonic case): (**a**) streaming current coupling coefficient; (**b**) effective net residual charge density.

For ideal soil with the same porosity, the larger the soil particle size, the greater the pore size and the greater the streaming current coupling coefficient.

In Figure 8, we investigate the effect of porosity on the time-harmonic seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 8a shows the influence of porosity on the streaming current coupling coefficient. Figure 8b shows the effect of porosity on the effective net residual charge density. The streaming current coupling coefficient is proportional to the porosity, and the effective net residual charge density is not affected by the porosity. When the porosity becomes larger, the number of pores becomes larger, and the volume of the pore fluid becomes larger, resulting in a stronger coupling ability between the acoustic field and the electric field and an increase in the coupling coefficient.

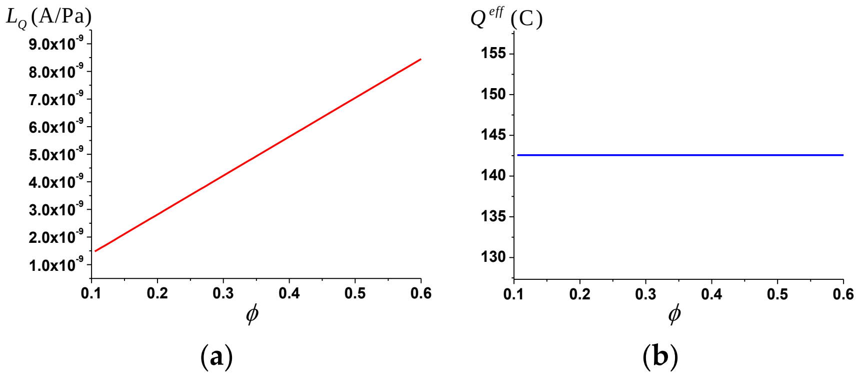


Figure 8. Effect of porosity (time-harmonic case): (**a**) streaming current coupling coefficient; (**b**) effective net residual charge density.

In Figure 9, we study the effect of water viscosity on the time-harmonic seismoelectric effect of oil-wetted porous media containing a two-phase flow. Figure 9a shows the influence of water viscosity on the streaming current coupling coefficient. Figure 9b shows the effect of water viscosity on the effective net residual charge density. As the viscosity of the water increases, the streaming current coupling coefficient gradually decreases, and the effective net residual charge density remains unchanged. According to Equation (25), when the viscosity of the water becomes greater, the seepage velocity of the water becomes lower, and, therefore, the electrokinetic coupling ability becomes weaker, resulting in a decrease in the coupling coefficient.

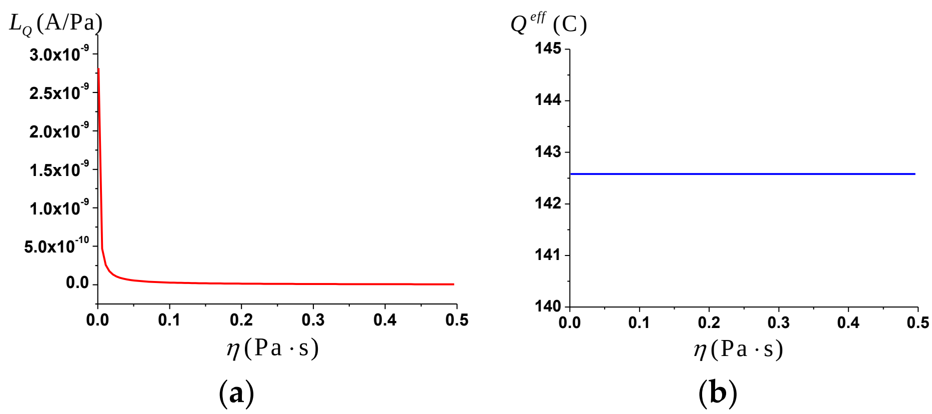


Figure 9. Effect of water viscosity (time-harmonic case): (**a**) streaming current coupling coefficient; (**b**) effective net residual charge density.

4. Conclusions

In this paper, we studied the seismoelectric effect of oil-wetted porous media containing both water and oil, derived the streaming potential coupling coefficient under the condition of a steady acoustic field and the streaming current coupling coefficient under the condition of a time-harmonic acoustic field and investigated the influence of formation parameters on the coupling coefficient. Through simulations and analyses, the following conclusions could be drawn:

The seismoelectric effect of oil-wetted porous media containing water and oil is mainly caused by the electric double layer at the oil–water interface, while the effect of the oil–solid interface is negligible.

Regarding the seismoelectric effect in the steady case:

(1) The streaming potential coupling coefficient has a non-monotonic relationship with water saturation.
(2) The streaming potential coupling coefficient is positively correlated with pore size and porosity.
(3) The streaming potential coupling coefficient is negatively correlated with water viscosity.
(4) For ideal soil with the same porosity, the larger the soil particle size, the greater the streaming potential coupling coefficient.

Regarding the seismoelectric effect in the time-harmonic case:

(1) The amplitude of the streaming current coupling coefficient gradually decreases with an increase in the frequency, and the phase gradually increases with an increase in the frequency, finally resulting in a constant value ($\pi/4$).
(2) The streaming current coupling coefficient is positively correlated with water saturation, porosity and pore size.
(3) The streaming current coupling coefficient is negatively correlated with water viscosity.
(4) For ideal soil with the same porosity, the larger the soil particle size, the greater the streaming current coupling coefficient.

Author Contributions: Conceptualization, Y.Z. and X.S.; methodology, Y.Z.; software, Y.Z.; validation, Y.Z., X.S. and Z.N.; formal analysis, Y.Z.; investigation, Y.Z.; resources, Y.Z.; data curation, Y.Z., X.S. and Z.N.; writing—original draft preparation, Y.Z.; writing—review and editing, X.S. and Z.N.; visualization, X.S.; supervision, Z.N.; project administration, Z.N.; funding acquisition, X.S. and Z.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Science Foundation of China (Grant No. 61727803) and the Sichuan Science and Technology Program (Grant No. 2023YFH0058).

Data Availability Statement: Data is unavailable due to privacy and ethical restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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