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Theoretical and Experimental Studies of Seismoelectric Conversions in Boreholes

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Abstract. We present theoretical and experimental studies on the effects of formation properties on seismoelectric conversions in fluid-filled boreholes. First, we derive the theoretical formulations for seismoelectric responses for an acoustic source in a borehole. Then, we compute the electric fields in boreholes penetrating formations with different permeability and porosity, and then we analyze the sensitivity of the converted electric fields to formation permeability and porosity. We also describe the laboratory results of the seismoelectric and seismomagnetic fields induced by an acoustic source in borehole models to confirm our theoretical and numerical developments qualitatively. We use a piezoelectric transducer to generate acoustic waves and a point electrode to receive the localized seismoelectric fields in layered boreholes and the electric component of electromagnetic waves in a fractured borehole model. Numerical results show that the magnitude ratio of the converted electric wave to the acoustic pressure increases with the porosity and permeability increases in both fast and slow formations. Furthermore, the converted electric signal is sensitive to the formation permeability for the same source frequency and formation porosity. Our experiments validate our theoretical results qualitatively. An acoustic wave at a fracture intersecting a borehole induces a radiating electromagnetic wave.

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1 Introduction

When a porous rock is saturated with an electrolyte, an electric double layer is formed at the interface between the solid and fluid: one side of the interface is negatively charged

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and the other is charged positively. Such a system is called an electric double layer (EDL). An acoustic wave propagating in the fluid-saturated formation moves the mobile ions in the EDL, and the moving ions generate an electric current. This current produces both electric and magnetic fields, which are called seismoelectric and seismomagnetic fields, respectively [8, 13].

Theoretical studies [3, 11] have confirmed the mechanism of the conversion. Inside a homogeneous, porous medium, the seismic wave induces localized seismoelectric and seismomagnetic fields. At an interface, the acoustic wave induces a radiating electromagnetic (EM) wave. Laboratory experiments [10, 15] measured the seismoelectric fields induced by acoustic waves in scaled models. Field experiments [2, 14] measured surface-to-surface seismoelectric signals. Seismoelectric borehole logging [5, 9] indicates a strong relationship between a seismoelectric response and a fracture. Hu et al. [4] simulated the electric waveforms based on the governing equations. Markov and Verzhbitskiy [7] simulated EM fields induced by acoustic multipole source in a borehole.

In this paper, we first conduct a theoretical and a numerical modeling studies of seismoelectric conversion in a borehole for monopole and dipole logging. Then we demonstrate the seismoelectric phenomena with a set of laboratory experiments. The particular geometry that we use is related to borehole measurements (e.g. acoustic/electric logging) in the earth. Laboratory models are scaled down by using the acoustic wavelength scaling. Borehole models are made to simulate a layered earth, and boreholes with a horizontal fracture. An acoustic transducer and an electrode are applied to record the acoustic wave and the electric field induced by an acoustic wave, respectively.

2 Theoretical and numerical studies

We first conduct theoretical and numerical studies of seismoelectric conversions in fluid-filled boreholes. We apply Pride's governing equations into the borehole model to conduct a theoretical study for multipole acoustic waves inducing seismoelectric fields. Both the acoustic pressure and the electric field strength are calculated by matching the mechanic and the electric boundary conditions at the borehole wall. We numerically calculate the acoustic and the seismoelectric fields generated by a monopole or a dipole acoustic source in a fast or slow formation borehole.

2.1 Mathematical formulation of the multipole seismoelectric field

According to Pride's equations [12] for seismoelectric wave propagation in porous media, the electric current density $\overline{J}$ can be written as

$$\overline{J}=\sigma\overline{E}+L\left(-\nabla p+\omega^2\rho_f\overline{u}\right), \tag{2.1}$$

and the displacement of the fluid phase $\overline{w}$ can be expressed as

$$-i\omega\overline{w}=L\overline{E}+\frac{k}{\eta}\left(-\nabla p+\omega^2\rho_f\overline{u}\right), \tag{2.2}$$