2D FINITE-DIFFERENCE MODELLING OF SEISMOELECTRIC LOGS

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Summary Seismoelectric logging which is based on the coupling between seismic and electromagnetic (EM) wavefields in a fluid-filled porous formation has potential applications to the detection of formation properties. In this study, a 2D finite-difference (FD) algorithm is presented for the simulation of seismoelectric logs. To neglect the reverse influence of the induced EM field on the propagating seismic wave in the porous formation, we first obtain the seismic field by FD discretizing Biot's poroelastic wave equations. Considering the known seismic field as the source of the induced EM field and applying Pride's electrokinetic coupling theory, we then calculate the distribution of the induced electric potential. The FD algorithm is validated by comparisons against the analytical method.

INTRODUCTION

Seismic and electromagnetic (EM) wavefields are coupled in a fluid-saturated porous formation due to the electric double layer at the grain/fluid interface and the relative pore fluid flow. This kind of seismoelectric phenomenon has potential geophysical applications to the detection of formation characteristics. By solving the governing equations given by Pride [1], Hu and Wang [2] firstly calculated the seismoelectric wavefields excited by an acoustic point source in a fluid-filled borehole surrounded by a homogeneous porous formation. Unfortunately, this analytical approach does not work for horizontally stratified formation or other heterogeneous formation. To solve this, Pain et al. [3] put forward a finite-element algorithm to simulate seismoelectric logs. Then Haines and Pride [4] proposed a finite-difference (FD) algorithm to simulate the electric fields induced by seismic waves in porous formation. In the present work, a FD algorithm for calculating the seismoelectric logs is developed.

FD MODELING SCHEME

According to Pride's theory [1], assuming an $e^{-i\omega t}$ time dependence, electrokinetic coupling between seismic and EM fields can be expressed as

$$\mathbf{J} = \sigma(\omega)\mathbf{E} + L(\omega)\left(-\nabla p + \omega^2 \rho_f \mathbf{u}\right), \tag{1}$$

$$-i\omega\mathbf{w} = L(\omega)\mathbf{E} + \left(-\nabla p + \omega^2 \rho_f \mathbf{u}\right)\kappa(\omega)/\eta, \tag{2}$$

where ω is the angular frequency, $\mathbf{E}$ and $\mathbf{J}$ are the electric field and the electric current density, respectively, $\mathbf{u}$ is the displacement of the solid phase, $\mathbf{w}$ is the relative flow between the fluid and the solid phase, p is the pore fluid pressure, ρ_f and η are the density and viscosity of the pore fluid, respectively, σ, L and κ are the conductivity, the electrokinetic coupling coefficient and the dynamic permeability, respectively, all of which are frequency dependent. The coupling between seismic and EM fields is reflected in Eqs. (1) and (2) through the terms with the coefficient L. If L is set to zero, seismic and EM fields are decoupled, and Pride's equations break up into Biot's poroelastic wave equations [5] and Maxwell's EM wave equations.

As the influence of the induced EM field on the seismic wave is weak enough and can be ignored (e.g. Pain et al. [3], Hu and Liu [6]), Eq. (2) changes to

$$-i\omega\mathbf{w} = \left(-\nabla p + \omega^2 \rho_f \mathbf{u}\right)\kappa/\eta . \tag{3}$$

This fact allows the seismic field in the formation to be completely decoupled from the generated EM field, and described by Biot's equations. Thus we can firstly obtain the seismic wavefields in the borehole and in the formation by FD method. The detailed FD implementation has been given in Guan et al. [7].

Then considering the known seismic field in the formation as the source of the induced EM field, we can calculate the seismoelectric wavefields by FD. Substituting Eq. (4) into Eq. (1), and using the principle of electric current continuity $\nabla \cdot \mathbf{J} = 0$, we have

$$\sigma\nabla \cdot \mathbf{E} = \nabla \cdot \mathbf{v}_w \, L\eta / \kappa . \tag{4}$$

As the frequency range of seismoelectric logging is in the order of several kilo hertz, the electric field in the interested region belongs to the near-field which is considered as a quasi-static field. This means that $\nabla \times \mathbf{E}(r,z) = 0$ throughout the modeled region, and $\mathbf{E}(r,z) = -\nabla\varphi(r,z)$, where φ is the electric potential. Thus, Eq. (4) can be changed into a Poisson equation

$$\nabla^2\varphi = L_0\eta\nabla \cdot \mathbf{v}_w \big/ \sigma_0\kappa_0 , \tag{5}$$

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where σ_0 and L_0 are the conductivity and electrokinetic coupling coefficient in low frequencies, which are independent of frequency. The source term on the right hand side of Eq. (5) is related to the seismic field in the porous media, and becomes zero for the electric potential in the borehole fluid.

By using FD approximations to discretize the electric potential in the borehole and porous formation, and applying the continuities of the electric potential and the electric current at the borehole wall, the following equations can be established, $\mathbf{A\Phi=d}$, where $\mathbf{A}$ is a sparse matrix that contains the coefficients of the electric potential in the discretized equations, and there are no more than five non-zero elements in each row of the matrix, $\mathbf{\Phi}$ is an array that includes the unknown electric potential at all the grid points, $\mathbf{d}$ reflects the effects of the seismic field on the electric field.

The preconditioned conjugate-gradient iterative method is applied to solve for $\mathbf{\Phi}$ and get the distribution of the electric potential in the borehole and porous formation. The precondition matrix is selected as that in Claerbout [8].

NUMERICAL EXAMPLES

To check the FD algorithm, comparisons of the FD against the analytical methods of the simulated seismoelectric logs for the case with a homogeneous porous formation are performed in Figure 1. In Figure 1a, the z-component electric field waveforms at different locations along the borehole axis simulated by the FD algorithm are compared with those from the analytical method. The waveforms are normalized with respect to the peak value of the response at a location of receiver-to-source distance z =0.5 m. The waveforms at different locations from z =0.5 m to z =3.0 m with the two methods show excellent agreement, as depicted in Figure 1a. More details at z =3.0 m are given in Figure 1b.

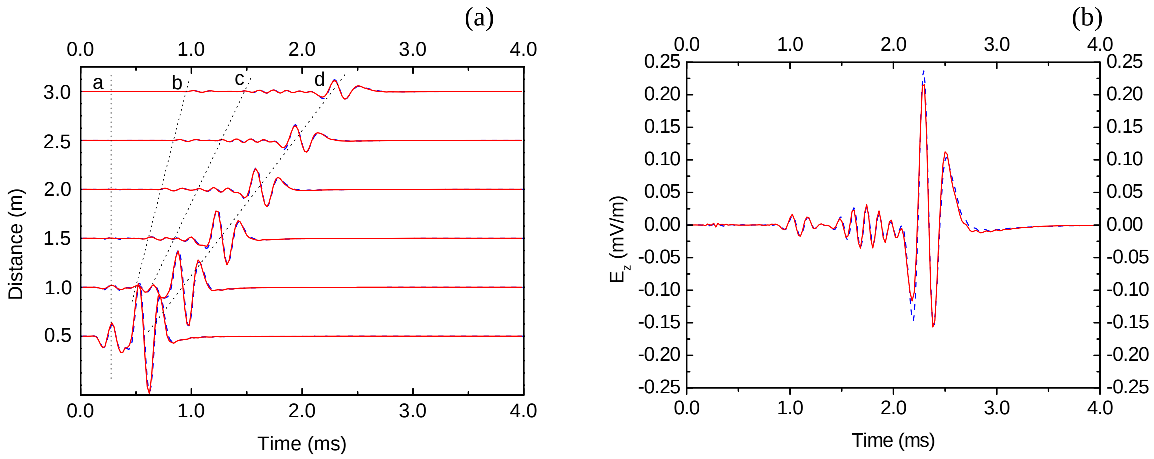

Figure 1: Comparisons between the FD (solid line) and the analytical (dash line) methods. a) the z-component electric field at different locations along the borehole axis. b) the z-component electric field at the location z=3.0 m.

CONCLUSIONS

A brief implementation of the FD modeling of seismoelectric logs has been given. The FD simulated waveforms have been compared with the analytical results for the case that the formation around the borehole is homogeneous. The excellent agreement in comparison confirms the validity and correctness of the proposed FD algorithm.

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References

[1] Pride S.R.: Governing Equations for the Coupled Electromagnetics and Acoustics of Porous Media. *Phys. Rev. B* **50**:15678-15696, 1994.
[2] Hu H., Wang K.: Coupled Acoustic and Electromagnetic Waves Around a Borehole Embedded in a Porous Formation: Theory (I). *Well Logging Technology* **23**:427-432, 1999.
[3] Pain C.C., Saunders J.H., Worthington M.H., Singer J.M., Stuart-Bruges W., Mason G., Goddard A.: A Mixed Finite-Element Method for Solving the Poroelastic Biot Equations with Electrokinetic Coupling. *Geophys. J. Int.* **160**:592-608, 2005.
[4] Haines S.S., Pride S. R.: Seismoelectric Numerical Modeling on a Grid: *Geophysics* **71**:N57-N65, 2006.
[5] Biot M. A.: Mechanics of Deformation and Acoustic Propagation in Porous Media. *J. Appl. Physics* **33**:1482-1498, 1962.
[6] Hu H., Liu J.: Simulation of the Converted Electric Field during Acoustoelectric Logging. *72nd Annual International Meeting, SEG, Expanded Abstracts* 348-351, 2002.
[7] Guan W., Hu H., He X.: Finite-Difference Modeling of the Monopole Acoustic Logging in a Horizontally Stratified Porous Formation. *J. Acous. Soc. Am* **125**:1942-1950, 2009.
[8] Claerbout J.: Multidimensional recursive filters via a helix. *Geophysics* **63**:1532-1541, 1998.