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Nonlinear inversion for fluid and stress parameters

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Summary

Based on Gassmann's fluid substitution model, we propose a workflow of employing observed seismic data to implement nonlinear inversion for dry rock moduli, fluid factor and stress-sensitive parameter. We derive a linearized reflection coefficient as a function of stress-sensitive parameter, and we also transfer the reflection coefficient to elastic impedance (EI). The proposed inversion workflow involves estimating EI datasets from partially-stacked seismic data and utilizing the estimated EI to implement the inversion for stress-sensitive parameter. We emphasize that a model-based least-squares inversion algorithm is used to implement the estimation of EI, and a nonlinear inversion approach is employed to estimate the unknown variables from the estimated EI. Synthetic data are utilized to verify the stability of the proposed approach. A test on real data set acquired over a gas-bearing reservoir reveals that the propose workflow appears to preserve as a useful tool to provide reliable results for fluid identification and stress prediction.

Introduction

One procedure to predict effective stress is first estimating vertical stress and pore pressure separately and then calculating the effective stress using the estimated results of vertical stress and pore pressure; hence, the accuracy of the effective stress prediction is affected by both the vertical stress estimation and the pore pressure calculation. The other procedure is relating reservoir properties (e.g. porosity) to stress parameter. In the present study, based on a relation between porosity and effective stress (Zoback, 2010), we will relate elastic properties (bulk and shear moduli, P- and S-wave velocities, etc.) to stress-sensitive parameter.

Gassmann (1951) proposed a fluid substitution equation to compute effective bulk and shear moduli for saturated rocks, in which the effective bulk modulus is related to mineral bulk modulus, porosity, dry rock bulk modulus and fluid bulk modulus. Krief et al. (1990) proposed a nonlinear equation to calculate the bulk modulus of dry rock using the total porosity. Based on the critical porosity (CP) model proposed by Nur et al. (1998), a linear relationship is proposed to compute the bulk modulus of dry rock using the total porosity and the critical porosity (Mavko et al., 2009). Combining the linear relationship between dry rock bulk modulus and porosity and the relation between porosity and effective stress, we re-express the fluid substitution equation in terms of the dry rock bulk modulus and the effective stress-sensitive parameter. We derive the stiffness matrix using the stress related bulk modulus of saturated rocks and express the perturbation in each stiffness parameter in the case of an interface separating two layers. We finally obtain a linearized P-to-P reflection coefficient as a function of stress-sensitive parameter, and elastic impedance (EI) is also formulated.

Possibility of combining amplitude versus offset (AVO) and FWI is investigated by Innanen (2014), in which the approximation of inverse Hessian matrix for different parameterizations is proposed. In the present study, we aim to establish a nonlinear inversion approach to estimate elastic properties and stress-sensitive parameter using observed seismic data based on the procedure of FWI. Novel parts of the inversion approach involves: 1) results of EI are employed as the input in the nonlinear inversion, and 2) gradients of EI with respect to unknown variables are clearly expressed. We finally apply the proposed inversion approach to synthetic and real data to verify the stability and reliability of estimating elastic properties and stress-sensitive parameters.

Theory and Method

1. Linearized reflection coefficient

Combining Gassmann (1951) fluid substitution model and critical porosity (CP) model (Nur et al., 1998), we simplified saturated rock bulk modulus K_{sat} as

$$K_{sat} \approx K_{dry} + \phi K_f \big/ \left(\phi_c\right)^2 , \tag{1}$$

where K_{dry} is dry rock bulk modulus, K_f is fluid bulk modulus, ϕ is porosity, and ϕ_c is the critical porosity. Smith (1971) proposed a simple exponential porosity-effective stress function as

$$\phi \approx \phi_0 P_e , \tag{2}$$

where P_e is a stress-sensitive parameter, and we assume ϕ_0 is approximately equal to ϕ_c in the present study. Combining equations (1) and (2) we obtain another simplified saturated rock bulk modulus as

$$K_{sat} \approx K_{dry} + K_f P_{\mathrm{e}} \big/ \phi_c . \tag{3}$$

We next express stiffness parameters in terms of fluid bulk modulus and stress-sensitive parameter

$$C_{33} = K_{\mathrm{sat}} + 4/3\mu, C_{55} = \mu . \tag{3}$$

Following Shaw and Sen (2006) we derive a linearized P-to-P reflection coefficient as a function of stress-sensitive parameter

$$\begin{aligned} R_{\mathrm{PP}} = & \frac{1}{2\cos^2\theta}\left(\frac{\gamma_{\mathrm{sat}}}{\gamma_{\mathrm{dry}}} - \frac{4}{3}\gamma_{\mathrm{sat}}\right)\left(\frac{\Delta K_{\mathrm{dry}}}{2K_{\mathrm{dry}}}\right) - 4\gamma_{\mathrm{sat}}\sin^2\theta\left(\frac{\Delta\mu}{2\mu}\right) + \frac{\cos 2\theta}{2\cos^2\theta}\left(\frac{\Delta F}{2F}\right) \\ & + \frac{1}{2\cos^2\theta}\left(2\sin^2\theta - \frac{\gamma_{\mathrm{sat}}}{\gamma_{\mathrm{dry}}}\right)\left(\frac{\Delta K_{\mathrm{f}}}{2K_{\mathrm{f}}}\right) + \frac{1}{2\cos^2\theta}\left(1 - \frac{\gamma_{\mathrm{sat}}}{\gamma_{\mathrm{dry}}}\right)\left(\frac{\Delta P_{\mathrm{e}}}{2P_{\mathrm{e}}}\right) \end{aligned} , \tag{3}$$

where $F = \rho K_{\mathrm{f}}$, which is a fluid-sensitive factor, $\gamma_{\mathrm{sat}} = \mu / \left(K_{\mathrm{sat}} + 4/3\mu\right)$, and $\gamma_{\mathrm{sat}} = \mu \big/ \left(K_{\mathrm{dry}} + 4/3\mu\right)$.

2. Nonlinear inversion for fluid- and stress-sensitive parameters

Based on the derived reflection coefficient, we proceed to seismic inversion for dry rock bulk modulus, fluid-sensitive factor and stress-sensitive parameter. We establish a two-step inversion, which involves estimation of EI datasets from the observed seismic data stacked over different ranges of incidence angle using a model-constrained least-square inversion algorithm proposed by Chen et al. (2018), and nonlinear inversion for unknown parameters including fluid- and stress-sensitive parameters.

A nonlinear relationship between EI and the unknown parameter vector is given by

$$\mathbf{d} = \mathbf{G}(\mathbf{m}), \tag{4}$$

where $\mathbf{d}$ is the vector of elastic impedance, $\mathbf{m}$ in the unknown parameter vector, and $\mathbf{G}$ is a vector related to parameters before reflectivities in equation (3).
We assume the vector of estimated EI that is the input for the nonlinear inversion to be $\mathbf{d}_{\mathrm{obs}}$; and given a model $\mathbf{m}_{\mathrm{mod}}$, we obtain the vector of synthetic EI data $\mathbf{d}_{\mathrm{mod}}$. If the data misfit or residual $\delta\mathbf{d}=\mathbf{d}_{\mathrm{mod}}-\mathbf{d}_{\mathrm{obs}}$ is small, the given model $\mathbf{m}_{\mathrm{mod}}$ can be approximately equal to the true model $\mathbf{m}$. Therefore we need to search for the model that makes the data misfit be much smaller to implement the estimation of unknown parameters. The L2-norm of the misfit is given by

$$\mathbf{E} = \frac{1}{2}(\delta\mathbf{d})^T(\delta\mathbf{d}), \tag{5}$$

where $\mathbf{E}$ represents the energy of the data residual. We observe the estimation of unknown parameter vector has been transferred to the problem of obtaining a model that can make the energy of the data residual be smaller. We employ an iteration procedure to obtain the appropriate model

$$\mathbf{m} = \mathbf{m}_{\mathrm{i}} + \delta\mathbf{m}, \tag{6}$$

where $\delta\mathbf{m}$ is the search direction for each iteration, and $\mathbf{m}_{\mathrm{i}}$ is an initial model. The main task is to determine the search direction for each iteration.

Numerical Results

1. Synthetic tests

We first use a well log model to generate synthetic data, and then we employ the generated data to implement the inversion for fluid- and stress-sensitive parameters using the proposed two-step inversion method. Figure 1 plots the generated synthetic seismic data, in which we add Gaussian random noise of signal-to-noise ratio (SNR) of 2. Figure 2 plots comparisons between inversion results and true values of unknown parameters.

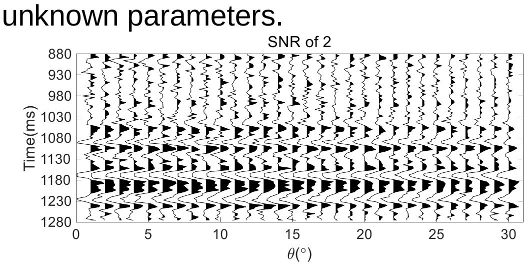

Figure 1. Synthetic seismic data.

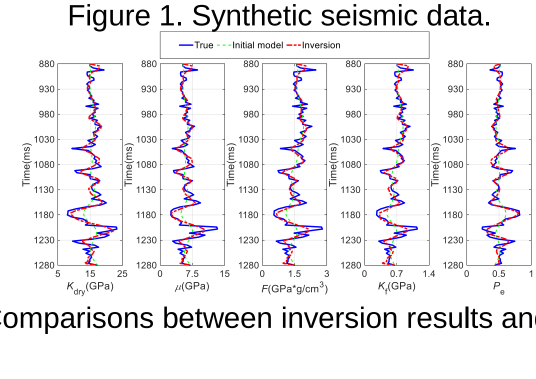

Figure 2. Comparisons between inversion results and true values

We observe that there is a good match between inversion result and true value of unknown parameter, which indicates the established inversion algorithm is stable and robust.

2. Example of real data

Since we have verified the stability of the proposed approach using synthetic data, we proceed to illustrate how to apply the inversion approach to a real data set that is acquired over a hydrocarbon reservoir to confirm its accuracy and reliability. Figure 4 plots inversion results of fluid- and stress-sensitive parameters.

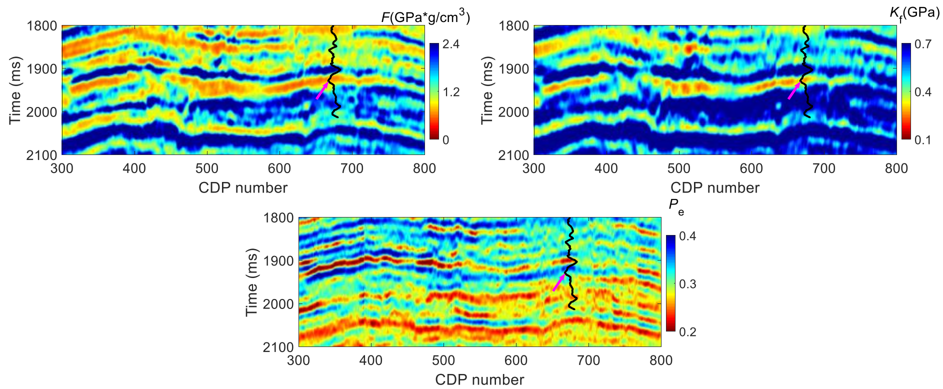

Figure 3. Inversion results of fluid- and stress-sensitive parameters.

We observe that the proposed approach generate inversion results of bulk and shear moduli of dry rock, fluid factor, bulk modulus of fluid and stress-sensitive parameter, which may match the curve of P-wave velocity well.

Conclusions

We first obtain simplification and approximation of fluid substitution equation, in which we introduce a stress-sensitive parameter based on the critical porosity model. Relating stiffness parameters to the stress-sensitive parameters, we express perturbations in stiffness parameters across an interface separating two layers. Using the perturbations, we derive a linearized reflection coefficient in terms of dry rock bulk modulus, shear modulus, fluid-sensitive factor, fluid bulk modulus and stress-sensitive parameter, and we also transfer the derived reflection coefficient to elastic impedance (EI). Based on the expression of EI, we establish a four-step nonlinear inversion approach to estimate dry rock elastic properties, fluid factor, and stress-sensitive parameter. The stability of the nonlinear inversion is verified using noisy synthetic seismic data. Applying the proposed inversion approach to real data that have undergone careful amplitude processing, we conclude the approach appears to provide results that can guide rock-physics interpretation, specifically fluid identification and stress prediction.

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