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Analysis and improvement for a linearized seafloor elastic parameter inversion method

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ABSTRACT

AVO inversion is an effective seismic exploration method to predict elastic parameters. In this paper, we review and analyze the linearized AVO inversion method previously published for seafloor elastic parameters, and present a modification strategy. Before the linearized inversion is performed, a proper near-angle range in which the relationship between the reflection coefficient and sine-squared incidence angle is linear needs to be provided. However, the near-angle range is determined by the elastic parameters which are to be estimated by inversion. Therefore, only an approximated value of the near-angle range can be provided for the linearized inversion. Model tests show that a too large near-angle range may cause inversion fault, and a too small near-angle range may cause unreliable estimation. Further analysis shows that the estimation stability can be further improved even though the linearized inversion is performed under an exact near-angle range. To mitigate the strong dependence on the near-angle range, we use the seafloor elastic parameters estimated from the linearized method as the initial model for an unconstrained optimization method. Compared with the previously published method, the modified method is more robust to noisy data and shows less dependence on the near-angle range.

1. Introduction

AVO theory is based on the Zoeppritz (1919) equations, which express the reflection and transmission coefficients of a plane wave incident on a planar interface between homogeneous media as a function of incidence angle and the elastic properties of the media. However, its intrinsic nonlinearity makes it less appropriate in practical applications. Although many linearized approximations to the Zoeppritz equations have been developed (e.g., Bortfeld, 1961; Aki and Richards, 1980; Shuey, 1985; Vedanti and Sen, 2009; Alemie and Sacchi, 2011; Zhu and McMechan, 2012), these approximations assume that the elastic contrast is weak. The weak contrast hypothesis of these approximations leads to big errors when the two media across the interface vary dramatically (e.g., Yin et al., 2013). The seafloor is a fluid–solid interface, where the elastic contrast is very strong. To extend the application of AVO inversion to the seafloor situation, we (Liu et al., 2015a) derived an approximation without any weak contrast hypothesis and presented a two-step linearized inversion method via a combination application of the derived approximation and the Zoeppritz equations. The two-step method overcomes the angle limit of the approximation by extracting near incidence angle information with the approximation and extracting far incidence angle information with the exact equation, which makes the inversion easy to be applied. However, it is impossible to determine the exact near-angle range before inversion. Therefore, only an approximated value of the near-angle range can be provided for the linearized inversion. In this paper, we analyze the effect of the near-angle range approximately provided before inversion. Then, a modification strategy is presented. Simulation comparison between the two methods shows that the modified method is more robust to noisy data and has less dependence on the near-angle range.

2. Theory

2.1. Basic theory for seafloor AVO

The basic theory for AVO is the Zoeppritz (1919) equations, which explain the transmission and reflection behavior of a plane wave incident on a planar interface. For the seafloor situation, the seawater does not support S-waves. When there is a P-wave incident through the seawater, only a reflected P-wave, a transmitted P-wave and a transmitted S-wave are generated (Fig. 1).

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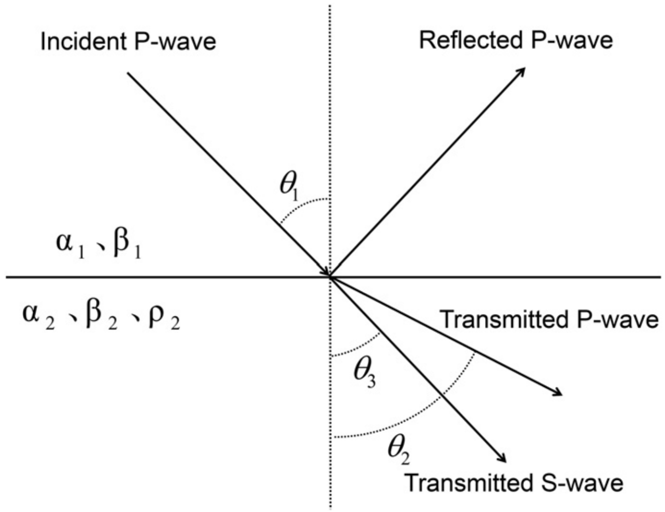

Fig. 1. Reflection and transmission at the seafloor resulting from an incident P-wave.

Three equations are involved in handling the reflection and transmission behavior at the seafloor (e.g., Riedel and Theilen, 2001; Riedel et al., 2003; Liu et al., 2015a, 2015b) (Eq. (1)):

$$\begin{bmatrix} \cos\theta_1 & \cos\theta_2 & \sin\theta_3 \\ 0 & \frac{\alpha_1}{\alpha_2}\sin 2\theta_2 & -\frac{\alpha_1}{\beta_2}\cos 2\theta_3 \\ 1 & -\frac{\alpha_2\rho_2}{\alpha_1\rho_1}\cos 2\theta_3 & -\frac{\beta_2\rho_2}{\alpha_1\rho_1}\sin 2\theta_3 \end{bmatrix} \begin{bmatrix} R_{pp} \\ T_{pp} \\ T_{ps} \end{bmatrix} = \begin{bmatrix} \cos\theta_1 \\ 0 \\ -1 \end{bmatrix} \tag{1}$$

where, R_{pp} and T_{pp} are the P-wave reflection and transmission coefficients respectively; T_{ps} is the S-wave transmission coefficient; α_1 and ρ_1 are the P-wave velocity and density of the seawater; α_2、β_2 and ρ_2 are the P-wave velocity, S-wave velocity and density of the seabed respectively; θ_1 is the incidence angle; θ_2 and θ_3 are the transmission angles of the P- and S-waves constrained by Snell's law:

$$\frac{\sin\theta_1}{\alpha_1} = \frac{\sin\theta_2}{\alpha_2} = \frac{\sin\theta_3}{\beta_2}. \tag{2}$$

By solving Eq. (1), the exact function of R_{pp} can be written as follows (Liu et al., 2015a):

$$R_{pp} = \frac{1+M}{1-M} \tag{3}$$

where:

$$M = -\frac{\frac{\alpha_1}{\beta_2}\frac{\cos 2\theta_3}{\sin 2\theta_1} + \frac{\sin\theta_3}{\cos\theta_1}}{\frac{\alpha_2^2\rho_2}{\alpha_1\beta_2\rho_1}\frac{\cos^2 2\theta_3}{\sin 2\theta_2} + \frac{\beta_2\rho_2}{\alpha_1\rho_1}\sin 2\theta_3}. \tag{4}$$

2.2. A brief review of the previous linearized method

In this section we will carry out a brief review of the previously published method for seafloor elastic parameters (Liu et al., 2015a). Conventional linearized AVO methods are always based on a weak contrast assumption. The weak contrast assumption may lead to big errors when dealing with the seafloor situation, where the elastic contrast is very strong. To extend AVO inversion to the seafloor situation as a linear method, we (Liu et al., 2015a) derived an approximation without any weak contrast assumption:

$$R_{pp}(\theta) \approx I + G\sin^2\theta \tag{5}$$

where,

$$I = \frac{\rho_2\alpha_2 - \rho_1\alpha_1}{\rho_2\alpha_2 + \rho_1\alpha_1} \tag{6}$$

$$G = -\frac{\rho_1\rho_2\alpha_1\alpha_2}{(\rho_2\alpha_2+\rho_1\alpha_1)^2} + \frac{\rho_1\rho_2\alpha_1\alpha_2}{(\rho_2\alpha_2+\rho_1\alpha_1)^2}\frac{\alpha_2^2}{\alpha_1^2}\left(8\frac{\beta_2^3}{\alpha_2^3} - 8\frac{\beta_2^2}{\alpha_2^2} + 1\right). \tag{7}$$

A two-step inversion method has also been presented based on the derived approximation (Eq. (5)). The two-step inversion method uses the approximation to extract near-angle information from the AVO data in the first step. Then, the far-angle information is extracted by the exact function in the second step. In the first step, I and G are estimated from the near-angle range. With the estimated I and G, we can estimate the value of k ($k = \frac{\beta_2}{\alpha_2}$) by the exact equation (Eq. (3)) from the whole incidence angle range in the second step.

The elastic parameters can be determined by I, G and k as follows:

$$\alpha_2 = \alpha_1\sqrt{\frac{G+H}{H\left(8k^3 - 8k^2 + 1\right)}} \tag{8}$$

$$\beta_2 = \alpha_2 \cdot k \tag{9}$$

$$\rho_2 = \frac{1+I}{1-I}\frac{\rho_1\alpha_1}{\alpha_2}. \tag{10}$$

In Eq. (8),

$$H = \frac{\rho_1\rho_2\alpha_1\alpha_2}{(\rho_2\alpha_2+\rho_1\alpha_1)^2} = \frac{1-I^2}{4}. \tag{11}$$

The two-step inversion strategy has overcome the angle limit of the approximation. Before the inversion is performed, a near-angle range, where the relation between reflection coefficient and sine-squared incidence angle is linear, is necessary to be provided. However, the near-angle range is determined by the elastic parameters of the seafloor which are unknown before inversion. Therefore, the near-angle range can only be provided approximately based on the a priori knowledge of the objective seafloor. We will study the influence of the approximately provided near-angle range on the inversion results in the following section.

2.3. Analysis of the linearized method

Shallow marine environments are often characterized by unconsolidated seabed sediments which typically have a P-wave velocity close to that of the seawater and low S-wave velocity (e.g., Hamilton, 1980). The influence of attenuation on the reflection coefficients is near the critical incidence angles (Riedel and Theilen, 2001). The incidence angle in our research is much smaller than the critical angle, so it is safe to assume an elastic model. The elastic parameters adopted for the seabed sediments and seawater are listed in Table 1.

Table 1
Elastic parameters for the simulation model.

Parameter	P-velocity (m/s)	S-velocity (m/s)	Density (kg/m^3)
Seawater	1500	–	1000
Sediments	1530	300	1600