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Full-waveform modeling and inversion of physical model data

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ABSTRACT

Because full elastic waveform inversion requires considerable computation time for forward modeling and inversion, acoustic waveform inversion is often applied to marine data for reducing the computational time. To understand the validity of the acoustic approximation, we study data collected from an ultrasonic laboratory with a known physical model by applying elastic and acoustic waveform modeling and acoustic waveform inversion. This study enables us to evaluate waveform differences quantitatively between synthetics and real data from the same physical model and to understand the effects of different objective functions in addressing the waveform differences for full-waveform inversion. Because the materials used in the physical experiment are viscoelastic, we find that both elastic and acoustic synthetics differ substantially from the physical data over offset in true amplitude. If attenuation is taken into consideration, the amplitude versus offset (AVO) of viscoelastic synthetics more closely approximates the physical data. To mitigate the effect of amplitude differences, we apply trace normalization to both synthetics and physical data in acoustic full-waveform inversion. The objective function is equivalent to minimizing the phase differences with indirect contributions from the amplitudes. We observe that trace normalization helps to stabilize the inversion and obtain more accurate model solutions for both synthetics and physical data.

1. Introduction

Full-waveform inversion (FWI), which is often implemented with the finite difference approach for forward modeling and backward propagation of the residual wavefield for gradient calculation, was originally proposed in the time–space domain (Lailly, 1983; Tarantola, 1984; Gauthier et al., 1986) and was successfully implemented in the frequency domain thereafter (Pratt, 1999). Because FWI naturally considers more effects of wave propagation compared to the high-frequency method of traveltime tomography, it should be able to estimate a wide range of slowness wavenumbers. FWI attempts to minimize the misfit between synthetics and input waveform data; therefore, the accuracy of synthetics is critical.

Because full elastic waveform inversion takes a great deal of computation time on forward modeling, especially in three dimensions, it is common to reduce the computational time by simply inverting for the P-wave velocities associated with acoustic wave equations. Acoustic FWI has been applied to both cross-well geometries and surface surveys (Song et al., 1995; Pratt, 1999; Ravaut et al., 2004; Brenders and Pratt, 2007a). Even if marine seismic data are dominated by P-waves, the acoustic approximation only holds for the kinematics and not for the wave amplitudes. Therefore, unexpected artifacts might be generated by this approximation.

Physical models provide a useful link between theory and field-scale experiments. Using a physical model, we are able to measure differences between synthetics and real data and to analyze the error due to those differences.

In this study, we use real data from a physical scale model of the Qianshan area (South China) (Wei et al., 2002; Wei and Di, 2006; Di et al., 2008) and apply FWI to assess the validity of 2D acoustic inversion. We first compare elastic and viscoelastic synthetics with physical data to determine whether they fit well. To evaluate the validity of acoustic inversion, we compare acoustic synthetics with elastic synthetics, viscoelastic synthetics, and physical data. To mitigate the wavefield differences that have been observed, we compare shot and trace normalization approaches in the FWI objective function. Although trace normalization does not mitigate the phase misfit, it changes the relative weighting of traces at different offsets, which helps stabilize the inversion and yield a more accurate velocity model. We shall discuss the theoretical implication and results of the methods.

2. Similarity criterion of physical model

Ultrasonic modeling seismic experiment, an important method in geophysical modeling studies, is based on real wave propagation, whereas numerical modeling is based on algorithms that deal with simplified and discretized version of the real world. Although observed on a much smaller scale, physical modeling obeys the same wave propagation rules, which is known as the similarity criterion (Sun et al., 1997).

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Table 1
Scaling factors for physically recorded data.

Scaling description		
Variant	Scaling factors	Unit of converted physical data
Space	10,000:1	m
Time	10,000:1	s
Velocity	1:1	m/s
Frequency	1:10,000	Hz
Sampling rate	10,000:1	KSPS
Q_p	1:1	
Q_s	1:1	

The frequency domain wave equation in a viscoelastic medium using the Kelvin–Voigt model is as follows:

$$v^2\left(1-\frac{i}{Q}\right)\nabla^2\Phi=\omega^2\Phi \tag{1}$$

where v is the model velocity, Φ is the displacement potential, ω is frequency, and Q is an attenuation factor. Assuming the model velocity in a physical model is v_m, the displacement potential is Φ_m, the frequency is ω_m, and the attenuation factor is Q_m, the corresponding wave equation is

$$v_m^2\left(1-\frac{i}{Q_m}\right)\nabla^2\Phi_m=\omega_m^2\Phi_m \tag{2}$$

We set the ratio of parameters to different scales as follows:

$$\begin{aligned}&R_L=\frac{L}{L_m}=\frac{x}{x_m}=\frac{y}{y_m}=\frac{z}{z_m}\\&R_\omega=\frac{\omega}{\omega_m},R_v=\frac{v}{v_m},R_\Phi=\frac{\Phi}{\Phi_m},R_Q=\frac{Q}{Q_m}\end{aligned} \tag{3}$$

where R_L, R_ω, R_v, R_Φ, and R_Q are the space, frequency, velocity, displacement potential and attenuation factor ratio, respectively. By substituting Eq. (3) into Eq. (2), we obtain

$$v^2\left(1-R_Q\frac{i}{Q}\right)\nabla^2\Phi=\left(\frac{R_v}{R_LR_\omega}\right)^2\omega^2\Phi \tag{4}$$

According to the similarity criterion, Eqs. (1) and (4) must be equivalent; thus, we derive the following equation:

$$\frac{R_v}{R_LR_\omega}=1\ ,\ \ R_Q=1 \tag{5}$$

Based on Eq. (5), we set the appropriate ratios for the properties and scales in the experiment (Table 1). With the above scaling factors, we are able to study seismic wavefield data from ultrasonic experiments and intend to investigate the validity of FWI in an actual seismic exploration scale.

3. Laboratory settings

The model used in the experiment simulates a fault in Qianshan (South of China) (Wei et al., 2002; Wei and Di, 2006; Di et al., 2008) with dimensions of 757.2 mm × 756.9 mm × 243.5 mm (Fig. 1a). Since the scale ratio is 1:10,000 according to Table 1, this is equivalent to an actual geological model of 7.572 km (X) × 7.569 km (Y) × 2.435 km (Z). The properties of the model are set to be similar to real geological media; the details of the material properties are presented in Table 2. Mixed materials of silastic and epoxy resin with different ratios are used to simulate geological media between P-wave velocity 1000 m/s and 2600 m/s. These two materials are ideal for mixing at room temperature without introducing chemical reaction (Wei and Di, 2006). The P-wave velocity of epoxy resin in solid state is about 2600 m/s, and that of silastic in solid state is about 1000 m/s. The velocity of two mixed materials varies between 1000 m/s and 2600 m/s depending on the actual ratio of the two materials. The designed velocities of the bottom two layers are higher, 2800 m/s and 3000 m/s, respectively. In Table 2, field P-wave and S-wave velocities are inferred from migration velocity analysis. Note that Vp/Vs ratios are too large, between 1.9 and 3.0, therefore, this model is not ideal for studying converted waves (Di et al., 2008).

A 27 mm column of water with a P-wave velocity of 1480 m/s is placed on top of the physical model to simulate a marine setting. According to the experiment parameters, we create a numerical model with the same properties as shown in Fig. 1b. The central frequency of the source generator is 225 kHz, and the diameters of the source and receiver are 3 mm and 5 mm, respectively. There are 161 shots in total, with 44 receivers for each shot. The shot and receiver intervals are both set to 4 mm in the experiment (equivalent to 40 m spacing in the actual scale).

4. Numerical simulations

We would like to conduct the forward modeling with the known model first, and intend to understand any discrepancy between real ultrasonic data and theoretically calculated waveforms under elastic, anelastic, and acoustic assumptions. The 3D forward elastic and anelastic modeling methods that we apply are implemented on the basis of a time-domain staggered-grid finite difference approach (Graves, 1996) along with a perfectly matched layer (PML) for boundary conditions (Berenger, 1994). The 2D acoustic variable-grid wave-equation FD is from Zhang and Zhang (2011) also along with a PML boundary condition. In the case of 2D, a true 3D wavefield dataset must be converted to 2D for comparison with 2D numerical modeling or inversion. The 3D-to-2D conversion method used in this study is the asymptotic filter

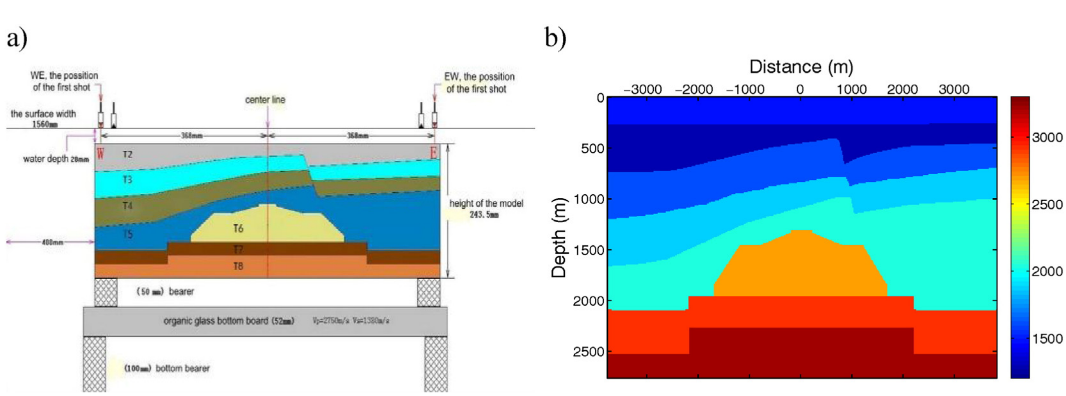

Fig. 1. (a) Sketch of the physical model and (b) synthetic model built from the sketch with the same properties.