Full Waveform Inversion of Borehole Data in the Presence of High-Velocity Screens

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Abstract

Objective: Compared to ray-based inversion methods, the strength of full-waveform inversion is that its forward modeling equations can represent the wave propagation in models with sharp variations. Based on this fact, we investigate how full-waveform inversion can help improve velocity estimations when the velocity model changes sharply. With the aid of differentiable dynamic time warping distance (DDTWD), which focuses on traveltime difference and mitigates the influence of amplitude discrepancy on misfit measurement, full-waveform inversion generates informative estimations from an initial model with 5% errors of long wavelength and data above 4 Hz. Methods and Procedures: We employ DDTWD for full-waveform inversion. The laterally homogeneous velocity model is inspired by actual field data that includes high-velocity carbonate layers in the overburden. Such layers act as screens preventing seismic energy from travelling to a deeper depth. We also add three low-velocity anomalies to introduce horizontal heterogeneity. 317 shot gathers are generated to represent the observed data where two receiver lines, with 176 receivers each, are active for all shots. For the inversion, we sort common-shot gathers into the receiver domain. In the end, we obtain 352 shots, 317 receivers each, and 176 shots per well. We then add the random noise to observed data such that the data below 4 Hz becomes completely unavailable. The initial model is generated by smoothing the true model and reducing values by 5% to simulate the typical errors. The inversion also follows the frequency continuation strategy, i.e., it starts with low frequencies and gradually introduces higher frequencies. We only focus on the inversion of diving early-arrival waveforms. Results: The challenge of this example for full-waveform inversion is associated with sharp velocity variations and presence of high-velocity screens. For example, a high-velocity carbonate layer in the near-surface exhibits an increase of 3 km/s over a limited distance of 0.7 km. The deeper part also presents sharp velocity variations because of the combinations of carbonate and low-velocity layers. The experiment starts from data of 4 Hz. The gradient of the differentiable dynamic time warping illustrates that full-waveform inversion provides a more extensive update. The update by ray-based inversion methods is centered around high-velocity layers. The inversion result from data of 4 Hz-4.5 Hz shows that full-waveform inversion with the DDTWD generates a geologically relevant model from the given initial model. It also shows the fast convergence. Conclusions: With the vertical seismic profile geometry, full-waveform inversion with the DDTWD enables building a more accurate velocity model in the presence of high-velocity layers with sharp contrasts. In this case, ray-based methods are limited to updating the model away from high-velocity layers.