2D elastic full-waveform inversion method for estimating fluid distribution in hydrocarbon reservoir

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Full-waveform inversion method is used to estimate subsurface velocity structure. This method directly utilizes observed waveform data that could deform by the change in the properties of subsurface materials. In general, the difference between the observed and the modeled waveforms are minimized to estimate the subsurface properties in terms of seismic velocities. In contrast to the existing FWI applications, our research focuses directly on the properties in the hydrocarbon reservoir to estimate the fluid distribution and alteration. We solve the elastic problem with FWI, updating P-wave velocity distribution. One parameter full-waveform inversion based on conjugate gradients algorithm for the synthetic model give us reconstruct the model similar to the true, separated-layer model.

1. INTRODUCTION

Seismic time-lapse survey is conducted for reservoir monitoring to estimate fluid distribution as a function of time. When the fluid distribution changed, the response of seismic waves travelling through the medium would change as well. We can estimate the fluid alteration using seismic exploration methods if we could utilize the change in the seismic waveform. The change observed through the time-lapse survey is related to the waveform residuals between before and after fluid alteration at the same receiver point. The seismic time-lapse experiment associated with the air-injection and computing the image of event zone has already been carried out by surface seismic survey¹⁾. The waveform observed by seismic exploration, both surface seismic survey and well logging survey, has a possibility to determine the fluid distribution.

As an imaging tool using waveform residuals, we present an algorithm based on the 2D elastic full-waveform inversion (FWI) method. FWI method is based on minimizing the misfit function, and it updates the model parameter iteratively. This method is applied in many papers for solving acoustic²⁾, elastic^{3) 4)} and poroelastic problem⁵⁾. In order to consider the fluid variation in hydrocarbon reservoir, we solve a poroelastic problem in finite-difference scheme.

2. METHOD

(1) Biot model

For deriving the seismic waveform changed with the fluid alteration, we use poroelastic model introduced by Biot⁶⁾. Poroelastic model can compute the propagating wave through the medium consists of solid and fluid phase. In this paper, we use a second-order, finite-difference Biot scheme with staggered grids for computing. The discretized equations are derived from the Biot equations and the velocity-stress formulation⁷⁾. Though poroelastic equations need 8 parameters to solve, we solve the elastic inversion problem which can handle only 3 model parameters, P-wave velocity, S-wave velocity and density. The fluid distribution is related to the distribution of velocity and density parameters.

(2) Full-waveform inversion

FWI method is implemented to estimate the velocity model for acoustic and elastic problem. It seeks the appropriate velocity model based on the minimization of the misfit function S . The misfit function is the difference between observed and calculated waveforms given by

$$S = \sum_{shots} \int_0^t dt \sum_{receivers} [d_{cal} - d_{obs}]^2 \quad (1)$$

Through the minimization of S , we need gradient calculation for model updating. In this paper, we apply conjugate gradients method⁸⁾. The inversion proceeds with computing the following a) - e) steps iteratively.

a) Solve the forward problem for the current model and derive calculated waveform.

- b) Compute the residuals of observed and calculated waveform at all receiver points.
- c) Solve the backward problem. Data residuals in are used as sources at receiver points.
- d) Compute the gradient at all inverted points. In this paper, we update only P-velocity (V_p) model.
- e) Update the model parameter with conjugate gradient method.

3. SIMULATION STUDY

(1) Calculation model

We simulate a synthetic model shown in **Figure 1**. The model size is 150m x 180m, and the [60m-90m] x [60m-120m] area enclosed by dashed line is model-updated by the FWI method. Sources and receivers are arranged at left and right respectively, 5m apart from computed area. Each source at 60m and 120m depth accompanies 16 receivers with 4m interval. The model consists of shale saturated by water and sandstone saturated by gas, separated by oblique boundary. The solid and fluid property is given in **Tables 1** and **2**.

(2) Inversion procedure

First, we derived the observed data at all receiver points by using Biot-FD method to the true model. Next, we implemented the FWI method. Both Biot-FD and elastic FWI calculation, the grid space is 1 m for both horizontal and vertical direction, and time space is 0.1 μ m. The iteration number is 19 times. The source is assumed as a Ricker wavelet with a center frequency of 100 Hz. We apply Cerjan's absorbing boundary condition for all model edges⁹⁾. In elastic problem, P-wave velocity, S-wave velocity and density are to be updated, but in this study, we consider only P-wave velocity update, and the other parameters assume to be updated proportional to the change of P-wave velocity. This is because P-wave velocity updating is most sensitive to the data residuals.

4. RESULT AND DISCUSSION

Figure 2 shows the true, initial and final inverted P-wave velocity model. In the initial model, the parameters change gradually with the depth, and at upper and bottom of the inverted area, the parameters are the same as the true one. In final

Table 1 Solid property

	shale	sandstone
Bulk modulus K_s [GPa]	10	40
Shear modulus μ [GPa]	5.1	0.82
density ρ_s [g/cm ³]	2.6	2.6
permeability k [m ²]	10^{-14}	10^{-12}
porosity ϕ	0.1	0.2
tortuosity T	10	5

Table 2 Fluid property

	water	gas
bulk modulus K_f [GPa]	2.25	0.000015
density ρ_f [g/cm ³]	1.0	0.001
viscosity [Pa $\cdot$ s]	0.001	0.00002

Figure 1 Simulation model and source-receiver set. Red points represent source position. Receivers are set along the red line. The model inside dashed line is updated.

model, the velocity boundary can be seen which exists in true model. **Figure 3** is the misfit function per iteration number. The misfit decreases as iteration step. At the final iteration, the decrement of the misfit function became less than 1%.

Figure 2 P-wave velocity model: a) initial model, b) true model and c) final model after FWI.

Through this simulation result, we got some elements to improve the inversion result. First, the arrangement of source and receiver effects on the result model. We utilized two sources in this simulation, but the velocity model will be clearer with dense source arrangement. Second, we updated only P-wave velocity and related the updating of the other parameters to the P-wave change. **Figure 4** shows waveforms for true, initial and final model, observed by the receiver at 88m depth. Before 0.05s, the final waveform change to the true one, but the latter waveform doesn't get close. Observed waveform has information of the medium through which the wave passes, though only P-wave information is used with P-wave velocity update. All waves (S-wave, P-S converted wave, etc) should be used to utilize the advantage of FWI method which can use all waveform data.

Figure 3 Misfit function.

Figure 4 Waveform change at one receiver point: a) initial model, b) true model and c) final model after FWI.

5. CONCLUSION

We demonstrated FWI algorithm for the media composed of fluid and solid phase. The FWI method updated the P-wave velocity model and found the true velocity boundary of two layers from initial gradually-changed velocity model. A consideration of better source-receiver arrangement and update of S-wave velocity and density will improve the final model.

For the next step, we will apply this FWI method for time-lapse problem. The waveform change observed in time-lapse survey can estimate the model change in subsurface reservoir directly by FWI method. The purpose of time-lapse survey is to see the small change of the medium in short time and FWI can find smaller movement in reservoir than ordinary inversion method. We need to reveal the resolution range of FWI for the reservoir monitoring. The surface seismic survey utilizes different frequency with well logging survey. The combination of two survey methods can give us a

broader resolution range to understand detailed fluid distribution. The FWI method for time-lapse model with poroelastic model will enable us to estimate the small fluid movement in subsurface reservoir.

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