Simultaneous estimation of subsurface properties from CSP gather

Tomoaki TANAKA[1], Hitoshi MIKADA[2] and Junichi TAKEKAWA[2]

[1]Dept. of Civil and Earth Res. Eng., Kyoto University (Now at AISIN COMCRUISE Co., Ltd.)
[2]Dept. of Civil and Earth Res. Eng., Kyoto University

The utilization of S-wave velocity has become an essential task in seismic reflection surveys for lithological properties of subsurface materials. In this research, we applied horizontal component of a common scatter point (CSP) gather produced in the application of the Equivalent Offset Migration (EOM) method to obtain S-wave wavefields. As an AVO analysis of both vertical and horizontal components of the CSP gathers estimates physical properties of subsurface reflectors, we use the full waveform inversion (FWI) technique to estimate the physical properties directly with observed waveforms. Our simple numerical experiments have shown high accuracy, the applicability, and the validity of our method. We would like to propose the processing of CSP gathers with FWI as a method of lithological interpretation of subsurface materials.

1. INTRODUCTION

Seismic reflection survey is one of the most well-practiced methods to visualize subsurface structure for exploring oil and natural gas resources. In a chain of seismic reflection data processing, seismic migration is an essential step to migrate reflection events to right location to visualize an accurate underground structure. Equivalent offset migration (EOM)[1)], which is one of pre-stack migration methods, is known as a simple and effective wave-equation-based method without any interpolation techniques. In our previous study, we noticed the effectiveness to use the horizontal component of Common Scatter Point (CSP) gather produced in the processing of EOM for both the normal moveout velocity and for AVO analyses of S-waves that have been recognized important for lithological interpretation[2)]. Following the initial results, we started to upgrade the method to utilize full waveforms in CSP gathers for more accurate analyses.

In the previous application of horizontal component CSP analysis, the maximum amplitude of recorded waveform was used without any consideration to the phase nor to the relativity to the vertical component. We would, therefore, like to propose a new method to use full waveforms of both horizontal and vertical components. As we analyze AVO for both P and S waves, a simultaneous waveform analysis using FWI would surely help estimating the lithological properties in the subsurface. Also, the inclusion of phase of the waveforms would bring more accurate estimation.

The proposed method is verified by a set of numerical experiments. We use a layered model with inclined layer boundaries just as general target structures for the application of EOM. To estimate physical properties, AVO has been used to estimate the kinematic parameters of the two layers interfacing at a boundary generating reflection signals. Finally, we introduced an inverse method in the estimation of the kinematic parameters of each layer through the minimization of the L2-norm error in the full-waveforms of received data. After the application of a generalized linear inverse theory, we estimate physical properties of each layer.

2. METHOD

We conduct numerical calculation of 2D seismic reflection survey in order to obtain received records of both horizontal and vertical components as observed information. After that, we apply the EOM to those records of each component with making the CSP gather to extract P-wave and S-wave AVO effects. Since the AVO effect includes reflected wave information from each geological boundary, we try to estimate the information about

P-wave and S-wave velocity structure and density structure from the CSP gathers. In typical CSP gathers using horizontal component, S-wave reflection event has an amplitude reversal point due to the AVO effect. The amplitude formation could include information about subsurface boundaries. The estimation of subsurface properties is implemented by least-squares method of using difference between observed and calculated data, as a misfit function. A misfit function is shown below.

$$\mathrm{E} = \bar{\mathbf{r}}_z^{\ T}\bar{\mathbf{r}}_z + \bar{\mathbf{r}}_x^{\ T}\bar{\mathbf{r}}_x \tag{1}$$

In equation 1, a misfit function is defined summation of residual vectors of horizontal and vertical components.

Equation 2 is used for making CSP gather[1].

$$h_e^2 = x^2 + h^2 - \left(\frac{2xh}{tV_{mig}}\right)^2 \tag{2}$$

In equation 1, h_e is equivalent offset, h is half offset between shot point and receiver point, x is horizontal distance between scattering point and the midpoint of shot point and receiver point, t is two-way travel time and V_{mig} is migration velocity.

Figure 1 is an example of CSP gathers as a result of EOM using horizontal component when the common scatter point is on the middle of the model. One of S-wave AVO effects is confirmed from the flipped point of amplitude on around h_e = -700m and t = 1.7sec.

We invert exact physical properties in the subsurface to minimize a misfit function by using BFGS method.

3. NUMERICAL MODEL AND RESULTS

First, we simulate 2D elastic wave propagation with finite difference method using fourth-order staggered grid[3]. The numerical model we used is shown in Figure 2. The upper boundary is set as the free surface boundary, and the others are set C-PML absorbing boundary condition[4]. The survey line is on the point from 500m apart from the edge. 201 sources and receivers are set at the surface with a constant interval of 20m. We use the second derivative Gaussian wavelet as vertical source and record horizontal component data on each receiver.

We calculate the misfit using equation 1. The result of minimization is shown in Figure 3, and the misfit of the minimization is shown in Figure 4. Initial values of those physical parameters are set to 5 to 7 % different from the exact solution. The inverted solutions converge to the exact values after 9 iterations.

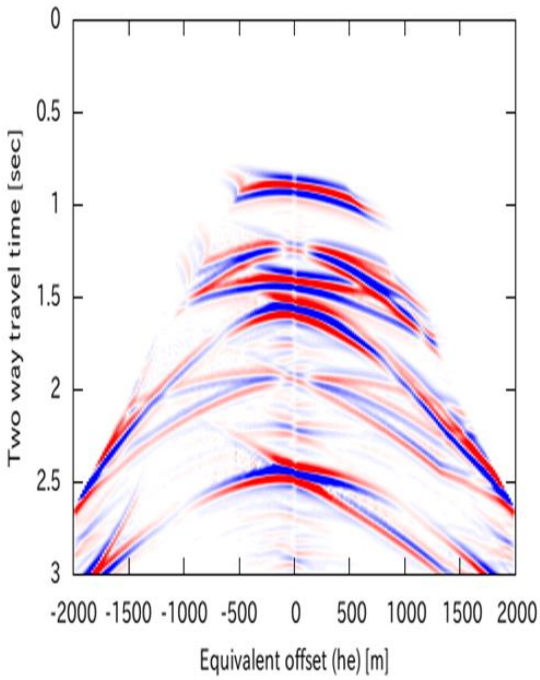

Figure 1 This is an example of CSP gather. It shows the scattered energy from scattering points on the same vertical line.

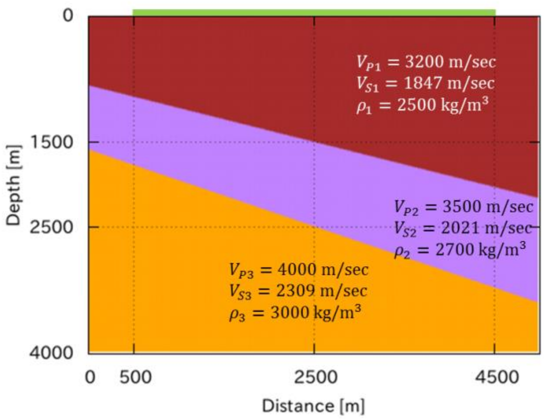

Figure 2 Multi-layered model for reflection survey simulation

5. CONCLUSION

We proposed a progressive approach to estimate physical properties in the subsurface by using whole part of CSP gather. Numerical results show the efficiency of simultaneous estimation of density and Lame's parameters. This result indicates that the lithological properties of the subsurface materials could be estimated by the utilization of horizontal and vertical records in the surface reflection survey.

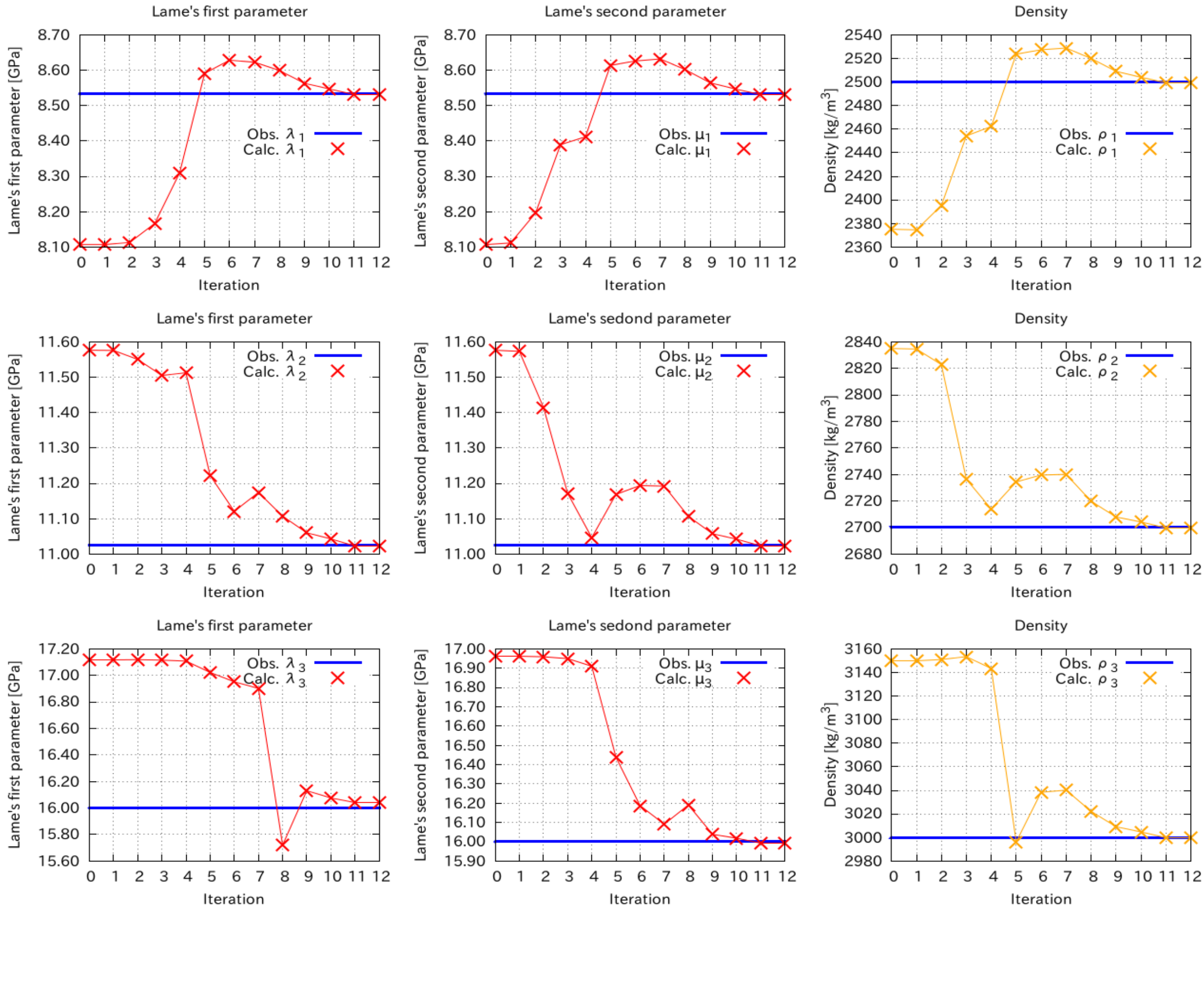

Figure 3 This is the result of estimation.

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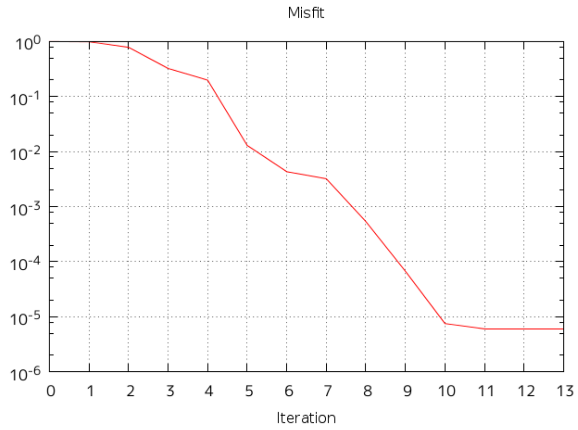

Figure 4 This shows the misfit of minimization. The misfit is normalized by the initial one.