Introduction

The importance of anticipatory knowledge on the dominant stress field orientation and the order of horizontal differential stress is well known in drilling planning or in the well stability analysis for production. For the estimation of horizontal stress field, the utilization of S-wave splitting is one of the most frequently applied methods (Crampin and McGonigle, 1981). When conducting S-wave survey, a S-wave source may be needed. When estimating horizontal stress field in a borehole, shear wave logging tools would become necessary. In the present situation, one may need to resort to only costly methods and a method simpler than the existing ones for the S-wave survey is still a challenging issue.

In our previous study (Watanabe, et al., 2017), we proposed a method for a cross-dipole S-wave survey in water using an interferometric approach originally developed by Clearbout (1968). Using the method, horizontal component waveforms acquired by an ocean bottom seismometer for a series of an airgun shots were successfully converted to cross-dipole data in numerical simulation. The effectiveness of the method has, however, not been confirmed working for real field example.

In this study, we investigate the applicability of our method to a field example for which the orientation of stress filed is known. We firstly conduct a feasibility test using a 3D numerical subsurface model with a single S-wave anisotropic layer in a horizontally stratified structure. Secondly, we conduct the real data test, which is Blackfoot, Spring Coulee, Alberta, Canada 2D-3C data to confirm the applicability of our method for field data.

Synthetic 3D data

We used the numerical 3D model with a free surface as shown in Figure 1. The 3D elastic wave equations and constitutive law are discretized by the finite-difference method with the rotated staggered grid (Saenger et al., 2000). For estimation target we set an anisotropic medium at upper layer. The anisotropic layer is assumed as the medium of transverse isotropy with the horizontally symmetry axis (HTI). In the anisotropic medium the 45 degrees or the 60 degrees of the orientation angle of fast S-wave is assumed. We call it “45deg. model” and “60 deg. model” later.

Blackfoot 2008-SC-01 data

For the real data test, we use Blackfoot 2008-SC-01 received by CREWS in Spring Coulee, Alberta, Canada. The survey settings and its location are shown in Figure 2.

![Figure 1](image1)

*Figure 1* 3D model for numerical test: The source point is set at the centre of the model and the source function is 10Hz Ricker Wavelet. The receiver array of three components geophone is set along the source point location. There are totally 300 points of receiver points in every 2m. The receiving time is totally 1.5s The PML absorbing boundary condition (Collino et al., 2001) is set in model edges except free boundary surface, which set on the model top.

![Figure 2](image2)

*Figure 2* Survey location and survey line layout of Blackfoot 2008-SC-01 (Bertram, et al., 2008 modified): Totally 652 flags are set on the survey line. The flags span is 10m, and the 3C geophones are set at every flag. The total receiving time is 4s with 2ms sampling rate. The source points are set on every three flags, flag No. 266 to No. 419. 2kg dynamite is used for excitation and the source depth is 15m beneath the surface.
Methodology

Firstly, some pre-processing is applied to the horizontal components data. For the numerical data, the direct wave is omitted, because it is the noise for the virtual S-wave cross-dipole data. Subsequently, the FK-filter is applied in order to extract the horizontal event from the target. For real data, we apply bandpass filter in order to suppress ground roll signal, and then, FK-filter is used in order to remove left ground roll and other coherent noise, such as S-direct wave. Finally, we kill the bad traces and signals, such as P-direct wave, missing records, and some traces which are close to source point or in which still the ground roll exists.

Secondly, seismic interferometry is utilized in order to generate the virtual S-wave cross-dipole data after pre-processing. Figure 3 shows its concept. Equation (1) represents its fundamental equation.

\[
\begin{align*}
U_{xx} &= U_{ix} \otimes U_{i+1x} \\
U_{yx} &= U_{iy} \otimes U_{i+1y} \\
U_{yx} &= U_{ix} \otimes U_{iy+1} \\
U_{yy} &= U_{iy} \otimes U_{iy+1}
\end{align*}
\]  

\(U_{ix}\) and \(U_{iy}\) are the received data of \(x\)-component on \(i\)-th and \(i+1\)-th receivers, respectively. \(\otimes\) means cross correlation. \(U_{xx}\) means \(x\)-direction virtual source at \(i\)-th receiver, and \(x\)-direction virtual receiver at \(i+1\)-th receiver. By using seismic interferometry, the virtual S-wave cross-dipole data which has source to source ray path shown in Figure 3 can be obtained. Because horizontal force in explosive source is extracted, S-wave survey without S-wave source becomes possible.

![Figure 3](image)

**Figure 3** Concept of the virtual S-wave cross-dipole data

Finally, Alford rotation (Alford, 1986) is applied in order to estimate fast S-wave orientation angle. When Alford rotation is utilized, the target anisotropic layer is assumed that it has uniform physical properties, or that it is the shallowest anisotropic layer. Equation (2) represents the fundamental equation of Alford rotation.

\[
\begin{bmatrix}
V_{xx} & V_{xy} \\
V_{yx} & V_{yy}
\end{bmatrix}
= \mathbf{R}(\theta)
\begin{bmatrix}
U_{xx} & U_{xy} \\
U_{yx} & U_{yy}
\end{bmatrix}
\]  

In equation (2) \(U_{ij}\) is one of components of the cross-dipole data with \(i\)-th source direction and \(j\)-th receiver direction. \(V_{ij}\) means the one of components of the cross-dipole data after rotation with \(i\)-th source direction and \(j\)-th receiver direction. According to equation (2) the cross-dipole data is virtually rotated with rotation tensor \(\mathbf{R}(\theta)\). When the energy of off-diagonal components of cross-dipole data \((V_{xy}, V_{yx})\) in application time window is minimum value, the rotation angle \(\theta\) is the estimated fast S-wave orientation.

Results

Figure 4 and Figure 6 show the common offset gathers of virtual S-wave cross-dipole data in each test. Adding to it, Figure 5 and Figure 7 show the estimation result of fast S-wave direction in each test.
Figure 4 The common offset gathers of virtual S-wave cross-dipole data in numerical experiments ((A): 45deg. model, (B): 60deg. model): The colored rectangle in the figure in each component is the theoretical time window for virtual S-wave primary reflection signal from anisotropic layer and the application time window of Alford rotation.

Figure 5 The estimation results of fast S-wave orientation in numerical experiments ((A): 45deg. model, (B): 60deg. model): The vertical axis is the estimated fast S-wave orientation [deg.], and horizontal axis is the location of virtual S-wave cross-dipole data’s source point on the survey line.

Figure 6 The common offset gathers of virtual S-wave cross-dipole data in real data

Figure 7 The estimation result of fast S-wave orientation in real data: The axis setting is same as Figure 5. The application time window of Alford rotation goes every 0.1 second with 0.4 s window span. The first significant trend appeared when the centre of application time window is set at 0.9 s.
Conclusions

In this study, we show a cross-dipole S-wave survey method using virtual S-wave cross-dipole data obtained by an interferometric approach. We start with a synthetic example for the feasibility test of our method, and then applied our method to real field data, which calls Blackfoot 2008-SC-01 received by CREWS in Spring Coulee, Alberta, Canada.

Our feasibility test show that the orientation of fast S-wave velocity could be estimated with the reasonable accuracy using Alford rotation to S-wave cross-dipole data virtually generated by the proposed method for explosive sources located within a distance of 150~200 meters from the receiver. The limitation in the offset range might be caused by the size of the first Fresnel zone overlapping with the boundary of the numerical model.

We then applied almost the same procedure to the real field data. The results indicate that we could produce virtual S-wave cross-dipole data using the method of seismic interferometry as in the numerical feasibility test. The fast S-wave orientation was estimated as about 74deg in the anticlockwise direction in N-S direction after the application of Alford rotation for a time window at 0.9s. Hu et al. (2017) shows that azimuthal anisotropic signal appears around 1.0s and the fast S-wave orientation of 50-130deg. from the N-S direction in Blackfoot, Canada 3D-3C data acquired in 1996. Since our results corresponds to what has been reported by Hu et al. (2017) in the orientation, we would like to conclude that our method of generating virtual S-wave cross-dipole data using seismic interferometry is applicable to real field data at least to estimate the orientation of fast S-wave even if real S-wave survey such as 3D-3C is not conducted.

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References