Converted-wave velocity analysis in the presence of anisotropy: a case study from
Shengli oilfield, China

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Summary

The Shengli Ken-71 multi-component seismic data were acquired with digital MEMS (micro-
electro-mechanical system) sensors over a mixed sand and shale sequence in the overburden.
This gives rise to serious non-hyperbolic moveout effects in the converted-wave data due to
both the asymmetry raypath and the anisotropic effects. Conventional velocity analysis based
isotropic methods cannot flatten the moveout. Here, we use a four-parameter theory
developed for vertical transverse isotropy (VTI) to evaluate these effects and process the data.
These four parameters include the PS converted wave stacking velocity ($V_{c2}$), the vertical
velocity ratio ($\gamma_0$), the effective velocity ratio ($\gamma_{eff}$), and the anisotropy parameter ($\chi$). The
method utilizes the moveout information at different offsets to estimate the different
parameters, and ensures that the events are properly aligned for stacking. As a result, this
four-parameter theory leads to an improvement in image quality and correlation between the
P-waves and converted-waves.
Introduction

Processing land multi-component seismic data in the presence of anisotropy is often a challenging problem. In this paper, we present such an example from the Shengli Oilfield in east China. The Shengli multi-component seismic data were acquired with digital MEMS (micro-electro-mechanical system) sensors over a mixed sand and shale sequence in the overburden. The data consisted of four swaths. For each swath, there are twelve receiver lines with 300 receivers per line and 220m of line spacing. Receiver interval is 20m, giving area coverage about 15km² for each swath. The shots are located in the centre of the receiver patch and orthogonal to the receiver lines with 66 shots per shot line and 100m of shot line spacing. The data are of good quality with some random noise and ground roll (Figure 1).

As we know, sedimentary layers such as shales and thin bedding sequences in the overburden often give rise to vertical transverse isotropy (VTI, or polar anisotropy). This leads to serious non-hyperbolic moveout effects in the converted-wave data due to both the asymmetric raypath and the anisotropic effects. Conventional velocity analysis based isotropic methods cannot flatten the moveout. One of the key issues during processing multi-component seismic data is how to account for these VTI effects. Here, we use a four-parameter theory developed by Li and Yuan (2003) to evaluate these effects and process the Shengli data.

The basic four-parameter theory for VTI

According to Li and Yuan (2003), the C-wave moveout signature in horizontally layered VTI media can be expressed as,

$$t_C^2 = t_{C0}^2 + \frac{x^2}{V_C^2} + \frac{A_4 x^4}{1 + A_4 x^2},$$

where

$$A_4 = \frac{\left(\gamma_0 \gamma_{eff}^{-1}\right)^2 + 8(1 + \gamma_0) \chi_{eff}}{4 \gamma_0 V_C^2 \gamma_{eff} (1 + \gamma_{eff})},$$

and

$$A_i = \frac{A_i V_C^2 (1 + \gamma_0) \gamma_{eff}}{(\gamma_0 - 1) \gamma_{eff}^2 (1 - \gamma_{eff})^2 - 2(1 + \gamma_0) \gamma_{eff} \chi_{eff}}.$$  

$V_C$ is the C-wave stacking velocity, $\gamma_0$ and $\gamma_{eff}$ are the vertical and effective velocity ratio, and $\chi_{eff}$ is the C-wave anisotropic coefficient. Equations (1) and (2) are accurate for offset-depth ratio up to 2.0 ($x/z \leq 2.0$) (Li and Yuan, 2003). Equation (1) controls the stacking process, and these four parameters are referred to as the C-wave stacking velocity model.

The C-wave diffraction curve from a point scatter in VTI media can be derived as (Dai and Li, 2001),

$$t_C = \sqrt{\left(\frac{t_{C0}}{1 + \gamma_0}\right)^2 + \frac{(x + h)^2}{V_{p2}^2} - 2 \eta_{eff} \Delta \tau_P^2} + \sqrt{\frac{\gamma_0 t_{C0}^2}{1 + \gamma_0}} \frac{(x - h)^2}{V_{S2}^2} + 2 \zeta_{eff} \Delta \tau_S^2,$$

where

$$\eta_{eff} = \frac{1}{8 \tau_0 V_{p2}^4} \left[ \sum_{i=1}^{n} V_{p2}^4 \Delta \tau_{p0} (1 + 8 \eta) - \tau_0 V_{p2}^4 \right],$$

and

$$\zeta_{eff} = -\frac{1}{8 \tau_0 V_{S2}^4} \left[ \sum_{i=1}^{n} V_{S2}^4 \Delta \tau_{s0} (1 - 8 \zeta) - \tau_0 V_{S2}^4 \right];$$

$$\Delta \tau_P^2 = \frac{(x + h)^4}{V_{p2}^2 V_{p0}^2 (1 + \gamma_0)^2 (1 + 2 \eta_{eff}) (x + h)^2},$$

and

$$\Delta \tau_S^2 = \frac{(x - h)^4}{V_{S2}^2 V_{S0}^2 (1 + \gamma_0)^2 (1 + 2 \eta_{eff}) (x - h)^2}.$$
of these, the four parameters $V_{p2}$, $V_{s2}$, $\eta_{\text{eff}}$ and $\zeta_{\text{eff}}$ are referred to as the C-wave PSTM velocity model. There is a one-to-one analytical link between the stacking and PSTM velocity models:

$$V_{p2} = V_{C2} \gamma_0 \frac{(1 + \gamma_0)}{1 + \gamma_{\text{eff}}}, \quad V_{s2} = V_{C2} \gamma_0 \frac{(1 + \gamma_0)}{\gamma_0 (1 + \gamma_{\text{eff}})}, \quad \eta_{\text{eff}} = \frac{\chi_{\text{eff}}}{(\gamma_0 - 1)\gamma_{\text{eff}}}, \quad \zeta_{\text{eff}} = \frac{\zeta_{\text{eff}}}{(\gamma_0 - 1)}.$$  \hspace{1cm} (6)

If the stacking velocity model ($V_{C2}$, $\gamma_0$, $\eta_{\text{eff}}$ and $\chi_{\text{eff}}$) is known, equation (6) can be used to build the PSTM velocity model.

Work flow for anisotropic velocity analysis

The following workflow can be used to determine the stacking velocity model ($V_{C2}$, $\gamma_0$, $\eta_{\text{eff}}$ and $\chi_{\text{eff}}$) using multi-component seismic data.

The first step is to estimate $\gamma_0$ through an initial processing sequence. The C-wave moveout is insensitive to the variation of $\gamma_0$ (Li and Yuan 2003). Thus, $\gamma_0$ cannot be determined from moveout analysis. A coarse correlation of the P- and C-wave stacked sections is required. This often involves processing the P- and C-wave data using hyperbolic methods to obtain two stacked sections. $\gamma_0$ is then obtained by correlating these two sections. Once $\gamma_0$ is determined, the second step is to estimate $V_{C2}$, $\eta_{\text{eff}}$ and $\chi_{\text{eff}}$ from the C-wave moveout signature by interactive analysis (Dai, 2003). This is because each of these parameters controls a particular data aperture of primary influence: $V_{C2}$ controls the hyperbolic moveout at near offsets ($x/z<1.0$); $\eta_{\text{eff}}$ controls the non-hyperbolic moveout at intermediate offsets ($x/z<1.5$) due to the asymmetric raypath; $\chi_{\text{eff}}$ controls the anisotropic moveout at far offsets ($x/z<2.0$).

The third step is to determine the migration velocity. The initial model is calculated from the stacking velocity model using equation (6), and common imaging point (CIP) gathers can then be generated using the initial velocity model through PSTM. Model updating is achieved by analyzing the residual moveout in the CIP gathers. Updating is often restricted to $V_{C2}$ and $\chi_{\text{eff}}$. After updating, a final PSTM is applied to the data. This requires one NMO run and two PSTM runs.

Applications to the Shengli multi-component seismic data

The above processing scheme has been successfully applied to the Shengli multi-component seismic data. Figures 2 and 3 illustrate the correlation analysis for determining $\gamma_0$, where we have successfully matched up the P- and C-wave stacked sections through compressing the C-wave section into P-wave time. Figure 4 illustrates the process of stacking velocity analysis, where the far-right panel illustrates the input ACP (asymptotic conversion point) gather after moveout correction. The far-left panel displays the $V_{C2}$ spectra for interactive picking. The second panel from the left displays the velocity ratio $\gamma_{\text{eff}}$. The third panel from the left displays the anisotropic coefficient $\chi_{\text{eff}}$. The flatness of an event over the intermediate and far offsets determines the values of $\gamma_{\text{eff}}$ and $\chi_{\text{eff}}$. This allows detailed analysis of the moveout and ensures that the proper moveout correction is applied to the data.

Figure 5 shows the results of migration velocity analysis, where a CIP gather generated by PSTM is input to the same interactive tool as in Figure 4 for updating the migration velocity model. Again, the criterion is to flatten the events in the CIP gather. This makes it possible to obtain an accurate migration velocity model for final migration.

The final stacked PP- and PS-sections are shown in Figure 6, where the regional events can all be mapped from both the PP- and PS-sections, giving rise to a very high degree of correlation. Figure 7 compares the migrated converted-wave section with the stacked section. We can see a clear improvement in the signal-to-noise ratio after migration, and the faults are generally better imaged.
Discussion and conclusions

We have evaluated the use of a four-parameter theory for processing the Shengli multi-component data. The four parameters are $V_{C2}$, $\gamma_0$, $\gamma_{eff}$ and $\chi_{eff}$, which can be determined from reflection moveout analysis and can then be used to build the anisotropic model for prestack time migration. This leads to an improvement in both image quality and event correlation between the PP and PS converted-waves in the Shengli multi-component seismic data.

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References

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Figure 1. PS Converted-wave data from Shengli, X-component, Swath 3.

Figure 2: Before compression: A coarse correlation of the (a) P- and (c) C-wave sections for estimating (b) $\gamma_0$.

Figure 3: After compression. As a result, the P- and C-wave sections are matched up successfully.
Figure 4: Interactive analysis for determining $V_{C2}$, $\gamma_{eff}$ and $\chi_{eff}$, and the input data are asymptotic conversion point (ACP) gathers.

Figure 5: Migration velocity analysis, and the input data are common imaging point (CIP) gathers.

Figure 6. Comparison of final stacked sections: (a) PP-wave and (b) PS converted wave.

Figure 7. Comparison of (a) final stacked with (b) migrated converted-wave sections.