Joint Anisotropic Parameter Inversion Based on Nonhyperbolic Moveout and Azimuthal Amplitude Variance

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Summary

Two types of anisotropies commonly seen in wide-azimuth, far offset reflection seismic data are VTI (vertical transverse isotropy) and HTI (horizontal transverse isotropy). Both types cause arrival time distortion of the seismic wave. Because of the layered sedimentary structure and presence of vertical fracture, the unconventional shale reservoir exhibits both nonhyperbolic moveout effect in far-offset gathers and azimuthal arrival time variations.

Previous studies on seismic anisotropy focus either only on either HTI or VTI. For HTI analysis, usually only near or middle offset gathers are used, while for VTI analysis, the far offset gathers are paid more attention. In addition, VTI analysis doesn't consider azimuthal changes, while HTI analysis focuses on azimuthal changes on either velocity or amplitude. It is obvious that in the field application both HTI and VTI exist, and they distort seismic reflection together. So, joint anisotropy parameter inversion is highly in need.

Thomsen weak-anisotropy parameters are sensitive to both HTI and VTI. We purpose a joint inversion method to estimate the anisotropic parameters simultaneously. In order to testify the reliability and precision of the proposed method, we build a synthetic elastic 3D anisotropy model. After that, the proposed method is applied on Barnett shale data, and the measured anisotropic attributes show good correspondence with production data and other seismic attributes.

Introduction

The tight fractured reservoir exploration and development become more and more important in petroleum industry (Sun and Scheter, 2014). Accurate unconventional resource play characterization draws more and more attentions. In seismic applications, anisotropy phenomenon is usually used as a tool for unconventional reservoir characterization. Commonly, seismic Anisotropy can be defined as the dependence of velocity on direction or upon angle (Thomsen, 2002). There are two main types of anisotropy, both of them are called transverse isotropy (it is called transverse isotropy because there is isotropy in the horizontal or vertical plane) or polar anisotropy (Rüger, 1998).

Transverse isotropy exists most simply in a system of hexagonally symmetric anisotropy which will have an axis of cylindrical symmetry (Zheng, 2006). In such a system, the properties of a given layer in a certain direction rely entirely upon the angle between that direction and the angle of symmetry. Vertical transverse isotropy (VTI) normally occurs in thinly layered soft sediments where the influence of gravity on grain orientation is the cause of the anisotropy and the layer therefore has a vertical axis of symmetry. Common causes of horizontal transverse isotropy (HTI) include regional stress or a system of vertical fractures in a brittle, isotropic medium.

VTI is most easily discernable on an offset-ordered CMP (common midpoint) gather (Zhang et al., 2013). The approximation for VTI correction is usually empirically derived as the measure of anellipticity. Although the VTI effects are more pronounced at far offsets, there is an effect at all offsets, including very short offsets. The
interaction of velocity alters the RMS velocity estimate that is determined just from the near offsets. There have been numerous papers on the topic of VTI and estimation of its effects from the non-hyperbolic moveout apparent on seismic gathers (Tsvankin and Thomsen, 1994) and semblance scan results (Zhang et al., 2014). In a horizontally transverse isotropic layer, the usual source of the anisotropy is regional stress or vertical parallel cracks, causing the axis of symmetry to be horizontal. The appearance of HTI is best organized on an azimuthally-ordered gather. A common empirical approach for estimating HTI is to display azimuthally-ordered CMP gathers and look for a sinusoidal appearance on events that can be used as an indicator of both the magnitude and direction of the ellipticity.

In the field seismic exploration, there are some geologic settings where a thick shale with strong VTI directly overlies a fractured layer (carbonate or clastic) that exhibits HTI. In this case, the effects of the VTI in the overburden and the HTI of the target become coupled in the time shifts observed in the data. VTI typically generates a greater magnitude time shift and the effects of VTI impact normal moveout measurements at all offsets. For data not corrected for VTI, the angle gathers used for HTI can look like noise. A simultaneous unconventional parameter inversion of both effects is required in order to properly estimate the velocity effects within the reservoir interval. By incorporating VTI in the HTI measurements, fracture attributes at the target reservoir can successfully be measured in order to create the fracture maps that are used in guiding the drilling program.

In this paper, we first introduce the fundamental conceptions of VTI and HTI seismic anisotropies. Then, the traveltime equations for CMP gathers are discussed in anisotropic media. We analyze the anisotropy parameters in coupled VTI and HTI situation. Next, a workflow is proposed to estimate the VTI and HTI anisotropy parameters simultaneously. The parameter inversion method is tested in synthetic examples.

**Seismic Anisotropy: VTI and HTI**

In exploration seismology, it is convenient to express the degree of seismic anisotropy using anisotropy parameters $\gamma$, $\delta$ and $\varepsilon$ proposed by Thomsen (1986). Figure 1 shows the analog of VTI and HTI models.

![Figure 1: The analogy between VTI and HTI models (After Rüger, 2002)](image)

After Thomsen (1986) and Rüger (2002), the stiffness matrix for VTI media is:

$$
\sigma^{\text{VTI}} = \begin{pmatrix}
C_{11} & C_{13} - 2C_{66} & C_{13} \\
C_{13} - 2C_{66} & C_{11} & C_{13} \\
C_{13} & C_{13} & C_{44}
\end{pmatrix}
$$

(1)
For HTI, compared to VTI, axes are interchanged (shown in Figure 1). Therefore, \( C_{11} \) and \( C_{33} \) are interchanged, and so on. The stiffness matrix becomes:

\[
\sigma^{HTI} = \begin{bmatrix}
C_{11} & C_{13} & C_{13} \\
C_{13} & C_{33} & C_{33} - 2C_{44} \\
C_{13} & C_{33} - 2C_{44} & C_{33} \\
\end{bmatrix}
\]

(2)

The parameter \( \varepsilon \) is used to characterize the relative difference between horizontal and vertical P-wave velocities:

\[
\varepsilon = \frac{C_{11} - C_{13}}{2C_{33}}
\]

(3)

Parameter \( \gamma \) can be defined as measuring the relative difference between horizontal and vertical SH-wave velocities

\[
\gamma = \frac{C_{66} - C_{44}}{2C_{44}}
\]

(4)

In addition, \( \delta \) quantifies the angular dependence of the SV-wave speed and near vertical P-wave speed variation required in seismic data processing (Tsvankin, 2002)

\[
\delta = \frac{(C_{13} + C_{44})^2 - (C_{33} + C_{44})^2}{2C_{33}(C_{33} - C_{44})}
\]

(5)

For VTI analysis, Alkhalifah and Tsvankin (1995) introduce the anellipticity defined \( \eta \) as

\[
\eta = \frac{\varepsilon - \delta}{1 + 2\delta}
\]

(6)

While, with the short-spread limitation, for weak anisotropy, the P wave normal moveout (NMO) velocity at an arbitrary azimuth is given by Tsvankin (1997):

\[
V_{nmo}(\varphi) = V_0 \sqrt{1 + 2\delta \cos^2 \varphi},
\]

(7)

where, \( V_{nmo} \) is the NMO velocity, and \( V_0 \) is the velocity of the seismic wave traveling vertically; \( \varphi \) is the azimuthal angle between seismic ray path and the normal direction of fractures.

**Anisotropic NMO Traveltime Equations**

The P-wave traveltime approximation for an isotropic medium can be expressed in a hyperbolic equation:

\[
t^2(x) = t_0^2 + \frac{x^2}{V_{nmo}^2},
\]

(8)

where, \( t_0 \) and \( t \) are the two-way travel times for zero-offset and offset \( x \).

Hyperbolic estimation is only suitable for estimation of elliptical anisotropy (or isotropy) which is rarely happened in practice. For the reflection moveout in a VTI layer, Alkhalifah (1997) proposed a nonhyperbolic approximation equation:
\[ t^2(x) = t_0^2(x) + \frac{x^2}{V_{nmo}^2} - \frac{2\eta x^4}{V_{nmo}^2 \left[ t_0^2 V_{nmo}^2 + (1 + 2\eta) x^2 \right]} , \quad (9) \]

If HTI effect is considered, Tsvankin and Thomsen (1994) obtained the following expression:

\[ t^2(x, \varphi) = t_0^2(x) + \frac{x^2}{V_{nmo}^2(\varphi)} + \frac{A_4(\varphi)x^4}{A(\varphi)x^2 + 1} , \quad (10) \]

where, \( V_{nmo} \) is the azimuthal as

\[ \begin{align*}
V_{nmo}(\varphi) &= V_0 \sqrt{\frac{1 + 2\delta}{2\delta \sin^2 \varphi + 1}}, \\
A_4(\varphi) &= -\frac{2\eta \cos^4 \varphi}{t_0^2 V_0^4 (1 + 2\delta)^2}, \\
A(\varphi) &= \frac{A_4(\varphi)}{1 - \frac{V_0^2}{V_{nmo}^2(1 + 2\delta)}} .
\end{align*} \]

\[ (11) \]

\[ (12) \]

\[ (13) \]

For zero azimuth, Equation (10) reduces to Equation (9). Note, for weak anisotropy, Equation (11) is approximated to Equation (7).

Jenner (2011) gave an approximation for coupled HTI and VTI anisotropy as follows:

\[ t^2(x) = t_0^2(x) + \frac{x^2}{V_{nmo}^2} - \frac{2\eta(\varphi)x^4}{V_{nmo}^2 \left[ t_0^2 V_{nmo}^2 + [1 + 2\eta(\varphi)]x^2 \right]} , \quad (14) \]

where, \( \eta(\varphi) \) is the azimuthally varying Alkhalifah-Tsvankin parameter from Equation (6). Note, in this case \( V_{nmo} \) is also azimuth dependent according to Equation (7). This equation is a simplified version of Equation (10).

In the case of pure HTI media, three parameters need to be inverted \((V_0, \delta, \text{ and } \varphi)\) and this is often a stable inversion for wide-azimuth acquisition geometries where the data contain sufficient offsets and azimuths at the target horizon. On the other hand, determination of VTI anisotropy requires just two parameters \((V_{nmo} \text{ and } \eta)\). Despite this, obtaining reliable estimates of \( \eta \) for land seismic data can be difficult. The inversion relies on the farthest offsets; however, the far offsets may be contaminated with coherent noise.

### Joint Anisotropy Parameter Inversion

Recently, seismic data may be acquired with a good azimuth distribution. The wide-azimuth data allow us to estimate the anisotropy parameters from the nonhyperbolic moveout effect on the offset gathers and azimuthal amplitude variances on azimuth gathers.

Figure 2 illustrates the proposed workflow for joint VTI and HTI parameter inversion workflow. The input data are prestack time-migrated CMP gathers and the initial migration velocity (isotropic velocity). The outputs are the inverted anisotropy parameter volumes of \( \delta \) and \( \eta \).

The prestack gathers are generated from a time-migrated gather that has been subjected to a reverse NMO correction using the migration velocity. The workflow starts by building an initial interval velocity model from migration velocity. \( V_{nmo} \) and \( \eta \) are then simultaneously inverted from the long offsets based on nonhyperbolic NMO. If the offsets are long enough, the analysis of \( V_{nmo} \) and \( \eta \) can be reliable. As the geometry could be irregular, so the
obtained $V_{nmo}$ and $\eta$ should be smoothed to make the workflow robust. After smoothing the results, an update would be applied to fix the residual NMO velocity.

The azimuthal NMO inversion will result in $V_0$, $\delta$, and $\varphi$, and the $V_{nmo}$ calculated from these parameters may be different than that in the VTI inversion. Based on the equations above, it is clear that the HTI approximations should be adopted in the near and mid offsets. So, there is also a possibility that a further update of $V_{nmo}$ will be needed. This can be achieved by another iteration VTI inversion. The updating of $V_{nmo}$ and $\delta$ with $\varphi$ ensures that the near-offset data remain aligned while the updated $\eta$ flattens the far offsets. Besides the anisotropy attributes, we can also do AVO (amplitude versus offset) analysis on the corrected gathers.

**Synthetic examples**

To examine the joint inversion formula, we design synthetic examples to invert anisotropy parameters.

![Figure 2: Workflow of joint VTI and HTI parameter inversion.](image)

![Figure 3: Percentage error of estimated $\eta$ for a model with $V_0 = 2$ km/s, $\varepsilon = -0.2$, from (left) joint HTI and VTI inversion, and (right) VTI inversion.](image)
Figures 3 to 5 show the percentage error results of $\eta$ estimation from joint HTI/VTI inversion and only VTI inversion. In the models, $V_0 = 2$ km/s, $\varepsilon = -0.2$, 0, 0.2, depth = 2km, $\delta$ changes from -0.25 to 0.25, azimuth changes from 0 to 180 degree. It is clear that the joint inversion achieves smaller errors.

Conclusions

Following the introductions of seismic anisotropy expressions, we propose a workflow that can be used to estimate both long-offset nonhyperbolic traveltimes (VTI anisotropy) and azimuthally varying traveltime variations (HTI anisotropy) parameters. The model puts both VTI and HTI into consideration, but the workflow separates their components at different stages so the VTI parameter estimation would not impact HTI parameter estimation. The synthetic examples show this workflow is practical because VTI and HTI are always coupled in the field applications.

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References


