Sensitivity analysis of seismic anisotropy parameter estimation

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Summary

Based on transversely isotropic (TI) layer-cake model randomly parameterized by the laboratory anisotropy measurement data, we apply the commonly used quartic non-hyperbolic moveout velocity analysis method to estimate the seismic anisotropy parameters. The methodology is tested on its sensitivity to the layering effect, the source-receiver offset, the vertical interval velocity error, and the time picking error. The simulation results show this methodology is theoretically well-established and it works better for deeper layers and shorter offset data. However, in presence of normal level noises, this method may not work because it is extremely sensitive to the time picking error and requires the offset be greater than the depth of the reflection event. The uncertainties in seismic anisotropy parameter estimating increase rapidly for deeper layers. Generally, δ is more reliably determined than ε because the normal move-out velocity is better determined than the horizontal velocity.

Introduction

There are different methods developed for the estimation of the anisotropy parameters (White et al., 1983; Gaiser, 1990; Alkhalifah and Tsvankin, 1995; Baan, et al., 2002; Isaac and Lawton, 2004). Xiao (2006) made a comparative study and found that the quartic non-hyperbolic moveout equation formulated by Alkhalifah and Tsvankin (1995) can be applicable to VTI media of arbitrary anisotropy and has the best performance among the methods of anisotropy parameter estimation using velocity analysis approach.

Laboratory anisotropy measurement is an important means to study the seismic anisotropic properties of subsurface rocks and calibrate the results of anisotropy parameter estimation from seismic data. Sedimentary basins primarily consist of shales or mudrocks in terms of volume fraction. In laboratory anisotropy measurement, the dimensions and orientation of the rock samples are known, and the measurement directions are controllable, but there are still significant uncertainties in the estimation of c_{13} and δ (Yan et al., 2012, 2013, 2014; Yan, 2015; Yan, et al., 2016).

For field seismic data, we do not know the subsurface geometry and have limited control on the measurement directions, it is expected that the estimation of the anisotropy parameters becomes more challenging. The goal of our study is to select one of the widely implemented anisotropy parameter estimation methods and study its sensitivity to various factors that may be encountered in the practical applications. The sensitivity analysis results should supply useful guidance for effective implementation of seismic anisotropy.

Procedure of TI Parameter Estimation

In this study, we follow the procedure of TI parameter estimation proposed by Alkhalifah and Tsvankin (1995) and Tsvankin (2012). This procedure mimics the procedure of velocity analysis for the isotropic media. First, we use equation (1) to compute the effective NMO (normal moveout) velocity ($V_{Pnmo}(i)$) and the effective horizontal velocity ($V_{Phor}(i)$) for each layer interface. Here the normal text (i) refers to the i-th layer. These velocities are similar to stacking velocities because they include the wave propagation effect from the overburden layers.

$$t^2(x,i) = {t_0}^2(i) + \frac{x^2}{V_{\mathrm{Pnmo}}^2(i)} - \frac{\left(V_{\mathrm{Phor}}^2(i) - V_{\mathrm{Pnmo}}^2(i)\right)x^4}{V_{\mathrm{Pnmo}}^2(i)\left({t_0}^2(i)V_{\mathrm{Pnmo}}^4(i) + V_{\mathrm{Phor}}^2(i)x^2\right)}. \quad (1)$$

For the second step, equation (2) is used to compute the interval NMO velocities,

$$V_{\mathrm{Pnmo}}^{(i)} = \sqrt{\frac{V_{\mathrm{Pnmo}}^2(i)t_0(i) - V_{\mathrm{Pnmo}}^2(i-1)t_0(i-1)}{t_0(i) - t_0(i-1)}}. \quad (2)$$

Here the superscript (i) refers to the interval properties. For the third step, the intermediate parameter $g(i)$ is computed for each layer:

$$g(i) = V_{\mathrm{Pnmo}}^2(i)(4V_{\mathrm{Phor}}^2(i) - 3V_{\mathrm{Pnmo}}^2(i)). \quad (3)$$

For the fourth step, equations (3) and (4) are used to compute the interval horizontal velocity ($V_{Phor}^{(i)}$).

$$V_{\mathrm{Phor}}^{(i)} = V_{\mathrm{Pnmo}}^{(i)}\sqrt{\frac{1}{4\left(V_{\mathrm{Pnmo}}^{(i)}\right)^4}\frac{\mathrm{g}(i)\,t_0(i) - \mathrm{g}(i-1)\,t_0(i-1)}{t_0(i) - t_0(i-1)} + \frac{3}{4}}, \quad (4)$$

If the vertical interval velocities are known from the well logging data or check shot survey, ε and δ can be calculated using the previously estimated parameters:

$$\varepsilon = ((\frac{V_{\mathrm{Phor}}}{V_{\mathrm{P0}}})^2 - 1)/2, \tag{5}$$

$$\delta = ((\frac{V_{Pnmo}}{V_{\mathrm{P0}}})^2 - 1)/2. \tag{6}$$

TI Model Parameterization and Ray Tracing

The sensitivity testing is based on synthetic layered TI model consisting of 15 layers with equal thickness of 50 meters. The elastic properties of each layer are parameterized based on laboratory anisotropy measurement data (Thomsen (1986), Johnston and Christensen (1995), Vernik and Liu (1997), Jakobsen and Johansen (2000), Wang (2002b, shale and coal samples only), and Sone (2012)). For each simulation, 15 data points are randomly selected and the corresponding elastic properties are assigned to each of the 15 layers in the synthetic model. 100 simulations are run for each type of sensitivity testing so that the test results are not specific to a certain sequence of rocks.

The traveltimes are computed using the seismic ray theory. For TI media, the Snell's law is in the same form as for the isotropic media (Slawinski et al., 2000):

$$p = \frac{Sin\theta_i}{V_{P\theta i}}, \tag{7}$$

where p is the ray parameter. It is a constant for a certain ray. "i" refers to the i-th layer. It should be emphasized here that the angle is a phase angle and the velocity must be the phase velocity. Since the actual traveltime is determined by the ray path and the ray (group) velocity, at each interface there is a need to convert the phase angle to the group angle and the phase velocity to the group velocity(Yan, 2015).

Figure 1 shows an example of ray tracing on one of the realizations of the synthetic TI model. From 0° to the maximum shooting phase angle, 20 rays are shot at the top of the top layer in equal phase angle intervals. For clarity, only rays reflected on the bottoms of layers 5, 10, and 15 are shown. The gray level of the layer represents the degree of P-wave anisotropy (Thomsen parameter ε), which lies around 0 to 0.5. It can be seen that anisotropy has a strong effect on bending of the rays. Based on the ray tracing the reflection traveltimes for each interface can be computed.

Sensitivity Testing of the Layering Effect

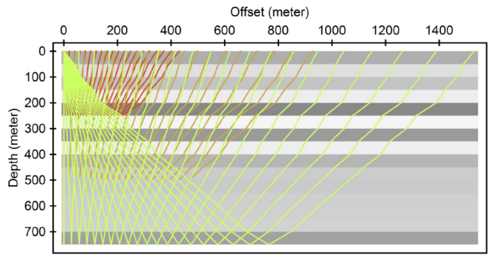

Figure 1: Seismic ray tracing on a synthetic TI model. The TI model consists of 15 layers with equal thickness of 50 meters. Only rays that are reflected on layers 5, 10 and 15 are shown. Parameterization of the synthetic TI model is based on the laboratory measurement. The gray level indicates the degree of P-wave anisotropy.

One of the important mechanisms causing seismic anisotropy is the layering effect. In a sedimentary basin, even if each of the formation layers of various thicknesses is isotropic, the effective properties of the formation are anisotropic (Backus, 1962). The layered structure causes non-hyperbolic reflection moveout. It would be good to know whether the anisotropy parameter estimation can achieve similar accuracy for the top layers and bottom layers. In this test, no errors were introduced for the vertical interval velocities and the reflection traveltimes. The maximum shooting phase angle is 30°.

Figure 2 shows the correlations between the actual model parameters and the estimated values for ε and δ. Since there is no time picking error, the estimation of the anisotropy parameters is generally excellent. Therefore, equation (1) is a very good approximation of the non-hyperbolic reflection time curve for TI media with arbitrary anisotropy and the anisotropy parameter estimation procedure introduced is theoretically valid. It can be seen that the estimation of the anisotropy parameters for layer 15 is slightly more accurate than for layer 5. The anisotropy induced by the layering effect should have no adverse effect on the anisotropy parameter estimation. It is observed that the estimation of δ has less uncertainty than the estimation of ε. From equations (5) and (6), it means the normal move out velocity is more reliably estimated than the horizontal velocity.

Sensitivity Testing on the Offset

In order to have reliable estimation of the horizontal velocities, it is often believed that seismic data with much longer offset than usual are required. In the last testing, the maximum shooting angle is 30°, which corresponds to an offset depth ratio of about 2.0(model-based, see explanation in Yan, 2015). To observe the effect of offset on anisotropy parameter estimation, we conducted similar testing using

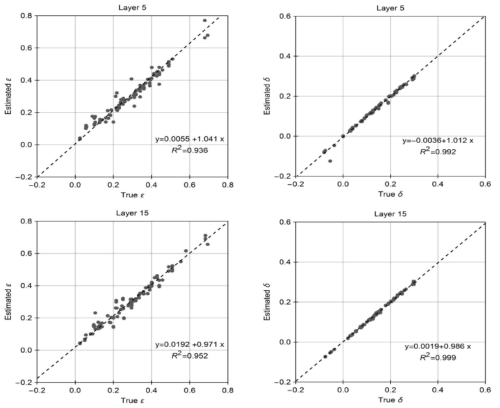

Figure 2: Uncertainty in estimation of ε and δ when there is no error in vertical velocity determination and traveltime picking. The maximum shoot phase angle is 30°.

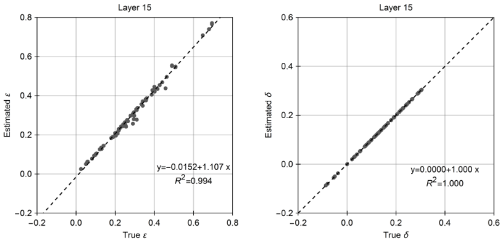

Figure 3: Uncertainty in estimation of ε and δ when there is no error in vertical velocity determination and traveltime picking. The maximum shoot phase angle is 5°.

maximum shooting angle of 5°, which corresponds to an offset depth ratio of about 0.25. It is assumed that there is no error in V_{P0} determination and traveltime picking. From the sensitivity testing in the last section, the layering effect has little effect on the anisotropy parameter estimation; therefore, only the simulation results for layer 15 are shown in this section. Figure 3 shows the uncertainties in the estimation of ε and δ for layer 15. Comparing Figure 3 with Figures 2, we can see that the estimation of the anisotropy parameters is more accurate by using the short-offset synthetic data than the long-offset synthetic data.

The above modeling results appear to be contradictory to our common sense, but it is theoretically explainable. Equation (1) is a quartic Taylor series approximation of the non-hyperbolic normal moveout curve. The Taylor series approximation is more accurate for smaller offset. Therefore, if there is no noise, a better estimation of the anisotropy parameters can be achieved using the shorter offset data. The normal moveout velocity is defined as the slope of the normal moveout curve when the offset goes to zero (Thomsen, 1986). Therefore, theoretically the normal moveout velocity can be more reliably estimated using the shorter offset data.

Sensitivity Testing of the V_{P0} Error

In traditional seismic data processing, the estimation of the vertical interval velocities can be challenging under assumption of isotropy. To estimate the extra anisotropic parameters, it is often necessary to assume the vertical interval velocities are known from the other data sources, such as the sonic logging data and VSP data. From the anisotropy parameter estimating procedure introduced in the earlier section, the vertical interval velocity is used to estimate the Thomsen parameter ε and δ after the normal moveout velocity and horizontal velocity are determined. Therefore, the error in the vertical interval velocities does not affect the estimation of the normal moveout velocity and the horizontal velocity. In this testing, it is assumed that there is no error in traveltime picking. The maximum shooting phase angle is 30°.

In Figure 4, we tested the effect of the random velocity error of [-2%, +2%] (upper panels) and [-5%, +5%] (bottom panels) on the estimation of ε and δ. The maximum random error of 2% may correspond to the vertical interval velocity data with good to excellent quality. The maximum random error of 5% may correspond to the vertical interval velocity data with fair quality. The estimation of ε is generally acceptable if the error in the vertical interval velocity does not excess the P-wave anisotropy. The estimation of δ is slightly more accurate than the estimation of ε.

Sensitivity Testing of Time Picking Error

There are always some noises affecting the traveltime picking along the reflection events in field seismic data. In this experiment, we will test the effect of random noise on the estimation of the anisotropy parameters. The random noise lies in between -0.1% and +0.1% of the theoretical two-way traveltimes. This error corresponds to a time error of about 1 ms for a reflection event lying around 1000 ms. Obviously, this noise level is much lower than the common noise level of field seismic data. For this experiment, a random error between -2% to +2% is also added to the interval vertical velocities. The maximum shooting phase angle is 30°.

Figure 5 shows the effect of the time picking error and the vertical velocity error on the estimation of δ for layers 1, 5, 10, and 15, respectively. It can be seen that the accuracy of the parameter estimation deteriorates rapidly the deeper the layers. Below layer 5, the estimation is too poor to be acceptable for δ. Similar is true for estimation of ε (Yan, 2015). As demonstrated in the previous sensitivity testing,

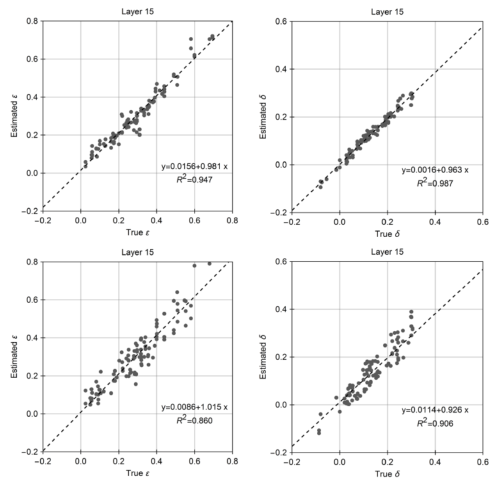

Figure 4: Uncertainty in estimation of ε and δ when there is error in vertical velocity determination but no error in traveltime picking. The maximum random error in determining V_{P0} is ±2% for the top panels and ±5% for the bottom panels.

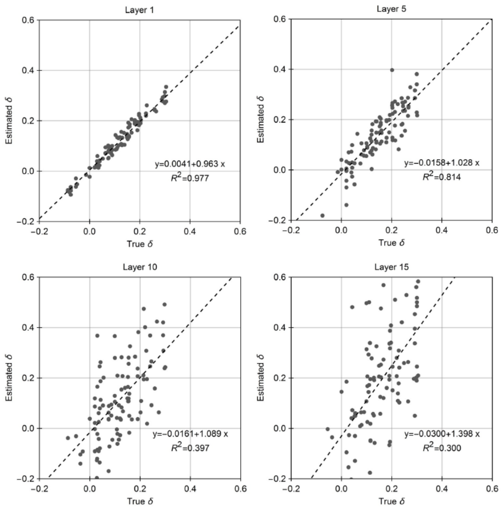

Figure 5: Uncertainty in estimation of ε when there are errors in vertical velocity determination and traveltime picking. The maximum random error in determining V_{P0} is ±2% and the maximum random error in time picking is ±0.1%.

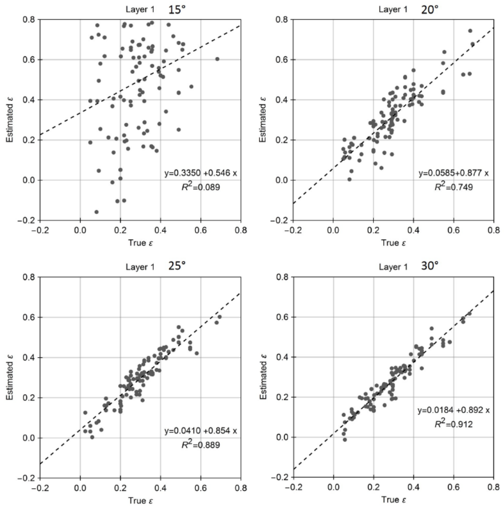

Figure 6: Effect of offset on estimation of ε when there are errors in vertical velocity determination and traveltime picking. The maximum random error in determining V_{P0} is ±2% and the maximum random error in time picking is ±0.1%.

theoretically, the shorter the offset, the better is the fitting of equation (1) with the non-hyperbolic traveltime curve; and therefore, the more accurate is the estimation of the anisotropy parameters. In practice, the traveltime variation is usually very small at the short offset. If the offset is too short, a tiny traveltime picking error will make the anisotropy parameter estimation infeasible. Figure 6 shows the effect of offset on the estimation of Thomsen parameter ε for the top layer when the maximum shooting phase angle is 15°, 20°, 25°, and 30°, respectively. The accuracy in estimating ε decreases remarkably around the maximum shooting phase angle of 15°.

Conclusions

The methodology for seismic anisotropy parameter estimation developed by Alikahlifah and Tsvankin (1995) is theoretically well-established. In general, δ can be more reliably estimated than ε. Theoretically, the anisotropy parameters are more reliably estimated on the seismic data with shorter offset, but in practical applications the offset should be greater than the depth of the reflection event. This methodology is not sensitive to reasonable errors in vertical interval velocities, but it is extremely sensitive to the time picking error. The uncertainty in anisotropy parameter estimation increases rapidly the deeper the layers, which may make this methodology infeasible for practical applications.

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EDITED REFERENCES

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