Estimation of anisotropy parameters VTI (vertical transverse isotropy) using velocity variation with offset (VVO) method, case study: BS oil field

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Abstract. Implementation of anisotropy value in seismic data processing greatly affect seismic cross section image. In addition to enhanced seismic imagery, anisotropy can be used for identification of hydrocarbons. In this study, the vertical transverse isotropy (VTI) anisotropy parameter estimation by the VVO method has been done. The magnitude of the velocity value of the offset/angle is due to the ever-greater velocity with a large incidence angle being the basis of the VVO method to demonstrate the anisotropy effect. The residual moveout result of the time transfer correction caused by the velocity increase will be used as input data. Validity of the VVO method is tested using a synthetic forward modelling to obtain anisotropy parameters that describe the subsurface conditions of the target area which are then applied to the actual data. The results found that residual values continued to increase due to the anisotropy effect and thereafter the angle of 30 degrees with the value of $\varepsilon = 0.14$ and $\delta = 0.049$.

Keywords: Velocity, offset, residual moveout, VVO, anisotropy parameter

1. Introduction

Generally seismic data processing is carried out with isotropic assumptions, so that it is less precise due to the fact that the subsurface layer is anisotropy. Wang explained from the many laboratory measurements of shale anisotropy, that the shale anisotropy velocity of 50% is seen in P and S waves so that anisotropy cannot be ignored in seismic processing and interpretation [1]. The implementation of anisotropy value in the processing of seismic data greatly influences the seismic section image [2]. In addition to repairing seismic images, anisotropy can be used to identify hydrocarbons.

Seismic anisotropy is the dependence of seismic wave velocity on the direction of propagation. Seismic anisotropy can occur by several factors. Crampin et al. divided these factors into three, inherent or intrinsic anisotropy, crack induced and long-wavelength [3]. The method for estimating anisotropy parameters in detection of hydrocarbon content using velocity variation with offset (VVO) or velocity variation with angle (VVA) from velocity information has been introduced by Supriyono [2]. Suroso stated that the identification of hydrocarbons in layered media was successfully carried out by the method of velocity variation with angle [4].
In this study, estimation of anisotropy parameter vertical transverse isotropy (VTI) will be made from P wave recording data using variation velocity with offset (VVO). Furthermore, validity of the VVO method will be tested using synthetic forward modeling with to obtain anisotropy parameters that describe the subsurface conditions that are targeted. After the VVO method success on the synthetic models, it will be applied to the actual data.

2. Data and method

2.1. Denoising
The data used as input to the processing process is prestack seismic gather migration and after the reformat process, which is changing the SEG Y data format to the machine data format so that it can be read during the data processing process, then the denoising is carried out. The denoising is carried out by applying the anomalous amplitude attenuation (AAA) module by separating noise that has an amplitude that looks different from the amplitude in general. Separation of noise with this method by using frequency parameter as input, where the first noise filter process at low frequencies is 3 Hz – 20 Hz, the second filter at high frequencies is twice that at 21 Hz-nyquist and 70 Hz-nyquist with 35 spatial median widths and the third filter at high frequencies is 20 Hz-nyquist. The results show that the noise reduction is quite maximal so that can be used for the next process.

2.2. Velocity analysis
In CDP gather the NMO correction is needed to correct each CDP so that the curved line becomes straight, so that when the stack is obtained the maximum signal. Velocity analysis method used correlation semblance with gather method. Velocity selection is carried out every distance of 20 CDP gather, where at that distance is sufficiently accurate and is expected to produce the right velocity to show gather images that have anisotropy effect.

Before do velocity analysis, firstly to determine the magnitude of the arrival angle so that it is known what the arrival angle values at the gather to have an anisotropy effect. Determination the angle magnitude is done by AVO (Amplitude Versus Offset) so that the angles are known for each offset. Angle determination is done every 5 degrees with the furthest angle 60 degrees and the middle angle 2.5 degrees, so that the determination of the angle of arrival is 12 (figure 1).

Determining the angle using AVO can simplify the velocity analysis process, because it has an overview at the angle where there is an anisotropy effect so that it can used as a reference. In accordance with the results of angle determination by AVO, it can be seen that the angle at near offset is 30 degrees so that the first velocity analysis is carried out at a 30 degrees angle and the second after 30 degrees. NMO correction process on the first velocity analysis is done by picking velocity which is considered appropriate enough to straighten the reflector. The results of the first velocity analysis show the gather image at an angle of 30 degrees looking straight and it has the same residual time, whereas after the 30 degrees angle at the far offset shows curved upward reflector (hockey stick) whereas each offset has different residual time. The curved upward reflector is shown in figure 2a a depth of 0–500 meters and figure 2b a depth of 1000–1300 meters which is the target area. The curved upward reflector is the basis that there is an anomaly in the layer because of the anisotropy effect.

The next process is the second velocity analysis, where the velocity analysis is carried out after a 30 degrees that is by choosing the right velocity of the $\eta$ anisotropy parameter which is expected to be able to flatten the reflector.

2.3. Residual moveout
NMO correction that produces an overview of gathering that is not flat or shows residual moveout or hockey stick due to anisotropy effect (figure 3) [2].
Figure 1. Anisotropy effect determination based on angle.

Figure 2. (a) Hockey stick image after velocity analysis and (b) Hockey stick on the target area.

Figure 3. Residual moveout (Δt) after NMO correction.

In the VVO method, the residual moveout (Δt) from the NMO correction results are calculated for all offsets where the calculation is based on the assumption that the trace on the initial offset has been corrected properly or is 0, so offset at the next trace reduced to the offset at the initial trace. Thus the
The deduction is carried out until the offset on the last trace. The residual moveout calculation is performed using the Supriyono equation as follows [2]:

\[ \Delta t_j = \Delta T_j - \Delta T_s \]

\[ \Delta t_j = \left( T_0^2 + \frac{x_j^2}{V_{rms}^2} \right)^{1/2} - \left( T_0^2 + \frac{x_j^2}{V_{stk}^2} \right)^{1/2} \] (1)

The reduction of \( \Delta T_j \) and \( \Delta T_s \) produces \( \Delta t_j \), whereas \( \Delta t_j \) is residual time of NMO correction travel time differences using \( V_{stk} \) and \( V_{rms} \) for each offset. NMO correction travel time differences using \( V_{stk} \) is \( \Delta T_j \) and the travel time differences using \( V_{rms} \) is \( \Delta t_j \). \( x_j \) is offset value and after NMO correction is done will get know \( V_{stk} \) (stack velocity) value. While the velocity of rms will be searched by the above equation by specifying:

Example \( d_j = \left( T_0^2 + \frac{x_j^2}{V_{rms}^2} \right)^{1/2} T_j^2 V_{rms}^2 \), then \( V_{rms} \) is obtained as:

\[ \frac{1}{V_{rms}^2} = \frac{1}{x_j^2} \left( \frac{\Delta t_j + d_j}{T_0^2} - \frac{1}{x_j^2} \right) \] (2)

If continued use (2.1) equation with approach of taylor series, then:

\[ \Delta t_j = \left[ \frac{x_j^2}{2 V_{rms}^2 T_0^2} \right] - \left[ \frac{x_j^2}{2 V_{stk}^2 T_0^2} \right] \] (1)

For example \( a_j = \left( \frac{x_j^2}{2 V_{stk}^2 T_0} \right) \), so that:

\[ V_{rms} : \frac{1}{V_{rms}^2} \approx \frac{(a_j + \Delta t_j) 2 T_0}{x_j^2} \] (3)

2.4. Velocity calculation
The velocity result from the derivative residual moveout is the RMS velocity that will be converted to the interval velocity and each offset is transformed into an angle. The offset transformation into the angle is done by using Resnick approach as follows [5]:

\[ \left( \frac{V_{rms}}{V_{stk}} \right) \left\{ x^2 + \frac{V_{stk}^2 T_0^2}{V_{stk}^2 T_0^2} \right\} = \sin \theta \] (4)

As it is known that the VVO method is based on the correlation between velocity and angle (offset), where the velocity value will increase along with the angle that increases also due to the effect of anisotropy in subsurface. In the case of weak anisotropy, Thomsen has formulated mathematically anisotropic equations as follows [6]:

\[ V_p(\theta) \approx V_{po} [1 + \delta \sin^2 \theta \cos^2 \theta + \epsilon \sin^4 \theta] \] (5)

\[ V_p(\theta) \approx V_{po} [1 + \delta \sin^2 \theta + (\epsilon - \delta) \sin^4 \theta] \] (6)

\( \eta = \epsilon - \delta \), hence:

\[ V_p(\theta) \approx V_{po} [1 + \delta \sin^2 \theta + \eta \sin^4 \theta] \]
Assume a small arrival angle, then $\eta \sin^4 \theta \ll \sin^2 \theta$ so that angular velocity is obtained:

$$V_p(\theta) \approx V_p(0)[1 + \delta \sin^2 \theta]$$

$$V_p(\theta) \approx [V_p(0) + V_p(0) \delta \sin^2 \theta]$$

(7)

The simplified velocity equation above for the case of weak anisotropy is a linear equation assuming the angle of arrival is small, so the velocity in the angular function is obtained. By using a linearity approach, $\delta$ anisotropy parameters will be obtained by first looking for the velocity gradient obtained from the multiplication between $V_p(0)$ and $\delta$ so then to obtain the gradient $V_p(\theta)$ plotted against $\sin^2 \theta$ so that it obtained:

$$G \approx \frac{V_p(\theta_2) - V_p(\theta_1)}{\sin^2 \theta_2 - \sin^2 \theta_1}$$

(8)

Through gradient velocity, the $\delta$ parameters can be obtained:

$$\delta \approx \frac{\text{gradient velocity}}{V_p(0)}$$

(9)

While the parameters $\varepsilon$ can be obtained through the ellipse approach whereby assuming the velocity of anisotropy follows the elliptical curve like the following equation [2]:

$$\left(\frac{x}{V_{90}}\right)^2 + \left(\frac{y}{V_0}\right)^2 = 1, \ x = V_p \sin \theta, \ y = V_p \cos \theta \ \text{hence:} \ y^2 = -\left(\frac{V_0}{V_{90}}\right)^2 x^2 + V_0^2$$

$y^2$ is plotted with $x^2$ so that a linear equation is obtained $y = ax + b$, with $a = -\left(\frac{V_0}{V_{90}}\right)^2$, $b = V_0^2$ whereas $V_{90} = V_0(1 + \varepsilon)$, hence

$$a = -\left(\frac{V_0}{V_{90}}\right)^2 \text{ and } \varepsilon = \frac{1}{\sqrt{a}} = 1$$

(10)

Whereas, $x$ and $y$ are velocity component. $V_0$ is P wave velocity value near vertical, so $V_{90}$ is the biggest velocity value at an angle 90 degree.

2.5. Synthetic forward modelling

The second process is validity of the VVO method on synthetic models for estimating anisotropy parameters. Acquisition is done by entering epsilon and delta anisotropy values and each lithological layer is given velocity. Through the synthetic model will be known the value of anisotropy parameters. If the value is appropriate will be applied to the actual data.

3. Results and discussion

3.1. Velocity analysis

Through the velocity analysis process, a section of the NMO correction result is obtained which shows the form of an anticline that describes the subsurface as shown in figure 4. While in figure 5 shows a section of anisotropy $\eta$. The section of anisotropy $\eta$ shows there is a considerable increase in certain areas. The increase is due to the anisotropy effect which is of different magnitude.

Banik explains that the value of $\varepsilon$ is much associated with the existence of lithology [7]. Whereas $\delta$ is an anisotropy parameter near vertical direction for P wave, which plays a role when data processing.
Herawati said that in the VVO method the selection of NMO velocity is more instrumental in determining the accuracy of the value of $\delta$, while the estimation of the value of $\varepsilon$ is more stable against NMO velocity variations [8]. Sayers says that the adjustment of the contact region between the clay and the degree of interference in the orientation of the clay make $\delta$ is sensitive [9]. Therefore, anisotropy parameter parameter itself can be negative and positive.

3.2. Residual moveout
The results of the calculation of the residual moveout obtained are correlated with the offset so that it shows there is no residual increase in the initial offset at CDP 3334 (below offset 1500). This is because the accuracy of the selection of the velocity and layer is assumed to be isotropy so that the gather looks straight. In contrast to the reflector at the far offset which shows residual increase where the farther the offset the residual increases due to the effect anisotropy as seen in figure 6a.
Likewise, through the correlation between residuals and angles, the effect of anisotropy can be seen as in figure 6b where the residual increase occurs after an angle of 30 degrees and there is no change at an angle below 30 degrees.

3.3. Anisotropy parameter

The anisotropic $\delta$ can be known after velocity gradient can be calculated through linear approach. Thomsen explains from his study that group velocity is not the same as phase velocity [6]. If the group velocity is the same as phase velocity, then the medium is considered isotropy. In the case of anisotropy, group velocity is different from phase velocity due to differences in angular variations, so for simplification in the VVO method, phase velocity can be approximated by group velocity and phase angle can be approximated by group angles based on weak anisotropy with a value of $\varepsilon < 0.2$ and $\delta < 0.2$.

The parameter $\varepsilon$ is obtained from the elliptic approach through the correlation of the $x^2$ and $y^2$, so that from the assumption the ellipse curve is obtained linear equation component $\theta$. Therefore, it can be concluded that the estimated anisotropic parameters of $\delta$ and $\varepsilon$ use linear equations. Details of the estimation of anisotropy parameters that have been known from the processing in table 1.

Alkhalilah et al. found the equation of anisotropy parameters $\eta$ as follows [10]:

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

(11)

This equation involves $\varepsilon$ and $\delta$ so that the $\eta$ value can be known which $0.083$. While based on velocity analysis, there is a hockey stick because anisotropy can be straightened with a value of $\eta = 0.082$ (around 8.2%). The calculation results obtained by the equation are not much different from the values $\eta$ velocity analysis. This value is in accordance with Thomsen who stated in his research that for weak anisotropy is worth 10–20 percent [6].

Figure 6. (a) Residual moveout and offset (b) Residual moveout and angle.

| Table 1. Anisotropy parameter information |
|------------------------------------------|
| Information                  | Value  |
|-----------------------------|--------|
| Elliptic approach result    |        |
| Gradient                   | -0.768 |
| $\varepsilon$               | 0.14   |
| Linearity approach          |        |
| Gradient                   | 113.19 |
| $\delta$                    | 0.049  |
| $V_0$ (m/s)                 | 2317.5 |
| Angle                       | > 30   |
4. Results validation

The results validation is done using forward synthetic modeling, where the anisotropy layer is located between 1200–1300m depth. Acquisition is done with stretch distance is 2800 and by entering anisotropic parameter value $\varepsilon = 0.14$ and $\delta = 0.046$. After the moveout process, the gather form is obtained as shown in figure 7, where there is an upward curve or a hockey stick in the target layer.

In the BS field is known to have lithology such as shale, coal, limestone and shaly sand. As is known that shale and coal can cause anisotropy. Based on this, through gamma ray logs and anisotropic parameters $\eta$ seismic data the presence of anisotropy can be seen. Certain depths are selected in the gamma ray log which approaches the target layer and together with the $\eta$ anisotropy parameter (figure 8). The gamma ray log in time 1.22 until 1.23 which is a coal layer is seen to have very high anisotropy value. The results can be seen that the coal seam is very thin so that it can cause anisotropy. Whereas in the other layer in time 1.19 until 1.2 which is a shale layer have anisotropy with a small value.

The effect of anisotropy on the shale, shaly sand has a value below coal around 2–3 %, so that from the data can analyzed based on the lithology in the area that the coal has a greater influence than the others.

![Figure 7. Gather image which has anisotropy effect.](image)

![Figure 8. (a) Log gamma ray, synthetic model, (b) Anisotropy parameter $\eta$.](image)
5. Conclusion
Through the process of data processing on research that has been done by using the VVO method and its application on synthetic forward modeling and in the field of research it can be concluded several things as follows: The anisotropy estimation results obtained from seismic data on the target medium is covered with a wave of $\delta = 0.049$, $\varepsilon = 0.14$ and after validation obtained $\delta = 0.046$, $\varepsilon = 0.14$. The results of anisotropy parameter estimation $\eta$ processing of seismic data and synthetic modeling are not so different that the calculation is said to be sufficiently precise where the value obtained from the velocity analysis is 0.082, the processing calculation is 0.083 and the synthetic model is 0.086. From the lithology that is known to have anisotropy influence, shale, shaly sand and coal, that coal has anisotropy effect with a greater value that is around 8% while shale and shaly sand is around 2–3%.

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