Estimation of Seismic Anisotropy Parameter and AVO Modeling of Field “G”

M S Rosid1,*, GR Samosir1, and HPurba2

1Physics Department, FMIPA Universitas Indonesia, Depok 16424, Indonesia
2PPTMGB, LEMIGAS Jakarta, Indonesia

*E-mail: syamsu.rosid@ui.ac.id

Abstract. Conventional seismic model assumed that seismic wave propagates within subsurface rock at the same velocity in all direction. The rock assumed as medium isotropic. In fact, the earth has a complex structure. The seismic wave actually does not propagate as ideal as within isotropic medium. Seismic anisotropy is defined as dependence of seismic velocity upon angle. The purpose of this study is to estimate the anisotropy parameters or Thomsen parameters of ε and δ for both reservoir and shale layer. The parameters have been estimated on the field “G”. It was done using well logs from 7 wells, including P-wave sonic log and the inclination angle of the wellbore. The velocity from the sonic log and the inclination angle were applied to a second order polynomial equation, which includes the anisotropy parameters. The Matlab software was utilized to perform the calculations of anisotropy parameters, while Microsoft Excel was utilized to plotting velocity versus inclination angle. The result of anisotropy parameters at reservoir is -0.2 – 0.8 for ε and -1.52 – 0.4 for δ. While the result at shale layer is -1.77 – 1.81 for ε and -1.31 – 1.44 for δ. The parameters were also applied in an AVO analysis for all wells to perform both the anisotropic and isotropic cases. The anisotropic was compared to the isotropic rocks by plotting reflection coefficient with incidence angle. Plotting the comparison shows that the difference between the isotropic and anisotropic case will begin to appear at small incidence angle and will be more noticeable at large incidence angle or at far offset.

1. Introduction

The conventional seismic model assumed that seismic waves propagate on the earth’s surface with the same velocity values in each direction. In fact, the earth has a complex structure and essentially anisotropic. This is caused by the many variations in stress due to the movement of the earth’s mantle and crust. Anisotropic elasticities on the earth’s surface are caused by folds or fractures, or because of the presence of rock layers in sedimentary formations (clay, sandstone). The fracture is caused by stress inside the earth. So that seismic waves do not actually propagate as ideal as in an isotropic medium. Seismic waves propagate at varies velocity depend on the direction. It is influenced by the anisotropic characteristic of the rock medium [1].
There are two types of anisotropy rock, intrinsic and induced. Intrinsic anisotropy is the result of preferential orientation of the sediment grains and pores that can be created by sediment composition, grain size and shape, and deposition, whereas induced anisotropy is caused by the strain associated with applied stress, fractures, and diagenesis [2]. There are also two styles of alignment in earth materials, horizontal with vertical axis of symmetry and vertical with horizontal axis of symmetry. These two types of alignments (symmetries) give rise to two types of anisotropy: transverse isotropic with vertical axis of symmetry (VTI) and transversely isotropic with horizontal axis of symmetry (HTI). Two oversimplified but convenient models have been created to describe how elastic properties, such as velocity or stiffness, vary in the two types [3].

In this study, anisotropy parameters or commonly called Thomsen parameters are obtained from well data. The Thomsen parameters are $\varepsilon$ (epsilon), $\delta$ (delta) and $\gamma$ (gamma) [4]. These parameters are the representation of the elastic tensor constant that obtained from the stress and strain in Hooke’s Law. In this study, we would like to estimate $\varepsilon$ and $\delta$ in detail. Then, AVO analysis will be performed for the anisotropic case and the isotropic case for comparison. This will lead us to an indication of how important the anisotropy parameters are in AVO analysis.

Amplitude Versus Offset (AVO) is one of the few exploration methods that is widely used to detect hydrocarbons, and lithology identification. The reflection coefficient depends on the angle of reflection, or the offset between the source and receiver, and the difference between the P and S wave velocities on both sides of the reflector. The presence of elastic anisotropy on both sides of the reflector can significantly distort the angular dependence on the reflection coefficient [5]. The amplitude is not only affected by the offset, but also by the presence of anisotropy in subsurface so that the dependence of velocity on the angle will affect changes in amplitude to reflectivity, as well as changes in reflectivity to offset.

2. Methodology

2.1 Thomsen Parameters for Weak Elastic Anisotropy

Thomsen proposed the notation for transverse isotropic materials for weak anisotropy. Three constants are known as Thomsen parameters which are shown in the following equation [4],

$$\varepsilon = \frac{c_{11} - c_{33}}{2c_{33}}$$  

(1)

$$\gamma = \frac{c_{66} - c_{44}}{2c_{44}}$$  

(2)

$$\delta = \frac{(c_{13} + c_{44})^2 - (c_{33} - c_{44})^2}{2c_{33}(c_{33} - c_{44})}$$  

(3)

$\varepsilon$ is expressed by $C_{11}$ and $C_{33}$, according to Hornby, et al. [6], the following equation will be,

$$C_{11} = \rho V_{PH}^2$$  

(4)

$$C_{33} = \rho V_{PV}^2$$  

(5)

then,
Walsh et al. [7] stated that the P-wave velocity will increase from the vertical direction to the horizontal. It indicates the value of $\varepsilon$ is always positive. In an anisotropic medium, the P-wave velocity perpendicular to bedding ($V_{PV}$) tends to move more slowly because it penetrates several layers which are absorbing layer. While the parallel P wave velocity to bedding ($V_{PH}$) will move faster because it only propagates in one layer.

Because rock formation is a weak anisotropic in general, Thomsen also gives a simpler equation of phase velocity for P-waves by giving a small value for the $\varepsilon$, $\delta$ and $\gamma$ parameters [8]. This linear equation is known as the weak polar anisotropy velocity which is expressed as:

$$V_p(\theta) \approx \alpha(1 + \delta \sin^2 \theta \cos^2 \theta + \varepsilon \sin^4 \theta)$$

where $V_p$ is the phase velocity, $\alpha$ is the vertical P-wave velocity (the same as $V_{PV}$), $\varepsilon$ and $\delta$ are the previously defined anisotropy parameters and $\theta$ is the angle of the wave vector relative to the $x_3$-axis, which is also called the incidence angle [8].

To solve the equation (7) for $\varepsilon$ and $\delta$, the equation can be compared to the second order general equation of

$$y = A + Bx + Cx^2$$

where $y$ indicates a function, $A$, $B$ and $C$ are constants and $x$ is the variable. Comparing equation (8) with equation (7) where $y = V_p(\theta)$ and $x = \sin^2 \theta$, gives equation $A = \alpha$, $B = \alpha \delta$, and $C = \alpha (\varepsilon - \delta)$. Based on the previous equation, the value of $\varepsilon$ dan $\delta$ are:

$$\delta = \frac{B}{A}$$

$$\varepsilon = \frac{B + C}{A}$$

Equation (7) was used to estimate the anisotropy parameters. In this equation, the phase velocity, P-wave velocity, and incidence angle, are needed to estimate the anisotropy parameters. $V_p$ is assumed to be the velocity obtained from the sonic log and $\theta$ is the inclination angle of the well. Thus, P-wave sonic log and the inclination angle log are needed to estimate the anisotropy parameters. As the purpose of this study is to find out how anisotropy affecting an AVO analysis, the logs were exported in intervals for the reservoir and shale layer.

2.2 Amplitude Versus Offset (AVO)

2.2.1 AVO for Isotropic Case

The equation used to calculate the reflection coefficient as a function of the incidence angle is the 3-term Shuey equation. This equation is an approximation of the PP reflection coefficient from the Zoeppritz equation. Equations for the isotropic cases are [8]:

$$R_p(\theta) = R_0 + R_2 \sin^2 \theta + R_4 \sin^2 \theta \tan^2 \theta$$
where, $R_p$ is the P-wave reflection coefficient and $\theta$ is the incidence angle.

\[
R_0 = \frac{1}{2} \left[ \frac{\Delta V_P}{V_p} + \frac{\Delta \rho}{\rho} \right]
\]  

(12)

\[
R_3 = \frac{1}{2} \left[ \frac{\Delta V_P}{V_p} - \frac{4V_S^2}{V_p^2} \left( \frac{\Delta \rho}{\rho} + \frac{2\Delta V_S}{V_S} \right) \right]
\]  

(13)

\[
R_4 = \frac{1}{2} \left[ \frac{\Delta V_P}{V_p} \right]
\]  

(14)

where $V_p$, $V_s$, and $\rho$ is the average of P-wave velocity, average of S-wave velocity, and average of density over an interface, respectively. And $\Delta V_P$, $\Delta V_S$ and $\Delta \rho$ are the change over an interface for each P-wave velocity, S-wave velocity and density, respectively.

2.2.2 AVO for Anisotropic Case

Equations for anisotropic case are also the 3-term Shuey equations [8];

\[
R_p(\theta_w) = R_0 + R_2 \sin^2 \theta_w + R_4 \sin^2 \theta_w \tan^2 \theta_w
\]  

(15)

where, $R_p$ is P-wave reflection coefficient and $\theta_w$ is the wavefront angle. The incidence angle is assumed to be equal to the wavefront angle, and

\[
R_0 = \frac{1}{2} \left[ \frac{\Delta V_{P0}}{V_{P0}} + \frac{\Delta \rho}{\rho} \right]
\]  

(16)

\[
R_2 = \frac{1}{2} \left[ \frac{\Delta V_{P0}}{V_{P0}} - \frac{4V_{S0}^2}{V_{P0}^2} \left( \frac{\Delta \rho}{\rho} + \frac{2\Delta V_{S0}}{V_{S0}} \right) + \Delta \delta \right]
\]  

(17)

\[
R_4 = \frac{1}{2} \left[ \frac{\Delta V_{P0}}{V_{P0}} + \Delta \epsilon \right]
\]  

(18)

where $V_{P0}$ is the average of P-wave velocity over an interface, $V_{S0}$ is the average of S-wave velocity over an interface and $\rho$ is the average of density over an interface. $\Delta V_{P0}$, $\Delta V_{S0}$ and $\Delta \rho$ is the change over an interface for each P-wave velocity, S-wave velocity and density, respectively. $\Delta \epsilon$ and $\Delta \delta$ are the changes across an interface in the anisotropy parameters.

3. Results and Discussion

3.1 Estimation of Anisotropy Parameters

The value of P-wave velocity and inclination angle has been plotted, adjusted for the second order polynomial function and compared to equation (7). The equation represents the phase velocity of the P-wave. The plot shows the velocity vs inclination angle for the reservoir and shale layer can be seen in the following figure:
Figure 1. The velocity values versus inclination angle from the (a) well G1, (b) well G2, (c) well G3, (d) well G4, (e) well G5, (f) well G6 and (g) well G7 for the reservoir layer.
Figure 1 shows the velocity plot vs the inclination angle for the reservoir layer of all wells G. From the curve, there are two conditions where the velocity decreases and increases against the inclination angle. Clean sand is isotropic, but in reality it is rare to find a clean sand layer, because it usually contains clay minerals which can affect reservoir quality. Sand is anisotropic if the sand has cracks, layered and contains clay. Sand is actually an induction anisotropic type, because randomly oriented clay granules will be rotated horizontally caused by compacting and also the accumulated weight of increased sediment (due to diagenesis process), the rotated granules will form rock fabric that shows elastic anisotropy.
Figure 2 show the plot of velocity against the inclination angle for the shale layer of G wells. From the curve, the condition of increasing the velocity versus the inclination angle is more dominant than the decreasing ones. Norris and Shinha said that positive signs in anisotropy parameters indicate the medium of Transversely Isotropic (TI) [9]. Then there are several wells that have a negative sign on the anisotropic parameters, it indicates the TI medium is formed by microlayering mineral clay on shale. Then according to Sayers et al., the + or - sign from $\delta$ can be understood by relating it to the level of disorder clay particles contained in the shale[10]. When the sign is positive, clay particles are not parallel or misaligned, while when the sign is negative, clay particles are well aligned.

**Table 1.** An overview of the anisotropy parameters, $\varepsilon$ and $\delta$ for the reservoir in all wells.

| Well | $\varepsilon$ | $\delta$ |
|------|--------------|---------|
| G-1  | -0.7         | 0.4     |
| G-2  | 0.8          | -0.056  |
| G-3  | -0.27        | -1.58   |
| G-4  | -0.68        | -1.6    |
| G-5  | -0.36        | -1.52   |
| G-6  | -0.2         | -0.8    |
| G-7  | 0.7          | -0.3    |

**Table 2.** An overview of the anisotropy parameters, $\varepsilon$ and $\delta$ for the shale layer in all wells.

| Well | $\varepsilon$ | $\delta$ |
|------|--------------|---------|
| G-1  | 1.36         | 0.7     |
| G-2  | 1.81         | 1.44    |
| G-3  | 0.3          | -0.42   |
| G-4  | 0.64         | 0.2     |
| G-5  | -0.87        | -1.31   |
| G-6  | -0.59        | -1.1    |
| G-7  | 1.77         | 1.35    |
It seen from equation (6), the value of the $\varepsilon$ parameter is always positive. Because in an anisotropic medium, the P-wave velocity that perpendicular to bedding ($V_{PV}$) tends to move more slowly. While the P-wave velocity that propagates parallel to bedding ($V_{PH}$) will move faster. However, it will be an anomaly when the P-wave propagates on the rotated layer towards the axis. Where if the angle more than 45°, then the $\varepsilon$ parameter will be negative. From equation (6), $V_{PV}$ will be greater than $V_{PH}$ which causes the $\varepsilon$ parameter to be negative since $V_{PV}$ is related to sin and $V_{PH}$ is related to cos (in the case of rotated layers towards the axis). The greater the angle value, then the greater the $V_{PV}$ value and the smaller $V_{PH}$ value. This only applies when the angle is 45° - 90°. Then, if the degree of slope of the layer structure is in the interval 0 - 45°, then the $\varepsilon$ parameter will be positive. Because in the interval 0 – 45°, $V_{PH}$ will be greater than $V_{PV}$ because $V_{PH}$ is related to cos. Therefore, by knowing the $\varepsilon$ parameter value, we can also determine the degree of slope (dip) of the subsurface structure.

3.2 AVO Modelling
The AVO analysis was applied for isotropic and anisotropic case. These formula are approximate solution for how the reflection coefficient of the P wave varies with the incidence angle (3-term Shuey equation). For the anisotropic case, $\varepsilon$ and $\delta$ are needed for reservoir and shale layer. The values of these two parameters can be seen in table 1 and table 2. Figure 3 shows the plot of incidence angle versus reflection coefficient for the isotropic case and anisotropic case in wells G.
These figures show when zero incidence angle the reflection coefficient is positive and has a value of about 0.015 - 0.2 in both cases isotropic and anisotropic. The amplitude (absolute value of the reflection coefficient) has decreased with respect to the incidence angle for both cases isotropic and anisotropic. Seen from the curve, the intercept value of the $R_0$ amplitude is small and then decreases against increasing offset or incidence angle until it becomes negative, and some wells remain in the positive range. The two curves coincide when the angle is small, but will start to deviate when the angle is around $3^\circ - 10^\circ$. The fact that the curve will coincide with zero offset can be seen in equation (15), where the first form is ignored, because it does not contain anisotropic parameters. Anisotropic parameters only exist in the second and third forms.

$\Delta \varepsilon$ and $\Delta \delta$ illustrate the differences of anisotropic parameters when across the interface. $\Delta \delta$ is related to $\sin^2 \theta$ and explained the effect of anisotropy on the small incidence angle of the reflection coefficient and slope of the AVO curve. While $\Delta \varepsilon$ is related to $\sin^2 \theta \tan^2 \theta$ and shows that the parameter is dominant when the incidence angle is large. This shows that $\delta$ parameter controlling the effect of anisotropy on an almost vertical P-wave and $\varepsilon$ parameter controlling the effect of anisotropy on an almost horizontal P-wave. The influence of $\varepsilon$ and $\delta$ on AVO has been tested by Kim et al.[11] based on the derivation by Thomsen [4] about variation of phase velocity as a function of the incidence angle of the AVO. The phase velocity is one of the important factors controlling the reflectivity of the transverse isotropic medium.

Figure 3. AVO plot for both the isotropic and anisotropic case in (a) well G1, (b) well G2, (c) well G3, (d) well G4, (e) well G5, (f) well G6 and (g) well G7. The reflection coefficient is unitless and $\theta$ incidence angles is in degree.
4. Conclusion
We can conclude our result that anisotropy parameters in the Field “G” for reservoir layer is in range of -0.2 – 0.8 for $\varepsilon$ and -1.52 – 0.4 for $\delta$. Then, anisotropy parameters in shale layer is in range of -1.77 – 1.81 for $\varepsilon$ and -1.31 – 1.44 for $\delta$. If the parameter $\varepsilon$ is negative, then the degree of dip is expected to be between $0^\circ$ – $45^\circ$. Whereas if the parameter $\varepsilon$ is positive, the degree of dip is expected to be between $45^\circ$ – $90^\circ$. When applying the anisotropy parameters in the AVO analysis, the difference between isotropic and anisotropic cases will begin to appear at incidence angle of $2^\circ$ – $5^\circ$ and will be more seen at large incidence angle or at a far offset.

Acknowledgements
We many thank PPTMGB LEMIGAS for permission using the data for this study. Thanks also to DRPM Universitas Indonesia for financial support of PITTA’s grant No: 2279/UN2.R3.1/HKP.05.00/2018.

References
[1] Haktorson H 2012 Estimation of Anisotropy Parameters and AVO Modeling of the Troll Field, North Sea PhD Thesis Norwegian University of Science and Technology
[2] Wang Z 2002 Seismic Anisotropy in Sedimentary Rocks, part 2: Laboratory Data Geophysics 55 pp. 1070-1088
[3] Melaku M T 2007 Velocity Anisotropy of Shales and Sandstones from Core Samples and Well Logs on the Norwegian Continental Shelf PhD Thesis University of Oslo
[4] Thomsen L 1986 Weak elastic anisotropy Geophysics 51 pp. 1954-1966
[5] Banik N C 1987 An effective parameter in transversely isotropic media Geophysics 52 pp.1654-1664
[6] Hornby BE, Howie JM, and Ince D W 2002 Anisotropy correction for deviated-well sonic logs: application to seisimk well tie Geophysics 68
[7] Walsh J, Sinha B, and Donald A 2006 Formation anisotropy parameters using borehole sonic data SPWLA 74th Annual Logging Symposium
[8] Thomsen L 2002 Understanding Seismic Anisotropy in Exploration and Exploitation Society of Exploration Geophysicists and European Association of Geoscientists & Engineers Tulsa
[9] Norris A N, and Sinha B K 1993 Weak Elastic Anisotropy and the Tube Wave Geophysics 58 pp. 1091-1098
[10] Sayers C M, Van Munster J G, and King M S 1990 Stress-induced ultrasonic anisotropy in Berea Sandstone Internat. J. Rock Mech. Min. Sci. & Geomech. Abstr., 27 p. 429-436
[11] Kim Y K, Wrolstad K H, and Aminzadeh F 1993 Effects of transverse isotropy on P-wave AVO for gas sands Geophysics 58 pp. 883–888