Determination of seismic anisotropy parameters using phase slowness method in one of Iranian Oil Fields

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Abstract

Primary assumption in most problems of elasticity theory in petroleum geophysics is that the elastic media is isotropic. Laboratory experiments confirmed that most rocks are anisotropic. If in one medium, properties vary with directions, it is named as anisotropic. Knowledge about anisotropy reduces risk and cost of hydrocarbon production. In the present study, anisotropy of a carbonate reservoir in southwest of Iran has been evaluated based on available walkaway vertical seismic profile (VSP) data. First break times have been picked and using horizontal and vertical slowness concept anisotropic module is computed. Direct arrival times and slowness from wide–aperture walkaway VSP data acquired in a layered anisotropic medium is processed to find a direct estimate of the phase slowness surface associated with the medium at the depth of the receivers. The slowness surface fits by an estimated transversely isotropic medium with a vertical symmetry axis (a "Vertical Transverse Isotropic (VTI)" medium). While the method requires that the medium between the receivers and the surface be horizontally stratified, no further measurement or knowledge of that medium is needed. The results show that this method provides the accuracy in the range of qualified accuracy with absolute errors of about 0.01 and 0.025 for Thomson's anisotropy parameters ε and δ, respectively.

Keywords: Anisotropy, Walkaway VSP, Phase slowness.

1– Introduction

In seismic exploration geophysics, send seismic waves into the subsurface and record the reflected energy at the surface using receivers. After processing the reflected energy, the shapes and characteristics of underground structures have been identified. In petroleum exploration, techniques of seismic surveying include the seismic reflection method and vertical seismic profiling (VSP) technique. Many models of exploration seismology assume that the earth is isotropic, and seismic velocities do not vary with direction. But, in fact, crystals and most common earth materials are observed to be anisotropic with elastic parameters (Shearer, 1999). Furthermore, it is experimentally proved that most upper crustal rocks are anisotropic (Crampin, 1981) and in addition anisotropy is evident in many other parts of the earth (Shearer, 1999). When the wavelength of seismic wave is larger than the thickness of layers (isotropic or anisotropic), layers will also show anisotropy.

White and Sengbush (1953) discussed measuring seismic velocities at shallow depths (low velocity layers). Postma (1955) showed the scale of layering than the wavelength of seismic signal for making anisotropy. Generally, he proved effect of anisotropy for the first time. Jolly (1956) reported SH–waves in horizontal directions move faster than Sv waves in vertical directions. Backus (1962) determined approximate equations for the variation of the P–wave velocity as a combination of elastic constants. Helbig (1964) discussed about variation of velocity in medium with elliptical anisotropy. Levin (1978) studied the travel time equations and analyzed their accuracy based on their derivatives. Berryman (1979) during the research into anisotropic medium examples found that shear waves having much stronger anisotropic behavior than compressional waves. Basic promotions on anisotropy topics are announced by Thomsen's paper (1986). At first glance, in a vertically transverse isotropic (VTI) media, it didn't make any special changesin the known equations that describe the velocities of waves propagating. In fact, parameters ε, δ and γ define combinations of the stiffness coefficients belong to quantities as normal–move out (NMO) velocities and amplitude versus offset (AVO). Martin and Davis (1987) reported that sedimentary rocks are anisotropic by experiments on shear waves velocity and compressional wave velocity. Grechka *et al*. (1999), Alkhalifah (1994), Tsvankin *et al*. (1994, 1995, 1996 and 2001) and Daley *et al*. (1977, 1979 and 2004) have done significant contributions to the field. For combination effect of the anisotropy parameters into seismic processing firstly its quantitation shall be done. The ratio between horizontal and vertical velocities is quantitated by measurement of P–wave anisotropy, varies normally ranging from 1.05 – 1.1, but sometimes their magnitude are 1.2 (Sheriff 2002). Recently Thomsen's parameters ε, δ and γ exactly describe anisotropy; ε and δ determine P– and SV–wave anisotropy, while γ describes SH–wave anisotropy. Significant research has been carried out in the determination of ε and δ from surface seismic and borehole measurements. Usual methods are considered such as move–out and travel time equations (e.g., Alkhalifah and Tsvankin, 1995; Grechka and Tsvankin, 1998a, b; Grechka and Tsvankin, 1999; Grechka *et al*.., 2001) or joint converted waves and compressional waves (e.g., Sayers, 1999; van der Baan and Kendall, 2002).

2– Anisotropy parameters

Equations are developed for the travel time in a VTI medium; the next sections explained physical understanding of the anisotropy parameters. For most sedimentary rocks, the parameters ε, γ and δ are usually less than 0.2. Field data and experiments indicated that horizontal shear waves (SH) velocity and compressional waves' velocity in isotropic plane are larger than those in the symmetry axis direction. Therefore, for the most crustal rocks the anisotropy parameters are positive. But it is possible for the anisotropy parameters to have negative values (Thomsen, 1986).

2–1– Epsilon (ε)

A physical meaning for the anisotropic parameter ε can be explained when considering the special case of horizontal event. By setting the angle θ equal 90 degrees,

$$v_p(\theta) = \alpha_0(1 + \delta\sin^2\theta\cos^2\theta + \varepsilon\sin^4\theta) \qquad (1)$$

$$\varepsilon = \frac{v(90) - v(0)}{v(0)} \qquad (2)$$

Where $v_{(0)}$ the vertical P–wave velocity and $v_{(90)}$ is the horizontal P–wave velocity. This parameter is a quantity of the anisotropic behavior of a rock and a measure of the fractional difference between the horizontal and vertical velocities (Figs 3 and 4). When a seismic wave propagates in a TI media at angles nearly perpendicular to the axis of symmetry the parameter ε dominates the *P*–wave velocity (Brittan *et al*., 1995). However, for relationship between group and phase velocities in a TI media used parameter ε in combination with δ.

2–2– Delta (δ)

For gaining physical understanding of δ, one can say that a critical factor controls the near vertical response and it determines the shape of the wavefront (Thomsen, 1986). If in equation (1) the angle θ be equal to 45 degrees and invoke equation (2) for ε then δ evaluates as,

$$\delta = 4\left[\frac{v\left(\frac{\pi}{4}\right)}{v(0)} - 1\right] - \left[\frac{v\left(\frac{\pi}{2}\right)}{v(0)} - 1\right]. \qquad (3)$$

When a *P*–wave propagates about parallel to the symmetry axis, the parameter δ dominates the anisotropic response. It can take on both positive and negative values; therefore it is not a function of the velocity normal to the axis of symmetry (Brittan *et al*., 1995). The parameter δ may be used to relate the group and phase velocities within an anisotropic media and is the controlling parameter for the NMO of compressional waves in a horizontally layered media.

3– Data of the oilfield

There are numerous methods for acquiring a vertical seismic profile (VSP). Zero–offset VSPs (A) has sources close to the wellbore directly above receivers. Offset VSPs (B) have sources some distance from the receivers in the wellbore. Walkaway VSPs (C) feature a source that is moved to progressively farther offset and receivers held in a fixed location. Walk–above VSPs (D) accommodate the recording geometry of a deviated well, having each receiver in a different lateral position and the source directly above the receiver .

A walkaway VSP has been run in this field in order to obtain a good time/depth relationship for 2D seismic and better understanding of the formations and recognition of the probable faults in this area is achieved.

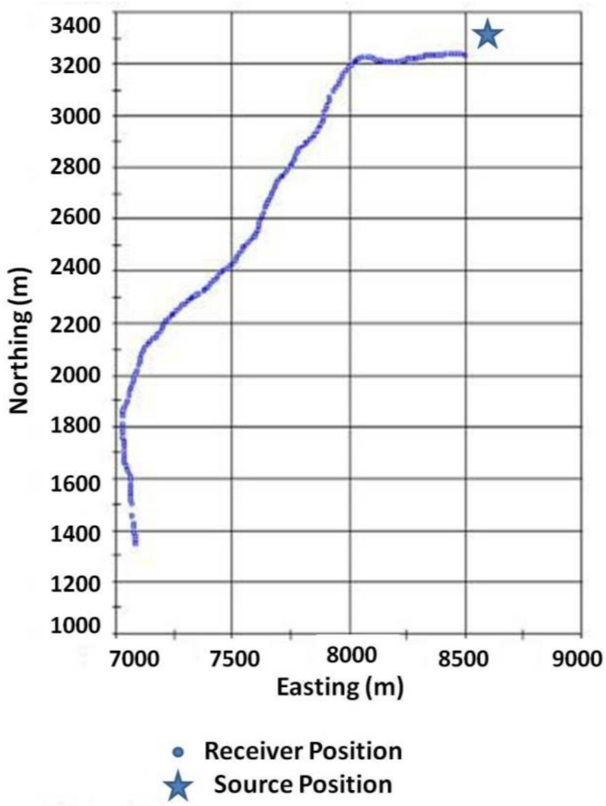

Figure 1) The coordinates of shot line of the Walkaway VSP in the oil field

Figure 2) Topography of the survey area

Figure 1 shows the position of well together with the shot positions. Furthermore, topography of the earth in this area is not uniformed (Fig. 2), therefore, static correction should be applied to the data. According to the fact that the shot line is not horizontal, the problem may arise about the plane wave assumptions.

4– Methodology

Determination of anisotropy be made using seismic data, and they can be used in various ways estimate anisotropy parameters. Phase slowness is one of these ways that has been applied in Iran to determine the existence of anisotropy (White *et al*., 1983; Gaiser, 1990).

4–1– Phase slowness method

This method use walkaway VSP data measured in a layered anisotropic media for giving an estimate of direct arrival times and the phase slowness in the surface associated with the media at the depth of the receivers. So, we can fit this slowness surface by an estimated transversely isotropic media with a vertical axis of symmetry (a "VTI" media). While the media between the receivers and the surface be horizontally stratified, no further knowledge of that media is required for this method.

Assuming that the medium is laterally homogeneous and elliptically anisotropic, the amplitude and the direction of the phase velocity $v_{ph}(\theta)$ will be calculated by the equations:

$$v_{ph} = (S_x{}^2 + S_z{}^2)^{-1/2} \qquad (4)$$

$$\theta = \arctan\left(\frac{S_x}{S_z}\right) \qquad (5)$$

where θ is the phase angle, S_x is horizontal slowness and S_z is vertical slowness (Figs. 3 and 4).

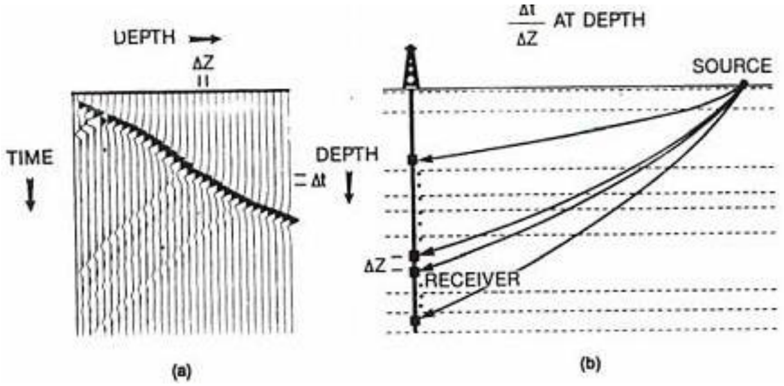

Figure 3) Vertical slowness

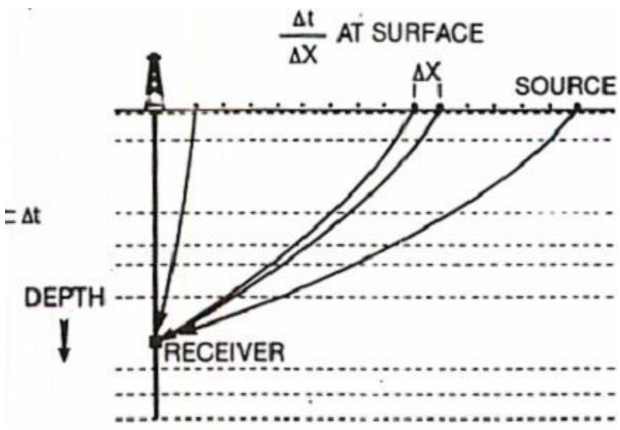

Figure 4) Horizontal slowness

5– Procedure

In this section, at first, we construct the model of slowness, and then, analyze this model and finally, these results in the range of the accepted accuracy are to be represented.

5–1– Constructing the slowness curves

For constructing the slowness curve, first arrival of the direct *P*–wave should be picked. If the arrival times of the third and first receiver levels are subtracted, the vertical slowness is measured at the second receiver level. In general,

$$S_{zi} = \frac{\mathrm{Time(i+1)-Time(i-1)}}{\mathrm{Depth(i+1)-Depth(i-1)}}. \qquad (6)$$

There is the same way except that the data should be arranged in common receiver gather i.e. all the data shares the same receiver position but the source offset is different.

$$S_{xi} = \frac{\mathrm{Time(i+1)-Time(i-1)}}{\mathrm{Offset(i+1)-Offset(i-1)}} \qquad (7)$$

In the cases that there is a deviated well, correction should be made for vertical slowness because the calculated slowness is apparent slowness (Sa) and Sa is the dot product between slowness vector (S) and receiver orientation (n).

$$S_a = S_z\cos\Phi + S_x\sin\Phi\cos\varphi \qquad (8)$$

Where *Φ* is the deviation angle and *φ* is angle between well trajectory and shot line.

5–2– Preparation of the data

In this section, the real data will be investigated using phase slowness method. Care should be taken with regard to that this method is a local method i.e. the parameters that are obtained are applicable for the depths in which the geophones exist. For the depths above the depths of geophones, one way is to do tomography inversion.

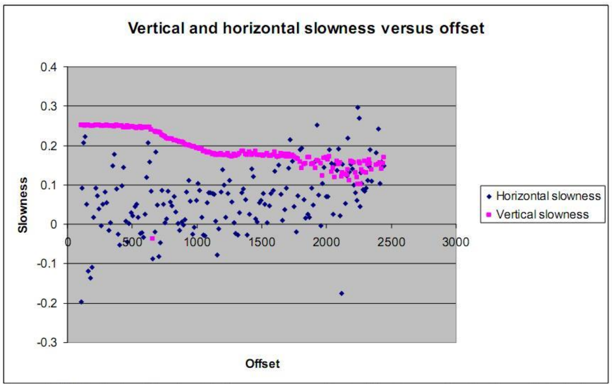

Figure 5) Vertical and horizontal slowness versus offset without correction for the well deviation

Slowness curves have been constructed using equations (6) and (7) (Fig. 5). The well is deviated about 14 degrees in the receivers locations, therefore, correction should be applied to the vertical slowness using equations (8) (Fig. 6) shows slowness data in which the correction for deviation has been applied. The data is not suitable for the phase slowness method since as can be seen from the (Figs. 5 and 6) the slowness does not obey desirable direction, which is necessary for this method. Nevertheless, the inversion has been carried out and the results are in Table 1.

There is a dip of 6–degree in the overburden, therefore, according to the synthetic model the absolute value error of 0.05 should be considered for ε and δ. Thus, the results obtained from this method would not be correct.

6– Results

The results have been shown as vertical slowness and horizontal slowness curves versus offset without any correction (Figs. 5 and 6). The well is deviated about 14 degrees in the receiver location, therefore, correction should be applied to the vertical slowness using equation (8). As can be seen from Figure 6a, vertical slowness with correction lose its continuity. Result after inversion is shown in this table. Absolute values of Thomson parameters must be less than 0.2. These are in acceptable range.

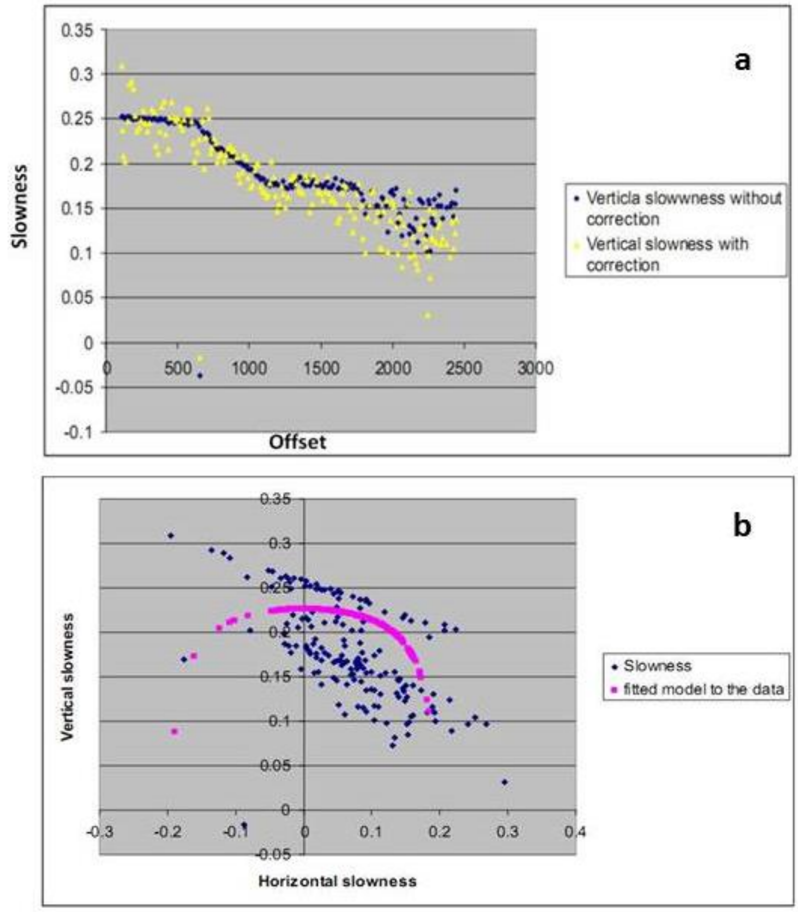

Figure 6a) Vertical slowness with and without correction. b) Fitted model to data.

7– Conclusions

There are different methods for determination of anisotropy parameters from seismic data. One of these is applied in an area in SW of Iran by phase slowness method. This method use direct arrival times and slowness from wide–aperture walkaway VSP data acquired in a layered anisotropic medium. After applying the method, the output is direct estimate anisotropy parameters that are explained above.

The following conclusions can be extracted from the research work presented in this paper:

1– Phase slowness method is precise for ε in horizontal layers with absolute value error of 0.01 δ is not accurate from this method and there is at least an absolute value error of 0.025. Therefore, it is better not to trust the δ obtained from this method.

2– The more the distance between geophones, the more precise is the method. From the results, it can be seen when the distance between geophones is 30m, ε is closer to the answer than the one in which receiver interval is 15.

3– The ε obtained with this method is still precise for slightly oblique–overburden. It can be reliable even if this dip is near to 6 degrees.

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References:

Alkhalifah, T., Larner, K. 1994. Migration errors in transversely isotropic media. Geophysics: 59, 1405–1418.

Alkhalifah, T.A., Tsvankin, I. 1995. Velocity analysis in transversely isotropic media. Geophysics: 60, 1550–1566.

Backus, G.E. 1962. Long–wave elastic anisotropy produced by horizontal layering. Journal of Geophysical Researchs: 67, 4427–4440.

Berryman, J.G. 1979. Long–wave elastic anisotropy in transversely isotropic media. Geophysics: 44, 896–917.

Brittan, J., Warner, M., Pratt, G. 1995. anisotropic parameters of layered media in terms of composite elastic properties. Geophysics: 60, 1243–1248.

Crampin, S. 1981. A review of wave motion on anisotropic and cracked elastic media. Wave Motion: 3, 343–391.

Dayley, P.F., Hron, F. 1977. Reflection and transmission coefficients for transverse isotropic media: Bulletin of Seismic Society of America: 69, 661–675.

Dayley, P.F., Hron, F., 1979, Reflection and transmission coefficients for seismic waves in ellipsoidally anisotropic media. Geophysics: 44, 27–37.

Dayley, P.F., Lines, L.R. 2004, Linearized quantities in transversely isotropic media. Canadian Journal of Earth Sciences: 41, 349–354.

Gaiser, J.E. 1990. Transversely isotropic phase velocity analysis from slowness estimates. Journal of Geophysical Research: 95, 11241–11254.

Grechka, V., Tsvankin, I. 1998. Feasibility of non–hyperbolic move out inversion in transversely isotropic media. Geophysics: 63, 957–969.

Grechka, V., Tsvankin, I. 2002. NMO surface and Dix type formulae in heterogeneous anisotropic media. Geophysics: 67, 939–951.

Grechka, V. 2001. Seismic anisotropy: Yesterday, today, tomorrow: CSEG Recorder: 9–10.

Helbig, K. 1964. Refraction seismics with an anisotropic overburden a graphical method of interpretation. Geophysical Prospecting: 12 383–396.

Jolly, R.N. 1956. Investigation of Shear Waves: Geophysics: 21, 9050–938.

Kendall, R.R., Gray, S., Miao, X. 2000. Anisotropic processing of converted wave data: Mahogany Field, Gulf of Mexico. SEG/EAGE Summer Research Workshop, Oct. 2000, Boise, USA.

Levin, F.K. 1978. The reflection, refraction and diffraction of waves in media with an elliptical velocity dependence: Geophysics, 43, 528–537.

Martin, M.A., Davis, T.L. 1987. Shear wave birefringence: a new tool for evaluating fractured reservoirs. The leading Edge: 6, 21–27.

Postma, G.W. 1955. Wave propagation in a stratified medium. Geophysics: 20, 780–806.

Sayers, C.M. 1999. Anisotropic velocity analysis using mode converted shear waves. Journal of Seismic Exploration: 8, 1–14.

Shearer, P.M. 1999. Introduction to Seismology. Cambridge University Press, United Kingdom.

Sheriff, R.E. 2002. Encyclopaedia Dictionary of Exploration Geophysics: Society of Exploration Geophysicists.

Thomsen, L. 1986. Weak Elastic Anisotropy. Geophysics: 51, 1954–1966.

Tsvankin, I. 1995. Normal moveout from dipping reflectors in anisotropic media. Geophysics: 60, 268–284.

Tsvankin, I. 1996. *P*–wave signatures and notation for transversely isotropic media. Geophysics: 61, 467–483.

Tsvankin, I., Grechka, V. 2001. Parameter estimation for VTI media using PP and PS reflection data, SEG Annual Meeting, September 9 - 14, 2001 , San Antonio, Texas. Society of Exploration Geophysicists, 857–860.

Tsvankin, I., Thomsen, L. 1994. Nonhyperbolic reflection moveout in anisotropic media. Geophysics: 59, 1290–1304.

Van der Baan, M., Kendall, J.M. 2002. Estimating anisotropy parameters and traveltimes in the τ–p domain. Geophysics: 67, 1076–1086. \

White J.E., Sengbush, R.L. 1953. Velocity measurements in near–surface formations. Geophysics: 18, 54–69.