ISSN: 0975-833X

Available online at http://www.journalcra.com

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

International Journal of Current Research
Vol. 14, Issue, 01, pp.20240-20243, January, 2022

DOI: https://doi.org/10.24941/ijcr.42982.01.2022

RESEARCH ARTICLE

DETECTION OF LAYER WITH ABNORMALLY LOW VELOCITY USING CONVERTED-WAVE EQUATION

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ARTICLE INFO

Article History:
Received 07th October, 2021
Received in revised form
16th November, 2021
Accepted 14th December, 2021
Published online 28th January, 2022

Keywords:

Seismic,Nonhyperbolic Event,Velocity Analysis,Inversion,Abnormally Low Velocity.

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ABSTRACT

In the hydrocarbon exploration is common to find reservoirs underlying complex formations, particularly in offshore conditions. From many possible complex characteristics, one of them is when a geological formation presents an abnormally low velocity. This kind of characteristic is so different, because the increasing overburden of rocks with the depth usually results in an increase of propagation velocity of seismic waves, for both compressional (P) and shearing (S) waves. An important step in the seismic processing is the velocity analysis, what helps to characterize the formation geologically and structurally. In complex situations, the travel-time curves associated to waves reflected in interfaces between layers are extremely distorted and present a nonhyperbolic behaviour. Thus, it is necessary to use an equation able to control the effects of the nonhyperbolicity of the reflection event. However, for the nonhyperbolic equations, it is assumed that the velocity always increases with the depth, and that is the reason for these equations present some difficulty to fit the calculated curve to the recorded curve. Despite this, the limitation of the capacity of fit in this kind of condition results in a good way to detect the layers with abnormally low velocity, once the quality of the curve fitting decreases abruptly. So, it was proposed in this work the utilization of this limitation in the curve fitting to identify this characteristic, testing in different models what allows to analyse in what kind of situation the proposed method works in a reliable way.

Citation: Nelson Ricardo Coelho Flores Zuniga. *"*Detection of layer with abnormally low velocity using converted-wave equation*", 2022. International Journal of Current Research, 14, (01), 20240-20243.*

INTRODUCTION

Many hydrocarbon reservoirs present geological structures which are extremely complex. These types of structures bring several difficulties in performing the seismic data processing, such as the complex variations in physical properties from a geological layer to another. An important example that can be found is concerning some structures which present abnormally low P (compressional) wave and/or S (shearing) wave velocities. This kind of characteristic increases a lot the difficulty in estimating structural properties (e.g., its spatial position) of these geological layers (8-9). Large offsets must be considered because they already cause an increase in the nonhyperbolicity of a seismic reflection event, since, for layered media, the discrepancy between the real velocity and recorded velocity increases with the offset and the number of geological layers.

The information of velocity recorded is actually a root mean squared (RMS) velocity, which considers the influence of all layers above the reflection point, that is the reason of it being different from the real velocity and also being sensitive to offset and number of layers variations. Another factor that also causes the nonhyperbolicity is the wave conversion that makes a compressional wave converts in a shearing wave. Therefore, strong nonhyperbolic seismic reflection events, originated from the combination of the wave conversion and discrepancy between the RMS and real velocities, have their complexity in being analysed increased specially for complex geological structure (7, 9). Even though the nonhyperbolic multiparametric trave-time equation proposed by Li and Yuan (3) is very versatile and considers important causes of nonhyperbolicity (1-2, 6), it presents an important behaviour regarding abnormally low seismic velocities (7, 8, 9). This equation presents few limitations in describing negative gradients in the velocity of a seismic wave regarding its raytracing (8, 10, 11). It happens because one of the premises of this equation is considering that the velocity is always increasing with depth. Therefore, this equation has difficulty in estimating few parameters for layer with abnormally low velocities, since the error in estimating the seismic velocity of a layer increases significantly when the velocity of the layer is lower than the velocity of the layer above it. Considering the limitation of the equation proposed by Li and Yuan (3), it is proposed to perform few analyses about the error in estimating parameters with this equation. Computing the error variation allows identifying the interface in which the error in performing the curve fitting increases abnormally, which is directly related to the velocity with an abnormally low velocity. In this work, it is proposed an inversion routine according an optimization criterion, aiming to fit the calculated curve with the nonhyperbolic travel-time equation to the recorded curve related to the seismic reflection event. With this, observing the variation in the quality of the curve fitting allows identifying if there is a layer with abnormally low velocity and its position.

METHODS

In this work, the use of a nonhyperbolic multiparametric travel-time equation in order to identify a layer with an abnormally low seismic velocity is proposed. Li and Yuan (3) proposed an equation able to describe the nonhyperbolicity generated by the wave conversion and the large offsets between source and receivers. For this, it uses the $\boldsymbol{\gamma}$ parameter, based on the anisotropic parameters proposed by Thomsen (5) to describe the nonhyperbolicity of a seismic reflection event.

$$t = \sqrt{t_0^2 + \frac{x^2}{v^2} - \frac{(\gamma-1)}{\gamma v^2}\frac{(\gamma-1)x^4}{4t_0^2v^2+(\gamma-1)x^2}} \qquad (1)$$

where each offset between source and receiver is represented by the vector x, to indicate at which point each wave information is received along the measurement line. t_0 is the time that the wave takes to reach an interface and travel back for an offset equals to zero, perpendicular to the plan at which the wave was reflected, and v is the root mean squared (RMS) velocity of the reflected wave. The equation proposed by Li and Yuan (3) is very sensitive to variations concerning abnormally low velocities, since it is not proposed to describe this kind of structural feature (7-9). For this reason, abnormally low velocities present a different residual error variation in comparison to velocities that increase gradually. In this work, it is proposed to perform the curve fitting by calculating the curve parameters with Equation 1 in order to fit it to the observed curve related to each interface between each pair of layers. The minimization method is the Least Squares and the optimization algorithm chosen to be used in this work is the one proposed by Nelder and Mead (4). With this, it is possible to analyse the residual error variation in each curve fitting to estimate which variation is abnormal in comparison to the others. Finding the abnormal variation allows to find the layer with the abnormally low seismic velocity.

RESULTS AND DISCUSSION

Model 1, is a numerical onshore model (Figure 1), in which there is a layer with abnormally low velocity starting at its top at around 1200 meters depth and finishing at its bottom around 1800 meters depth (6th layer). The second model (Figure 2), also a numerical one, presents similar structural characteristics when compared to Model 1. However, it presents two layers with abnormally low velocities; the first one with the top at 560 meters depth and its bottom at 760 meters depth (5th layer), and the second one with its top at 1240 meters depth and its bottom at 1360 meters depth (8th layer). In Figure 3, it is possible to observe the third model used in this work, which is modelled based on well log information from a structure in the pre-salt from Santos Basin. This model, similarly to many other structures from this region, is very complex and very deep. It presents a layer (7th layer) with an abnormally low velocity above the carbonate reservoir, a thin layer with the top at 3400 meters depth and the bottom at 3500 meters depth.

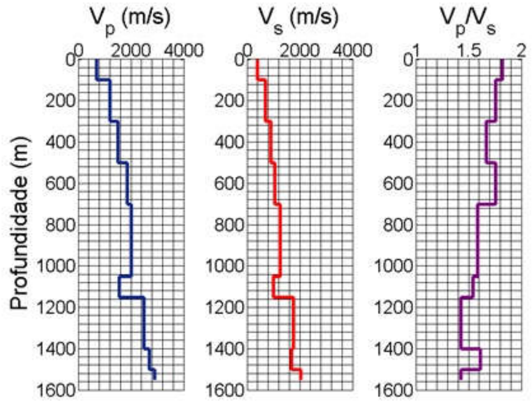

Figure 1. Velocity profile of the P wave, the S wave and the ratio between the P wave velocity and S wave velocity with depth for Model 1

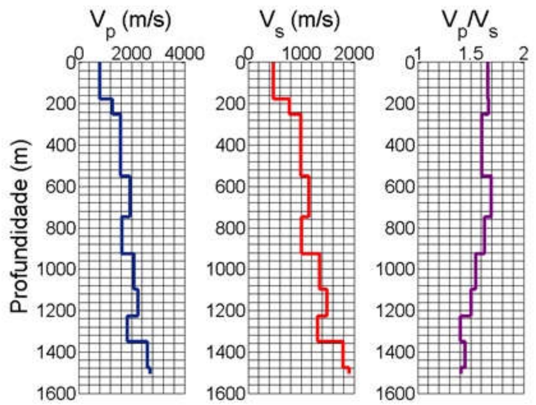

Figure 2. Velocity profile of the P wave, the S wave and the ratio between the P wave velocity and S wave velocity with depth for Model 2

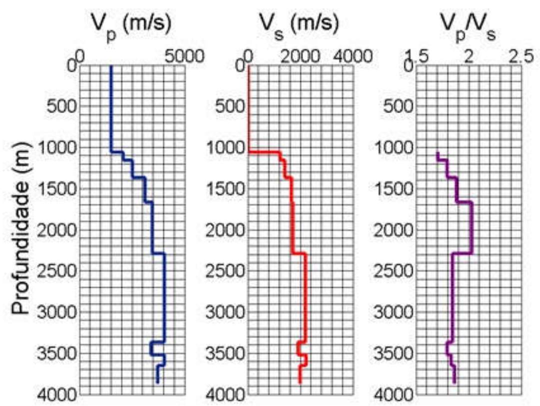

Figure 3. Velocity profile of the P wave, the S wave and the ratio between the P wave velocity and S wave velocity with depth for Model 3

In Figure 4, where the curve fittings for each interface between layers of Model 1 are shown, it is possible to observe a good fitting, with all curves not exceeding an error of 10^{-4} order. However, it is possible to observe that the quality of the curve fitting gradually decreases from the 1st until the 5th interface. This soft decrease in the quality of the curve fitting is related to the increase of the depth, which with more layers above the target layer there is an increase in the discrepancy between the real velocity and the RMS velocity. However, in the 6th interface, a significant decrease in the quality of the curve fitting is observed. After the 6th interface, the quality of the curve fitting starts again to decrease gradually, until the last analysed layer. With this, it is possible to observe that the layer below the 6th interface presents an abnormally low velocity, which causes the significant increase of the error to fit this curve.

A similar behaviour can be observed in Figure 5, where the interfaces from the 1st to the 4th present a gradual decrease in the quality of the curve fitting. This allows identifying that the abnormally low velocity is related to the layer below the 5th interface, since the error in the curve fitting for the 5th interface increases abruptly in comparison to the curve fittings for the interfaces above it. However, even with the variation in the residual error being very homogeneous, the second interface below the layer with abnormally low velocity (8th layer), cannot be identified by observing the residual errors in travel-times. This show that this approach cannot identify more than one layer with abnormally low velocity in the same structure in a reliably manner, since only the shallower layer with abnormally low velocity can be identified effectively.

Differently from the previous models analysed in this work, Figure 6 present a model built with real data, which brings more complexity in performing the curve fitting. In this case, despite of it presenting higher errors in comparison to the numerical models, it is possible to observe that the variation is less soft between the errors of each layer. This results in a harder identification of the layer with abnormally low velocity. Even though, the variation in the quality of the curve fitting from the 1st interface until the 6th one is very homogeneous, and presents a gradual decrease in the quality of the curve fitting. Nevertheless, there is an abrupt increase in the error between the curve fitting related to the 7th interface and the one related to the 6th interface. For this reason, it is possible to identify the layer below the 7th interface, as the one with an abnormally low velocity.

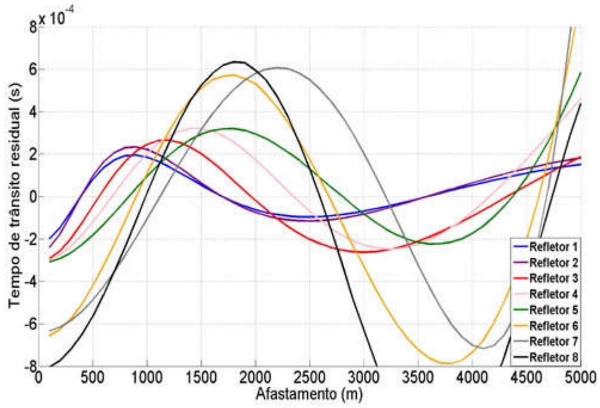

Figure 4. Difference between calculated travel-times during the inversion and the travel-times observed in the PP reflection events for each layer in Model 1

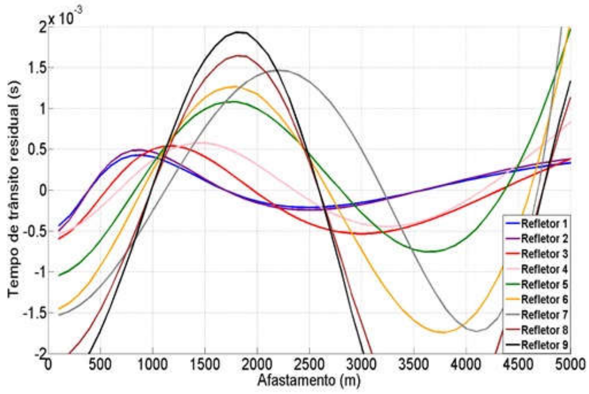

Figure 5. Difference between calculated travel-times during the inversion and the travel-times observed in the PP reflection events for each layer in Model 2

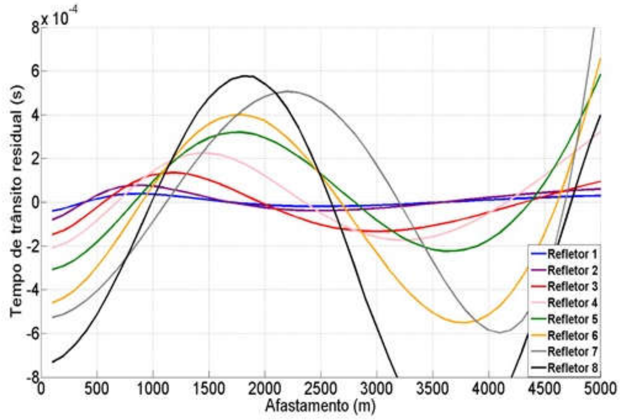

Figure 6. Difference between calculated travel-times during the inversion and the travel-times observed in the PP reflection events for each layer in Model 3

CONCLUSION

With an error related to each travel-time curve significantly low in a general manner, it is clearly possible to observe the variation between the curves related to each interface, which allows performing the analysis for numerical models and also for real models. In numerical models (Models 1 and 2), it was possible to clearly identify the layer with an abnormally low velocity, as it is the only one or the first one in the geological structure with this characteristic. For this, this approach is more effective for structures which present only one abnormally low velocity. It is also important to note that, for identifying a layer with abnormally low velocity, the most the layer is in the center between other layers easier is to identify it. It happens because there are more samples of error variation above and below the target layer, which allow a better characterization in its spatial position. Concerning the real data (Model 3), it is observed that there is a higher difficulty in identifying the layer with an abnormally low velocity, in comparison to the previous models. However, it is possible to identify the target layer with the abnormally low velocity with an acceptable value of residual error. For this reason, this approach presents to be a reliable and effective manner to obtain this kind of structural and geological information.

Conflict of interest statement: The author declares that there is no conflict of interest regarding this work.

Funding statement: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. This study was financed in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil (CNPq).

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