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

ISSN: 0975-833X

International Journal of Current Research
Vol. 14, Issue, 01, pp.20203-20205, January, 2022

DOI: https://doi.org/10.24941/ijcr.42984.01.2022

INTERNATIONAL JOURNAL
OF CURRENT RESEARCH

RESEARCH ARTICLE

COMPARISON OF NONHYPERBOLIC TRAVEL-TIME EQUATIONS OF MULTICOMPONENT SEISMIC DATA USING DIFFERENT OPTIMIZATION ALGORITHMS

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ARTICLE INFO

Article History:
Received 17th October, 2021
Received in revised form
18th November, 2021
Accepted 25th December, 2021
Published online 28th January, 2022

Keywords:

seismic,nonhyperbolic Event, Multicomponent, Inversion, Optimization Algorithms.

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ABSTRACT

Multicomponent seismic data processing is a challenge concerning the velocity analysis for offshore surveys, and the difficulty increases when OBN (Ocean Bottom Nodes) technology is used. The ray tracing asymmetry caused by wave conversion from P-wave (compressional wave) to S-wave (shearing wave), and the difference of depth between source and receiver generate a nonhyperbolicity in the travel-times of a reflection event of a seismic wave. Large offsets between source and receivers and the complexity of pre-salt structures from Santos Basin also contribute to the event being strongly nonhyperbolic. Aiming to solve this problem, three nonhyperbolic multiparametric equations are used to characterize this behaviour. Since the equations have many variables, the study was treated as an inverse problem according an optimization criterion. Three optimization algorithms were used to accomplish the curve fitting. To understand the behaviour of each equation, the complexity analysis of the objective function topography using L1-norm and L2-norm was performed. Hence, it was possible to determine which combination of equation and optimization algorithm showed the best results and the lower processing time for the studied structure.

Citation: Nelson Ricardo Coelho Flores Zuniga. "Comparison of nonhyperbolic travel-time equations of multicomponent seismic data using different optimization algorithms*", 2022. International Journal of Current Research, 14, (01), 20203-20205.*

INTRODUCTION

Travel-time approximation are essential for the conventional seismic processing of multicomponent data, more specifically when applied to velocity analysis and correction of normal moveout. The hyperbola definition must be used to perform the seismic velocity estimation for homogeneous media with short offsets, without difference of depth between source and receivers, and for conventional PP events (in which the incident compressional seismic wave reflects as compressional wave) (5, 8). However, the hyperbolic approximation is not valid for stratified media, with large offsets, difference of depth between source and receivers, and for converted PS waves (when the incident compressional seismic wave reflects as a shearing wave) (5, 6, 7).

The nonhyperbolicity generated by these factors can be described by using equations which considers these characteristics. Therefore, recovering the target parameters, as seismic velocities of a geological layer, is possible. Several equations were developed to describe different nonhyperbolic effects and their causes (5, 6, 9). However, most of them are not proposed to describe conditions studied in this work, because the multicomponent seismic (which considers PP and PS reflection events) with OBN (Ocean Botton Nodes) technology, which allows the obtaining of S waves in an offshore acquisition, generate a difference of depth between the source and the receivers (7, 9). This makes the recorded events strongly nonhyperbolic (5). In this work, a velocity analysis as an inverse problem according an optimization criterion in order to obtain seismic wave velocity parameters is proposed.

The difference between the calculated curve with nonhyperbolic multiparametric travel-time equations and the recorded curve is computed, and, with this residual error, it is possible to determine the best approach to recover a reliable seismic velocity estimation. For this, the complexity analysis of the topology of the objective function of each equation in each condition is performed.

METHODS

The first of the nonhyperbolic multiparametric equations used in this work is the one proposed by Malovichko (3), which consider layered media and large offsets.

$$t = t_0^2\left(1-\frac{1}{S}\right)+\frac{1}{S}\sqrt{t_0^2+\frac{Sx^2}{v^2}} \qquad (1)$$

where x is the vector of offset, t is the arrival time for each offset, v is the velocity of the seismic wave in the medium, t_0 is the time for zero offset, and S is the nonhyperbolic parameter which represents the influence of layered media in the wave propagation. Another equation which uses the same S parameter is the one proposed by Blias (1), which considers large offsets in a fractional form.

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

The third equation used in this work is the one proposed by Li and Yuan (2), which uses γ parameter to describe wave conversion and the nonhyperbolicity originated from it.

$$t = \sqrt{t_0^2+\frac{x^2}{v^2}-\frac{(\gamma-1)}{\gamma v^2}\frac{(\gamma-1)x^4}{4t_0^2v^2+(\gamma-1)x^2}} \qquad (3)$$

The optimization algorithms used in this work are Nelder-Mead (4), CRS, and Genetic algorithm. The data used here are from an offshore model with stratified layers from pre-salt from Santos basin, Brazil. The modelling simulates an acquisition with large offsets, using OBN technology and multicomponent seismic.

The complexity analysis of the objective function was performed by studying the topology of each equation for PP and PS reflection events with L2 and L1-norm. The calculated travel-time curve was subtracted by the recorded curve to analyse the residual error in travel-times, and, therefore, determining which equation presents the best set of results. The Model used in this work (Figure 1) is an offshore layered model with a carbonate reservoir (V_P= 4010 m/s and V_S= 2012 m/s) sealed by a salt structure composed by three layers (3rd, 4th and 5th layers) of salt with different physical properties (Table 1).

Table 1. The parameters of the Model: Layer thickness (Δz), P-wave velocity (V_P), S-wave velocity (V_S) and V_P/V_S ratio.

Layer	Δz (m)	V_P (m/s)	V_S (m/s)	V_P/V_S
Water	2157	1500	0	-
1	496	2875	1200	2.40
2	108	3505	1628	2.15
3	664	4030	2190	1.84
4	262	5005	2662	1.88
5	1485	4220	2210	1.91

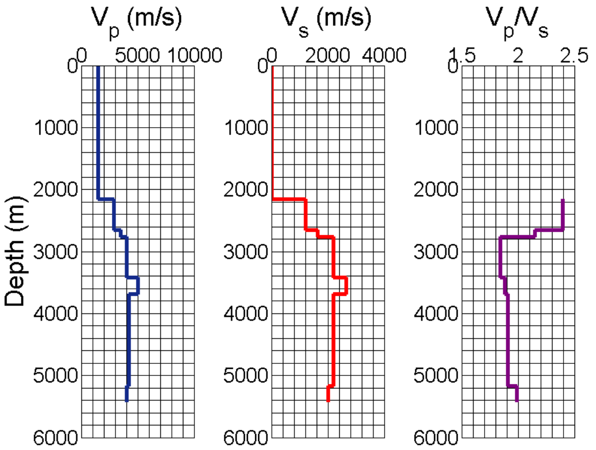

Figure 1. P-wave velocity (V_P), S-wave velocity (V_S) and V_P/V_S ratio profiles of the Model.

With the parameters, it is possible to generate the travel-time curves and the seismograms of the PP and PS reflection events by the ray tracing simulation, showed in Figure 2.

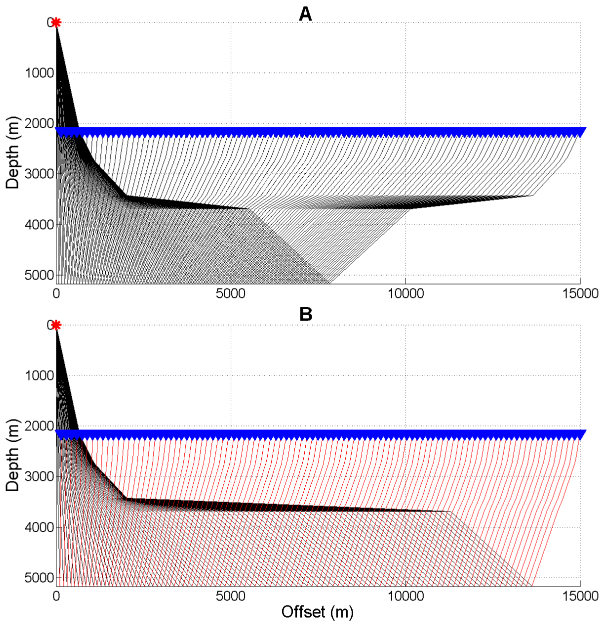

Figure 2. Ray tracing of the (A) PP wave reflection event and (B) PS wave reflection event of the Model.

RESULTS AND DISCUSSION

Equation 3 presents, for all conditions analysed in this work, the best set of results and the second-best relative processing time. Equation 2 presents the second-best set of results and the highest processing time. Equation 1 presents the worst set of results, however, also presents the best processing time. Nelder-Mead optimization algorithm presents the lowest processing time and the worst set of results. CRS algorithm presents the second-best set of results and the second-best processing time. Concerning the genetic algorithm, there is the best set of results with the highest processing time. Figure 1 shows that it is possible to observe the Equation 1 as unimodal, presenting only one minimum region (a global minimum region) in all the cases. Equation 2 presents a multimodal behaviour (with both global and local minimum regions) for PP and PS events with L2-norm; however, for L1-norm, it presents a unimodal behaviour. For Equation 3, it is possible to observe a multimodal behaviour for all the cases. Each equation presents strong variation concerning the topological structure of the objective function; however, a softer difference is identified when the PP events is compared to the PS events. A strong difference in the gradients is also shown in the residual function maps when L2-norm is compared to L1-norm.

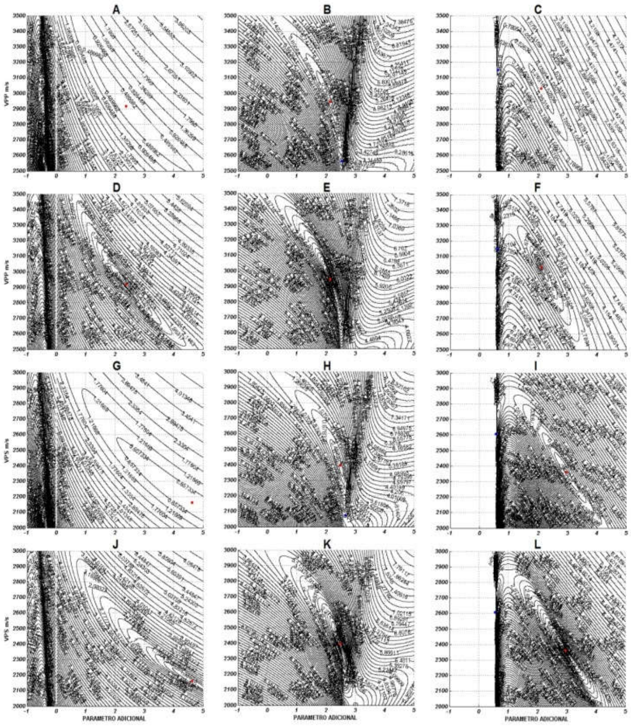

Figure 3. Residual function maps of the objective function presenting the complexity of the topology of each equation, respectively for Malovichko (1978), Blias (2009), e Li and Yuan (2003) for (A, B, and C) the PP event with L2-norm, (C, D, and E) the PP event with L1-norm, (F, G e H) the PS event with L2-norm, and (I, J e K) the PS event with L1-norm. The red dispersions represent the global minimum region

CONCLUSION

Equation 3, together with CRS optimization algorithm, presents the best set of results with a practicable processing time. Even with the worst set of results, Equation 1 is very efficient and presented a significantly low relative error in travel-times; and, for being unimodal in all the cases, it does not demand the use of a robust optimization algorithm. For this reason, Nelder-Mead optimization algorithm can be used in this case. All nonhyperbolic multiparametric equations presents significant enhancement in processing time and a small increase in accuracy when L1-norm is used. However, Equation 2 presents the best enhancement, since with L1-norm it becomes unimodal, which allows the use of a local search optimization algorithm.

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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