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A Quantitative Evaluation of Input Data Variables for Model-based PP Inversion Using Conjugate Gradient Algorithm

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SUMMARY

Using any model-based pre-stack inversion process requires three types of input data: wavelet, initial model and seismic gathers. In this paper we analyze the impact of the errors possible, such as wavelet estimation errors, initial model errors and seismic signal to noise ratio (SNR), using the non-linear conjugate gradient method for inversion to P-wave velocity (V_p), S-wave velocity (V_s) and density (ρ) data. Using this synthetic model response as the recorded seismic data, we compare the inversion results to the V_p , V_s and density from actual well data for three zones of interest. Improper rock properties from the inversion will lead to incorrect conclusions about the viability of a prospect. We arrive at conclusions about the impact of wavelet, initial model and seismic SNR required for acceptable inversion. We also offer suggestions for future research and development to increase the accuracy of the inversion results.

Introduction

The usefulness of any prestack seismic inversion process comes from the accuracy of inverted rock properties which affect the interpretation of lithology and fluid types. The input data for the conjugate gradient inversion (Yu, 2009) requires a wavelet, an initial model and prestack migrated seismic gathers in time or depth domain. The condition of the input data has a direct effect on the accuracy of the inversion results and, therefore, on the interpretation of the subsurface rock properties. If the P-wave velocity (V_p), S-wave velocity (V_s) and density (ρ) values generated by the inversion are inaccurate, the interpretation of the subsurface lithology, porosity and hydrocarbon content can create invalid prospects or miss valid prospects.

Although we actually tested over 300 possible input data variations, three input variables found to be more critical to the accuracy of the results are presented here – wavelet, initial model and seismic signal to noise ratio (SNR). First we will see the synthetic data created for study including the logs, actual wavelet and noise free moveout corrected synthetic model response PSTM gathers. Second we will examine the V_p , V_s and ρ errors from the conjugate gradient inversion compared to the actual well data from three zones of interest (Neep, 2008). Finally we will draw conclusions about the estimated wavelet accuracy, initial model accuracy and the seismic SNR level required for correct interpretation of the subsurface and suggest additional research needed to achieve better inversion results.

Data Generation

We created synthetic reflection coefficients using the Aki-Richards formulation (Aki, 1980) from actual well logs, V_p , V_s and ρ , shown in Figure 1a. Three zones of interest are labelled on the log display and are used for evaluating the accuracy of the inversion results. The reflection coefficients were convolved with a zero phase wavelet (4/8/50/100 Hz) as the actual wavelet, shown in Figure 1b to create the noise-free synthetic model response gather with perfect moveout correction shown in Figure 1c. We also created many other wavelets (partially shown in Figure 2) to emulate potential wavelet estimation errors. We also added band-limited random noises to the noise free synthetic to create synthetic gathers with different SNR. Two examples are shown in Figures 3b and 3c for SNR at 3 to 1 and SNR at 1 to 1 respectively. The initial model was created by applying a low-pass filter to the well logs (low frequency initial model). Other initial models with errors were created by using a constant value for each log type (constant initial model) or by shifting the original log values up to $\pm 25\%$ before applying low pass filter (shifted low frequency initial model) as illustrated partly in Figure 4.

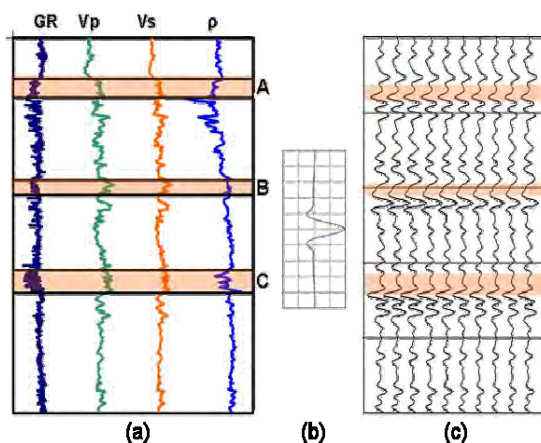


Figure 1 Well logs, zero phase wavelet and synthetic model response with no noise.

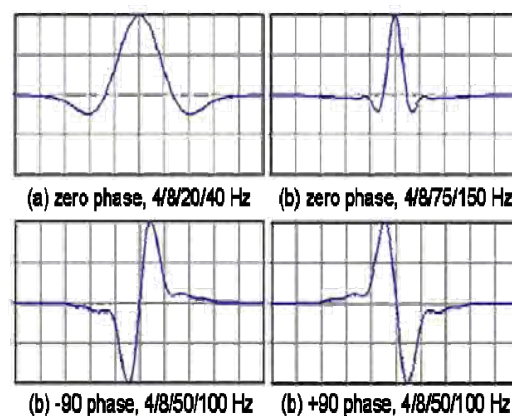


Figure 2 Examples of estimated wavelets with errors for testing.

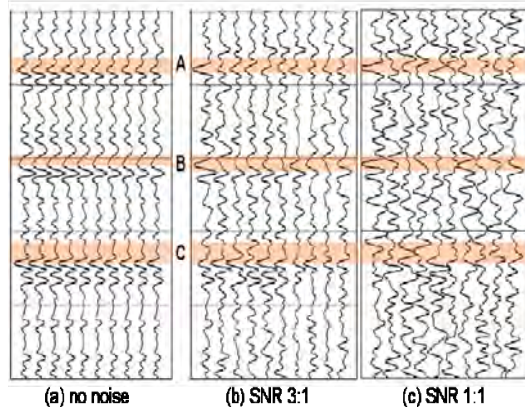


Figure 3 Comparison of the examples of synthetics with different SNR.

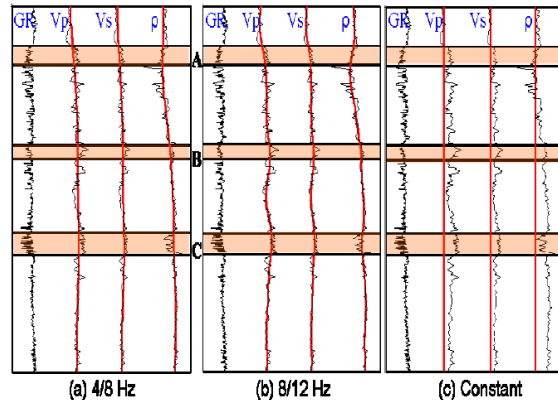


Figure 4 Examples of initial models with different low frequency bandwidths or constants.

Many other input data variables were tested but not presented here mainly due to space limitation. For example, imperfect seismic prestack migrated gathers due to acquisition and processing can manifest themselves in many ways such as un-flattened primaries, improper balanced amplitudes, imperfect offset to incident angle conversion due to velocity errors, far offset stretch, etc. Furthermore, the bandwidth of real seismic data, the number of angle stacks and the algorithm parameters can also contribute the inversion inaccuracy.

Results

Comparisons of the inversion accuracy are made using the normalized difference between the RMS average of the actual well data and the RMS average of the inversion results for each zone of interest shown in Figure 1. Based on the feasibility study of rock and fluid properties (thickness, porosity, saturation and fluid) in this area, differences of about 50 m/s for Vp, 25 m/s for Vs and 0.02 g/c for ρ in the zones of interest would not appreciably change the interpretation of reservoir quality or prospect ranking and were used as the benchmark for inversion accuracy. Note that the ρ differences are plotted in g/10 liters for visibility purpose in display.

Wavelet estimation errors. The synthetic without noise (Figure 1c) created with the wavelet of 4/8/50/100 Hz (Figure 1b) was used as the real seismic input data with the initial model (Figure 4a) for testing the impact of wavelet estimation errors. In stead of using the actual wavelet in Figure 1b, imperfect estimated wavelets (partial examples in Figure 2) were used as the input wavelets by using zero phase wavelets with the bandwidth varying from 4/8/20/40 Hz to 4/8/75/150 Hz at 5 Hz steps and non-zero phase wavelets of 4/8/50/100 Hz with the phase varying from -90° to $+90^\circ$ at 10° steps. The test results at the zones indicated on Figure 1 are shown in Figure 5.

We can conclude from the upper row of Figure 5 that the estimated wavelet must contain sufficient frequency to invert better. Although a higher bandwidth is better than a lower one, the bandwidth only increases marginally the accuracy of the inversion results once the estimated wavelet reaches the actual wavelet bandwidth. On the other hand, it is better to have correct wavelet phase estimation because it produced the smallest inverted errors as demonstrated in the lower row of Figure 5. Furthermore, although we may achieve acceptable results with inaccurate wavelets, the number of iterations required increases dramatically and thus the inversion cost could increase significantly for a large 3D volume.

Initial model errors. The same aforementioned noise free synthetic model response for testing wavelet errors was used here. We tested many initial models (partial examples shown in Figure 4 by using three main types of initial model described in Data Generation section: low frequency initial model, constant value initial model and shifted low frequency initial model. The idea here is to test

the impact of the low frequency bandwidth and the proximity of true log value in the initial model. The test results at the zones of interest are shown in Figure 6. We can conclude that the inversion accuracy is acceptable as long as the initial model is approximately representative of the real geology, but if the model is significantly different from the real geologic conditions (e.g., using constant values for V_p , V_s and ρ shown at the left edge of the X-axis in each display in Figure 6) the results are not acceptable (or misleading) and the number of iterations required increases dramatically.

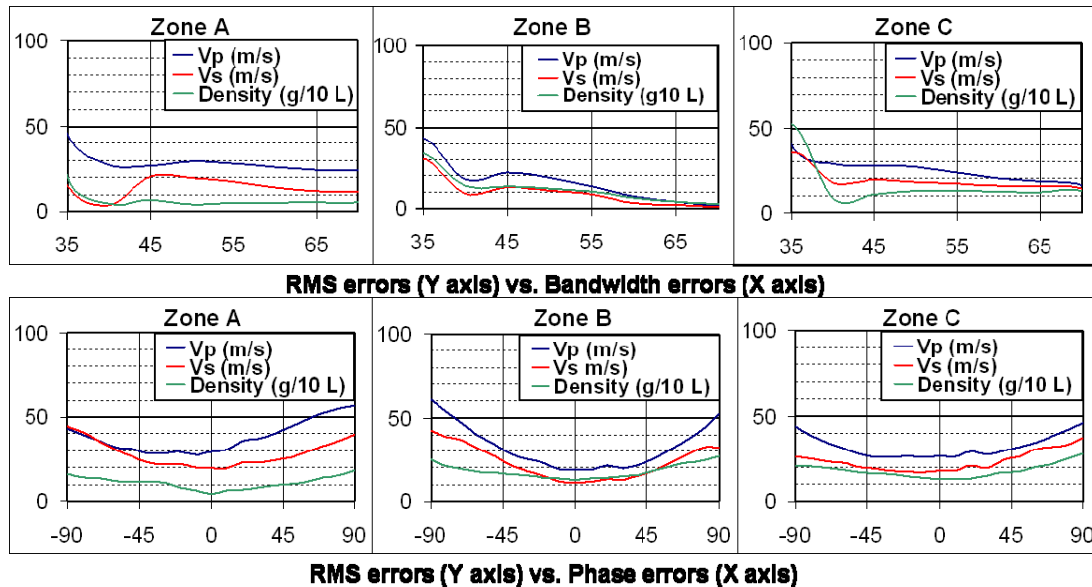


Figure 5 Comparison of inversion errors due to wavelet estimation errors in bandwidth and phase.

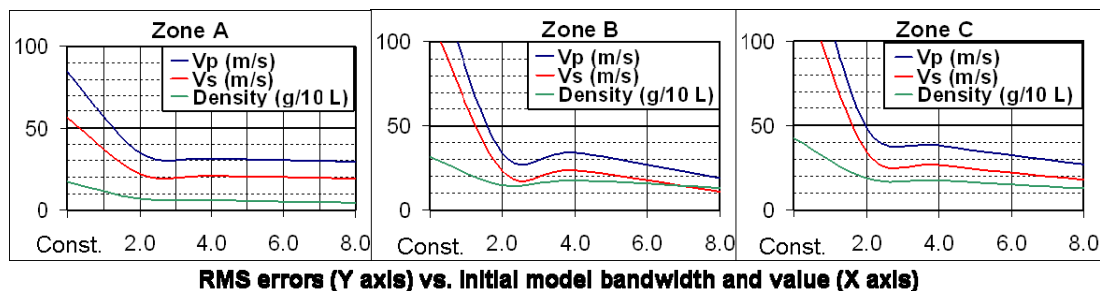
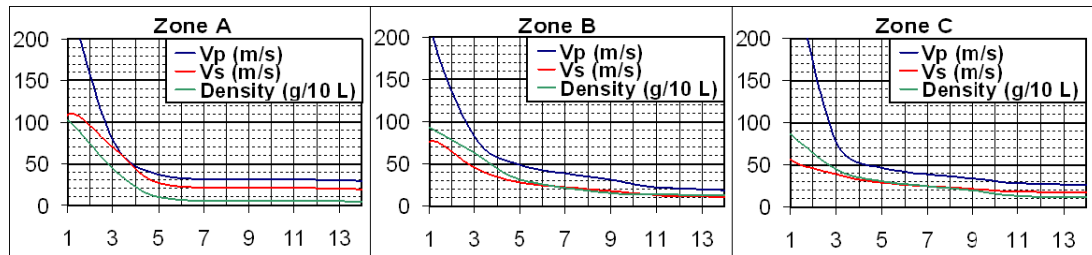


Figure 6 Comparison of inversion errors caused by imperfect model estimation. Note that the errors for using constant value as initial model is located at the left edge of the X-axis of each display.

Seismic signal to noise ratio. In previous tests the input seismic data are noise free or SNR is perfect to evaluate the impact of wavelet errors and initial model errors. Here we tested the impact of SNR of input seismic data but using the correct wavelet (Figure 1b) and the initial model (Figure 4a). We created several synthetic model responses with different SNR levels (partial examples shown in Figure 3) for input to inversion. The test results at the zones of interest are shown in Figure 7. We can conclude from Figure 7 that the seismic SNR is the most critical variable for the accuracy of the inversion results because the RMS errors are higher than the aforementioned variables – wavelet and initial mode for the three zones of interest. Furthermore, tests also indicated that as the seismic SNR decreases the conjugate gradient inversion cannot achieve convergence to a solution and the number of iterations actually decreases.



RMS errors (Y axis) vs. SNR levels (X axis)

Figure 7 Comparison of inversion errors due to SNR difference caused by acquisition or non-ideal processing workflow.

Conclusions

We have concluded that the seismic SNR is critical to the inversion results. If the input seismic data are not as clean as possible, the inversion results could cause us to miss prospective hydrocarbon accumulations or interpret hydrocarbon accumulations where none exists.

Although the bandwidth and phase of estimated wavelet can be moderately different from that actually in the seismic data, we can still achieve inversion results which are close to the actual geologic conditions. However, the computation time is increased if the estimated wavelet is not a close match to the actual seismic wavelet. For a large 3D volume, the increased computation time could rapidly become prohibitive.

Although the initial model can be somewhat different from the actual geologic conditions, we can achieve inversion results which are close to the actual geologic conditions. However, if the initial model is significantly different from the real geology, the conjugate inversion results can become unacceptable for interpretation. Additional research is needed to eliminate the improper results from the conjugate inversion when the initial model may be poorly or virtually unknown.

In summary, we must assure the match of the input wavelet to the actual seismic wavelet, estimate the best initial model using available well controls with statistical sensitivity study and optimize the SNR of input seismic data in order to achieve the best inversion results and minimize the inversion time and cost. Since SNR is the most critical variable in this study one must apply the best processing to improve SNR by eliminating all multiples and random noise and flattening primaries with the best velocity. More research is also required in developing additional constraints in algorithm to eliminate the improper results. Besides external variables discussed in this paper, internal variables in the algorithm such as cost function, tolerance acceptance between real data and model response and convergence step also require careful evaluation to achieve better inversion results.

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