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Comparative Analysis of Hessian-Based and Optimization Techniques for Elastic FWI: Applications to Synthetic Models

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Introduction

In recent years, full-waveform inversion (FWI) has become an essential methodology for improving velocity models used in seismic imaging. Initially developed to enhance imaging in complex geological environments, FWI has since expanded its applications to include the generation of reflectivity-derived information by computing directional derivatives of the final velocity models obtained. More recently, efforts have been made to apply FWI to elastic multi-parameter inversion schemes, enabling the estimation of key elastic properties that could provide valuable insights into hydrocarbon presence. Although these methodologies are not new—dating back to the late 1980s—their industrial adoption was delayed due to the significant computational demands and seismic data limitations of that era, including low signal-to-noise ratios (particularly in streamer acquisitions) and the lack of long offsets and azimuthal coverage. Other challenges, such as crosstalk between different parameterizations, were well-documented during the early theoretical development of FWI but remain unresolved or lack effective solutions even today. Crosstalk, for example, is thoroughly discussed in Tarantola's seminal book on seismic inversion, as well as in other key reference papers about Elastic FWI.

Even now, crosstalk between parameters remains an active area of research, with new proposals aiming to address this issue through alternative parameterizations for elastic FWI inversion. Instead of relying on traditional parameters such as Vp, Vs (compressional and shear velocities), and density, researchers have explored alternative parameterization schemes to mitigate crosstalk. Another well-known approach involves utilizing the Hessian matrix or approximations of this computationally expensive and enormously large matrix, whose dimensions are determined by the number of parameters involved in the inversion. Strategies for estimating the Hessian matrix vary, but one possible alternative involves approximating its main diagonal using expressions derived by the first-order Taylor series employed in the gradient computation for elastic inversion, as resulting from the Adjoint State Method. This approximation forms what is known as the pseudo-Hessian matrix, which, in this work, is further treated as a block (3 by 3) matrix (one block for each parameter) and inverted using a block scheme known as the Schur complement. Alternatively, iterative optimization techniques, such as the limited-memory Broyden-Fletcher-Goldfarb-Shanno algorithm (l-BFGS), are applied to approximate the inversion of the Hessian matrix as the iterative inversion process evolves.

Results and Conclusions

In this study, these approaches are compared and analyzed using synthetic examples. The first example is a highly simplified scenario that poses a significant challenge due to the complete lack of correlation between parameters variations. The second example is more representative of a geological setting, specifically modeled after the Brazilian pre-salt environment. Both examples utilize an elastic wave propagator to generate the datasets required for elastic inversion. The results provide partial conclusions regarding the effectiveness of these approaches, as well as guidance for future research directions aimed at advancing the practical application of multi-parameter elastic FWI in real-world industrial scenarios in the oil and gas industry.