Simultaneous seismic inversion applied to geotechnical analysis of near seabed sediments

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Abstract

This paper describes a near seabed geotechnical characterization study in Campos Basin, offshore Southeastern Brazil, including the analysis of elastic moduli distribution such as shear modulus and Lamé's coefficient (μ and λ, respectively). These two moduli were calculated from rock physics properties such as acoustic (P) and shear (S) impedances and density, derived through and as results of a prestack simultaneous AVO seismic inversion which algorithm uses a global optimization procedure including simulated annealing. Inverted 3D cubes allowed near seabed mapping of the elastic parameters that showed acceptable qualitative correlation with direct geotechnical measurements. This study will be applicable to improve understanding of sub-bottom sediments stiffness for engineering purposes, like future subsurface installation of oil platforms foundations.

Introduction

As the Oil Industry migrates into deeper waters, exploration and production facilities on the seafloor must be safely installed in variable and sometimes chaotic seabed conditions. A geotechnical characterization of the shallow sub-bottom sediments (up to 50-100 meters below sea floor) is mandatory, for optimally placing and anchoring these engineering structures.

This characterization is normally conducted by carrying out a number of shallow geotechnical boreholes, where a piezocone measures soil resistance and, besides, soil samples are tested in order to convert resistance to undrained shear strength (Su), usually expressed in pressure units, such as kPa. These *in situ* measurements may be regarded as direct geotechnical information and are sometimes followed by coadjutant physical measurements such as shear velocity.

Although high-resolution and direct, these boreholes are restricted to a single point (thus providing rather local information) and are very expensive. An alternative was then sought to extract useful geotechnical information indirectly from 3D simultaneous AVO seismic data inversion results, given the areal coverage and regional distribution of these datasets. Further motivation lies in their low cost, since 3D seismic data are generally available from earlier exploration and/ or development stages of an oil field.

Seismic inversion is a valuable tool used in reservoir characterization, reducing risks in exploration, development and production operations. The main question is whether this technique can be applied to successfully derive elastic parameters embedded with geotechnical significance.

As shown below, exemplified by a 3D seismic dataset in Campos Basin, offshore Southeastern Brazil, a seismic-based approach reveals potential usage for geotechnical applications, in spite of the different strain regimes between invasive geotechnical measurement (where sediments are disrupted) and seismic perturbation (which only elastically disturbs the medium).

Method

The idea of Amplitude Versus Offset (AVO) analysis is to utilize the fact that information about acoustic impedance as well as shear impedance is contained in ordinary acoustic reflection seismic data, if the variation of the reflection coefficient with the angle of incidence is taken into account. Combined information of acoustic and shear impedance can be very useful to differentiate for instance between porosity and fluid changes, or between pressure and saturation changes for a particular area of study. Another noteworthy application is to carry out some lithological identification, for example, between sand and shale that in a few cases have almost the same acoustic impedance, but different shear impedance.

A frequently used method of examining AVO effects is to compute angle stacks and analyze them qualitatively. In order to perform a quantitative analysis, the angle stacks can be inverted using the concept of the effective impedance at a constant angle of incidence. This impedance is called angle impedance.

The seismic inversion process consists in converting seismic data to elastic properties such as acoustic impedance, shear impedance, Poisson's ratio and density. The steps of the inversion are seismic and well log preconditioning, well log calibration, wavelet extraction, low frequency model building and the inversion itself (figure 1). The inversion engine is based on a global optimization algorithm with a non linear cost function to simultaneously invert a number of input stacks to an earth model. The inversion uses a convolution model generating synthetic seismic data via an iterative process which seeks to reduce the error between observed and modeled seismic data. The algorithm uses a modified version of the Aki and Richards (1980) reflectivity approximation.

The implementation of angle impedance makes it possible to invert angle stacks as if the data were ordinarily stacked seismic data. Using angle reflectivity and angle impedance logs computed for the effective angle of the stack makes the application of the convolutional model valid for inversion.

The angle reflectivity logs are used for the wavelet estimation. The angle impedance logs are used in the low frequency model generation and for quality control of the inversion results.

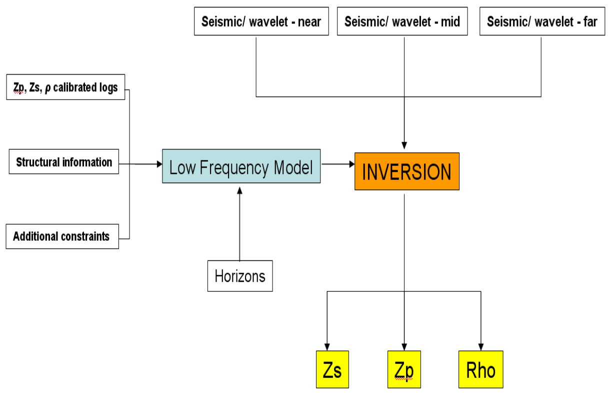

Figure 1 – General scheme of simultaneous inversion inputs and outputs.

The simultaneous AVO inversion is characterized by all partial stacks being simultaneously inverted directly to the desired true layer quantities. Consequently, the need for defining a problematic quantity like angle impedance is eliminated as the reflection coefficient as a function of incidence angle is computed directly from the true layer quantities using for instance the Aki and Richards approximation (Aki and Richards, 1980).

The layer quantity parameterization and the low frequency models are partly independent from the forward seismic modeling algorithm. Acoustic impedance and either shear impedance or Poisson's ratio are always included. In the case of the Aki and Richards AVO model, density is also included in the parameterization.

Available data and inversion

The seismic data available for this inversion project comprised a high-resolution and dense 3D streamer (and thus P-wave only) data from shallow to deep water Campos Basin. These make up a rectangular area trending NW-SE where several industry wells, besides geotechnical boreholes, are available.

Initially, four angle stacks (near, mid, far and ultra-far) were analyzed and it was observed that the near angle stack presented zeroed and incomplete traces due to acquisition problems and for this reason this dataset was excluded from the inversion workflow.

Shear velocity and density log data from two geotechnical boreholes were used on this inversion project but the compressional velocity was calculated from shear velocity using the mudrock equation of Castagna *et al.* (1985). Well log data from an exploratory well available in the studied area were used to extract wavelets applied in the inversion model.

Shallow horizons (including sea bottom) previously interpreted, were also required to provide structural guidance for the inversion process.

Differently from most seismic inversion studies, where targets are generally deeper, here the main interest zone lies on the shallower sediments corresponding to the first few hundred milliseconds, where the geotechnical characterization is pursued.

The available borehole and well logs were calibrated and wavelets were extracted. The low frequency model was generated by extrapolating the filtered logs (from both geotechnical boreholes and exploratory well available in the area) using a 25 Hz low pass filter, guided by the interpreted horizons.

The angle stacks were inverted using their corresponding wavelets, and the direct results of acoustic impedance, shear impedance and density were employed to calculate the elastic moduli, used to study the rigidity of shallow sub-bottom sediments.

The shear modulus (μ) and the Lamé's coefficient (λ) equations are given by:

$$\mu = \frac{\sigma_{shear} / A}{\Delta l / l} \qquad (1)$$

$$\lambda = k - 2/3\mu \qquad (2)$$

Equations 1 and 2: elastic constants μ and λ, where σ_{shear} is the shear stress, A is the area, Δl is the distance between shearing planes, l is the shear displacement and ***k*** is the bulk modulus.

Additionally, a combination of these constants like $\lambda\rho$ (*lambda*rho*), $\mu\rho$ (*mu*rho)* and λ/μ (*lambda/mu*) can be derived from the direct inversion results *e.g.* acoustic and shear impedances, using the following equations:

$$\lambda\rho = Z_p^2 - 2Z_s^2 \qquad (3)$$

$$\mu\rho = Z_s^2 \qquad (4)$$

$$\frac{\lambda}{\mu} = \left(\frac{Z_p}{Z_s}\right)^2 - 2 \qquad (5)$$

Equations 3 to 5: elastic moduli derived from P and S impedances, where Z_p and Z_s are respectively the P and S impedances and ρ is density.

Results

Elastic parameters derived from the inversion results were used to generate maps across the study area in order to be compared with the geotechnical measurements. These maps correspond to attributes that can be called “pseudo-geotechnical attributes”.

Lamé’s coefficient (λ) and shear modulus (μ) are elastic moduli known for their high sensitivity to elastic contrasts. Additionally these elastic moduli have the same units of pressure as the geotechnical indicator *Su*, which allows direct comparisons among them.

The pseudo-geotechnical attributes maps shown in figures 2 to 6 were calculated extracting each attribute at the seabed horizon. Based on local estimates, the seabed event is thought to approximately represent the elastic behavior of the upper 20 meters of sediments. Seabed horizon is shown in seismic section in figure 7 and corresponds to the shallowest interpreted horizon (green). The location of this section is shown in figures 2 to 6 as a solid line.

An analysis from figures 2 to 6 shows a general qualitative correlation among the attributes and the compartmentalization of three zones with different behavior. The main difference among the attribute maps lies in the richness of detail, apparently greater for attributes such as acoustic impedance and $\lambda\rho$ with a few of them looking smoother (such as shear impedance).

Interpreted horizons shown in figure 7 highlight the fact that younger and, in this case, less rigid sediments dominate shallow water (proximal) and deep water (distal) regions, oppositely to older and, in this case, more rigid sediments outcropping in the intermediate region.

From these maps and the seismic section, it can be seen that most attributes exhibit the following trend: high values correlate to the occurrence of more rigid sediments and low values correlate to less rigid sediments. λ/μ map is an exception, showing an opposite trend. This may simply indicate that shear modulus (μ) might be a potentially more sensitive pseudo-geotechnical indicator than Lamé’s coefficient (λ).

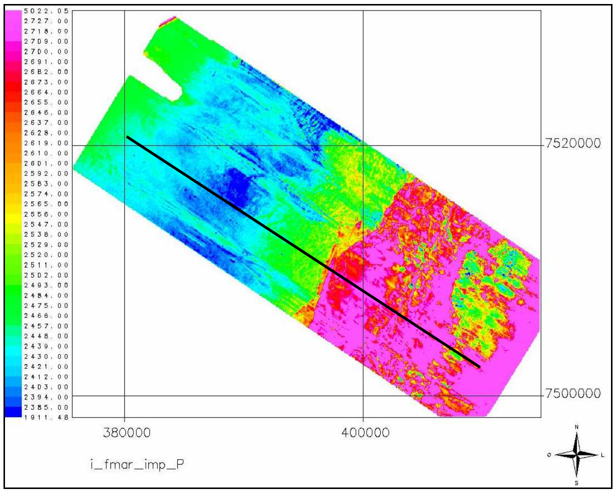

Figure 2 – Acoustic impedance map. From the color bar, high values = pink and low values = dark blue.

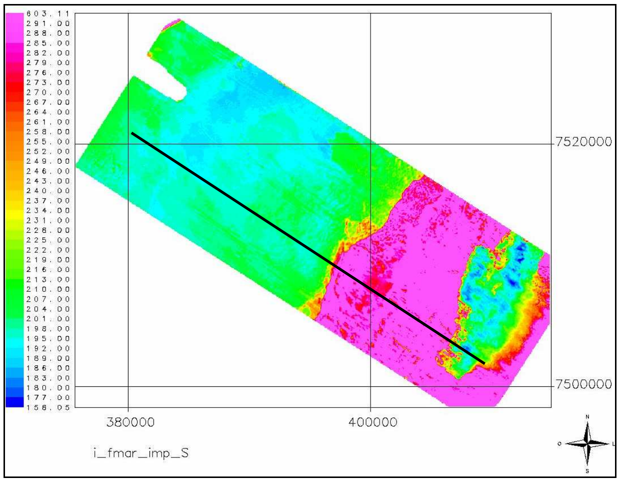

Figure 3 – Shear impedance map. From the color bar, high values = pink and low values = dark blue.

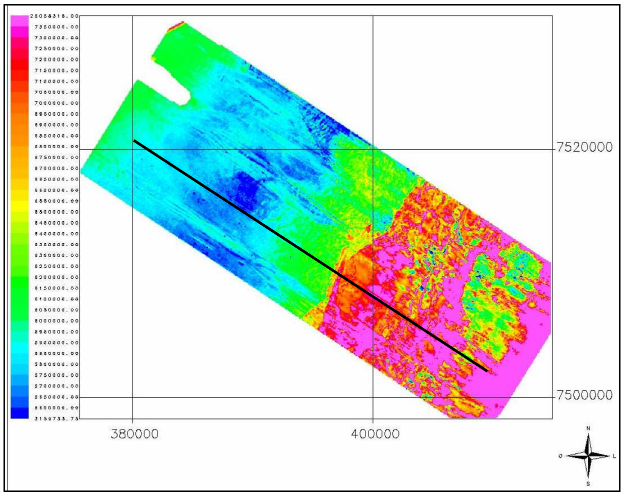

Figure 4 – $\lambda\rho$ map. From the color bar, high values = pink and low values = dark blue.

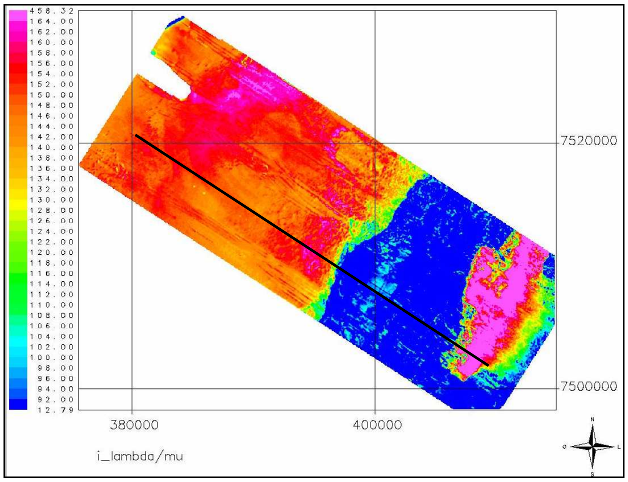

Figure 5 – λ/μ map. From the color bar, high values = pink and low values = dark blue.

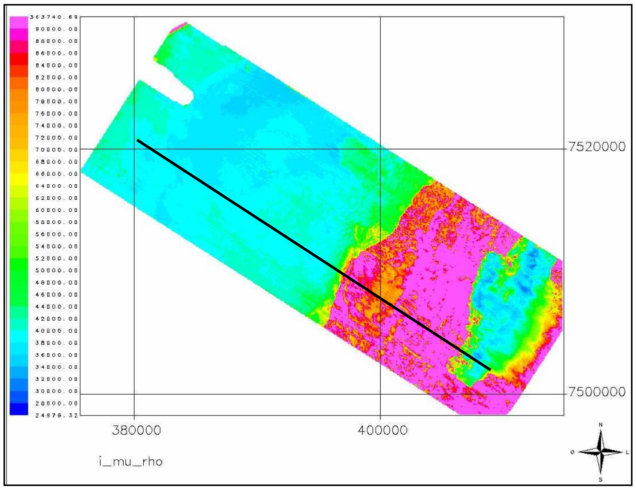

Figure 6 – $\mu\rho$ map. From the color bar, high values = pink and low values = dark blue.

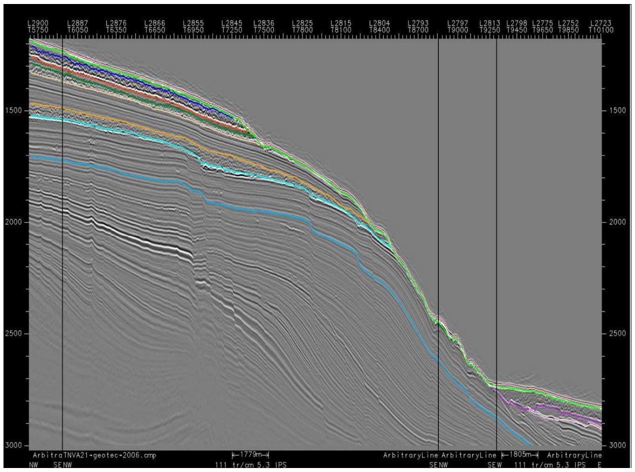

Figure 7 – Representative NW-SE seismic section along the study area.

Conclusions

Preliminary analysis from this study, aimed on the ability of simultaneous AVO seismic inversion to derive attributes to qualitatively reproduce geotechnical behavior of the near seabed, showed the potential of such approach. Intrinsic limitations such as different strain regimes between seismic method and direct geotechnical experiments is expected to become a major issue if more quantitative inferences are to be made. Complementary work and analysis should be done.

The AVO simultaneous seismic inversion method has been successfully applied for non-conventional applications, such as the one here depicted, focused on unusually shallow targets and thus poorly consolidated rocks.

Acknowledgments

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