Extraction of geotechnical attributes from seismic data: towards a quantitative approach

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Abstract

This paper describes a method to obtain geotechnical attributes through empirical relations established between geotechnical parameters from field surveys and seismic inversion derived elastic moduli. Thus a quantitative rather than former qualitative approach (Sobreira *et al.* (2009, 2010 a, 2010 b, 2010 c) is pursued so that one can reproduce the expected geotechnical behavior anywhere within a given volume (3D) or vertical section (2D) of seismically derived elastic moduli.

The method was tested in the same areas the original qualitative work was performed, that is, Marlim-Voador and Albacora fields' regions, in Campos Basin, Southeastern Brazilian Continental Margin. Geotechnical logs were predicted in arbitrary locations within the seismic volume or section. The correlation of these so-called pseudo-logs with the real ones has proven satisfactory enough, since at least the main natural geotechnical contrasts could be reproduced.

Introduction

The installation of E&P infrastructure offshore is necessarily preceded by a dedicated geotechnical survey in which several shallow boreholes are drilled in order to test the soil mechanical characteristics. As a result, geotechnical parameters such as qnet (net cone resistance) and Su (undrained shear strength) are directly obtained as a measure of the soil resistance or strength. Previous work from Sobreira *et al.* (2009, 2010 a, 2010 b, 2010 c) dealt with extracting elastic attributes embedded with geotechnical significance from seismic data in two different areas of Campos Basin, Southeastern Brazilian Continental Margin, through an essentially qualitative approach. Several elastic attributes were derived through seismic inversion (by using *in situ* Vs and density information available from special geotechnical boreholes as constraints) and compared with direct geotechnical parameters, obtained from boreholes.

Primary output of elastic seismic inversion is acoustic (P-wave) impedance (or Zp), shear (S-wave) impedance (or Zs) and density (or ρ). From these, and through algebraic manipulation, several elastic moduli can be derived. Within these we have favored the ones with the same dimension of pressure as the geotechnical parameters. Those moduli include shear modulus (*μ*), Young modulus (*E*).and bulk modulus or incompressibility (*k)*, which were then qualitatively compared with direct geotechnical parameters.

The need to achieve more quantitative estimates led us to pursue a different approach, in order to predict the geotechnical behavior and the corresponding predicted geotechnical parameters (Su and qnet) here referred as "pseudo-geotechnical parameters", in the sense they are not obtained from a direct experiment. This was done on the same investigated areas as the original qualitative work, which are Marlim-Voador and Albacora fields' regions. The basics of the quantitative approach thus conducted as well as examples of their results are depicted hereafter.

Geotechnical parameters

The geotechnical characterization of shallow sediments near seabed (up to 50 – 100m below seafloor) is normally conducted by carrying out a number of shallow boreholes, where soil resistance to the penetration of a device known as piezocone (or CPT) is measured *in situ*. This measurement is converted into geotechnical parameters such as the net cone resistance (qnet) and the undrained shear strength (Su), both usually expressed in pressure units (such as kPa for Su and MPa for qnet). Although the information thus provided is direct and high resolution (in terms of vertical spatial sampling), it is expensive and has limited spatial significance.

qnet is defined as:

$$qnet = qt - \sigma_{v0}$$

where qt is the total cone resistance (which is primary, tip resistance, corrected for the effects of cone geometry and excess pore pressure) and σ_{v0} is the vertical stress related to the total overburden pressure with respect to the mudline,

and Su is defined as:

$$Su = \frac{qnet}{N_{kt}}$$

where N_{kt} is a factor specific to each area, and variable according to soil properties such as plasticity.

In the qualitative approach carried out previously, Sobreira *et al.* (2009, 2010 a, 2010 b, 2010 c) focused on the geotechnical parameter Su. In this new quantitative approach another geotechnical parameter was considered for comparisons with seismic inversion derived elastic attributes, which is qnet. This intended to provide further comparisons with the elastic moduli.

Differently from the dynamic moduli derived from seismic data (which relate to a medium disturbance caused by the seismic wave propagation, and thus, to a typically elastic strain regime) the direct geotechnical parameters (Su and qnet) relate to a rather brittle strain regime, several orders of magnitude higher, since the geotechnical experiment they are derived from leads ultimately to rock failure. Besides, geotechnical parameters concern resistance while elastic moduli stand for stiffness. But nothing that prevents some mathematical relation between them to be reasonably established.

Review of former qualitative approach

Geophysical data (such as seismic) are recognized as a potential source of information embedded with geotechnical significance. Sobreira *et al.* (2009, 2010 a, 2010 b and 2010 c) have used seismic data offshore in order to extract information useful for geotechnical characterization of the shallow section, in an essentially qualitative approach. This method consists of deriving elastic moduli, such as shear modulus, Young modulus and bulk modulus through AVO (amplitude versus offset) simultaneous seismic inversion of high resolution P-wave or eventually 4-component, PP and PS-wave data, which are generally available and ready to use from E&P assets, what implies lower costs as compared to a typical geotechnical campaign. Another attractiveness of using this type of data lies in their areal or regional character, oppositely to the rather local character of the information provided by geotechnical boreholes.

The same papers quoted above also stress how important is to incorporate elastic information into the process, be it derived from simultaneous inversion of subsets (partial angle stacks) of seismic data or from adding real PS-wave mode to the more usual P (or PP) wave mode, whenever multicomponent data are available, into a preferentially simultaneous inversion scheme too. Moreover, it was found that the elastic attributes which provided better qualitative correlation with Su were those related to S-wave, such as μ and E. These exhibit a positive correlation with Su, besides sharing the same dimension (that is pressure). On the other hand, elastic attributes related only to P-wave, such as k, exhibit a rather poor, although positive as well, qualitative correlation with Su.

Method

Our quantitative approach was conducted in the same areas formerly investigated under a qualitative approach (that is, Marlim-Voador and Albacora fields, offshore Campos Basin), and comprises generically, the following main steps:

a) identification of key geotechnical boreholes and logs to be related with the elastic moduli (considering their representativeness in depth: GS-28, GS-49, GT-29 and GT-12 in Marlim-Voador, and GS-08 and GS-27 in Albacora), and collection of their corresponding Su and qnet existing logs;

b) extraction of the vertical trace (in the same location as those geotechnical boreholes) of three different elastic moduli: shear modulus, Young modulus and bulk modulus, from the respective seismic volume or section;

c) high cut filtering of geotechnical parameters' logs (Su and qnet) to approximately the same frequency content as the seismic traces (since geotechnical logs are generally higher-frequency), in order to make correlation easier, yet keeping the main natural contrasts;

d) time-depth tie (since seismic traces are in time and geotechnical logs are in depth) to allow effective correlation between them to be made;

e) crossplotting on an orthogonal set of axis of the three elastic moduli previously chosen with each one of the two geotechnical parameters considered, in their corresponding depths, all in the same units (Pa), totaling essentially six different combinations for each investigated area;

f) attempting different mathematical adjustments for the crossplotted data such as linear, logarithmic and power law, until a best fit was achieved that maximized the correlation coefficient for each pair "inverted elastic modulus" X "geotechnical parameter"; this considered both individual boreholes as well as several boreholes ("global adjustment") for making up the population of crossplotted points;

g) derivation of "best fit" mathematical expressions for each one of the areas (Marlim-Voador and Albacora) and each one of the geotechnical parameters considered, so that pseudo-Su and pseudo-qnet could be built from the desired seismically derived elastic modulus anywhere from its respective volume;

h) "blind test": generation of pseudo-Su and pseudo-qnet volumes, and then, of pseudo-logs, on the locations of known geotechnical behavior (geotechnical boreholes not used for crossplot and correlation), so that the robustness of the approach could be assessed.

Thus, in the absence of a generic, analytical relation linking dynamic elastic moduli and geotechnical parameters, empirical relations were pursued. Due to this empirical nature, the validity of the relations must be considered as rather local: the farther one departs from the area where they were derived, the less effective the predictions are expected to be. Furthermore, it must be stated that the trend of the empirical curves obtained is guided by the behavior of siliciclastic sediments (and not really by bioclastic or carbonate sediments) and within these, by the fine-grained, cohesive sediments (silty-muddy in nature) that generally prevail in the shallow section of the investigated areas. To a certain extent, this is already accounted for in the final expressions of the derived empirical equations (including their local character of validity).

Results

Different mathematical adjustments were considered for each crossplot (linear, logarithmic and power law), and for all of these a best fit with an even high degree of correlation could be obtained. After several trials, our general choice would rely on the power law adjustment, generically, $y = a.x^b$, “y” and “x” being the variables to crossplot and “a“ and “b” being coefficients captive to each case and/ or area, the former standing for the inclination of the curve, and the latter for its concavity). The crossplots between geotechnical parameters and elastic moduli considered both individual and several geotechnical boreholes (that is, a “global adjustment”) to make up the population of points to be fitted.

Although we have undertaken this best fit search with all three selected elastic attributes (μ, *E* and *k*), the results indicate better correlation (or less dispersion) for the first two - as expected from our findings on the previous qualitative work – although for the latter a positive relation with geotechnical parameters might still be recognized (curves obtained for shear and Young modulus actually resemble each other a lot). This is exemplified as comparing figures 1 (adjustment based on the crossplot between Su and Young modulus) and 2 (adjustment based on the crossplot between Su and bulk modulus), which regard Albacora area. While for the former a correlation coefficient as good as 0.788 was obtained, for the latter, this is no better than 0.404. For the best fit on this particular case (crossplot between Su and inverted Young modulus) an empirical expression was derived so that

$Su_p=9.138*10^{-6}*E^{1.1629}$,

where Su_p stands for the predicted Su (from Young modulus *E*, in this case) and * stands for the product.

Figure 3 illustrates the best-fit for power-law adjustment, based on the crossplot between Su and shear modulus for Marlim-Voador area. Correlation coefficients here are even better and as high as 0.955 (in this case, considering borehole GS-28 alone for adjustment). For this particular fit, an empirical expression was derived so that

$Su_p=2.0045*10^{-10}*\mu^{1.8309}$,

where Su_p stands for the predicted Su (from shear modulus μ, in this case) and * stands for the product. Figure 4 exemplifies a comparison between real and predicted or pseudo-Su logs for a geotechnical borehole location in Marlim-Voador area, after such a power-law fit was considered (based on the crossplot between Su and inverted shear modulus using several geotechnical boreholes, that is a “global adjustment”). Part of the produced pseudo-Su section (coloured) is included in the background.

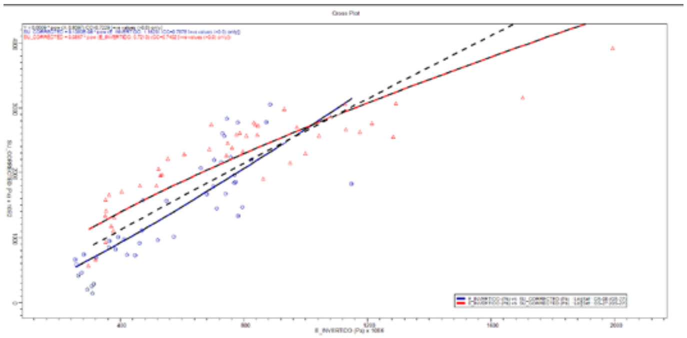

Figure 1 - Example of power-law fit for Albacora: individual adjustments for geotechnical borehole GS-27 (in red), borehole GS-08 (in blue) and global adjustment, considering both boreholes (in black), based on the crossplot between Su (vertical axis) – varying from 0 to 4,000 Pa x 10^2 - and inverted Young modulus (horizontal axis), varying from 0 to 2,000 Pa x 10^6

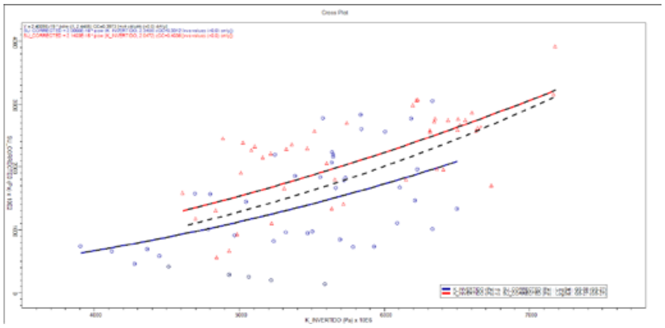

Figure 2 - Example of power-law fit for Albacora: individual adjustments for geotechnical borehole GS-27 (in red), borehole GS-08 (in blue), and global adjustment considering both boreholes (in black), based on the crossplot between Su (vertical axis) - varying from 0 to 4,000 Pa x 10^2 - and inverted bulk modulus (horizontal axis), varying from 0 to 7,800 Pa x 10^6

Figure 5 is an example of a “blind test” in Albacora area, but now comparing real qnet log with predicted or pseudo-qnet log derived through power-law fit and based on the crossplot between qnet and inverted Young modulus, using two geotechnical boreholes. By examining this example, as well as the one depicted in figure 4, it’s clear that the main natural geotechnical contrasts are caught in the pseudo-logs, both for Su and qnet. On the other hand, figure 6 shows the same as figure 5, but now considering inverted bulk modulus instead of inverted Young modulus. As expected from our previous findings, pseudo-qnet log here can hardly reproduce the behaviour of the real one.

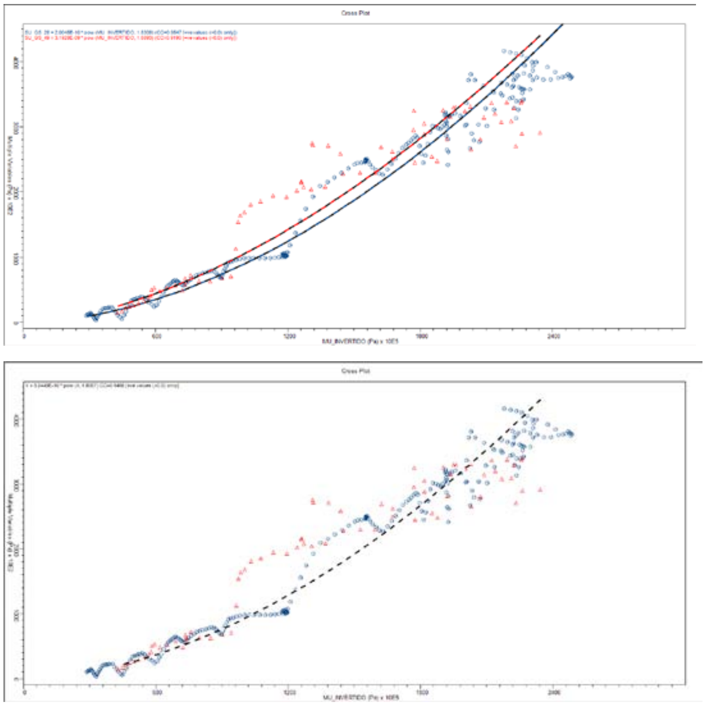

Figure 3 - Example of power-law fit for Marlim-Voador, based on a crossplot between Su (vertical axis) - varying from 0 to 4,000 Pa x 10^2 - and inverted shear modulus (horizontal axis), varying from 0 to 3,000 Pa x 10^5: above, individual adjustments for borehole GS-28 (in blue) and borehole GS-49 (in red); below, global adjustment considering both boreholes

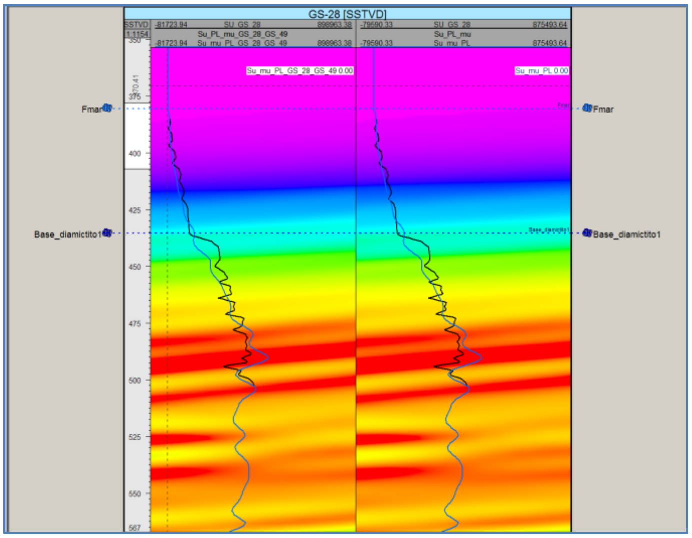

Figure 4 - Example for Marlim-Voador area: Su log (high cut filtered) from geotechnical borehole GS-28 (in black) and pseudo-Su log (in blue) empirically derived through power law fit between Su and inverted shear modulus for global adjustment using two geotechnical boreholes (on the left) and four boreholes (on the right); vertical scale is depth below sea level and ranges from 350 to 567 meters, and horizontal scale ranges from 0 to 900 kPa; background is part of the pseudo-Su section (higher values: red and lower values: magenta)

Conclusions

A quantitative approach was pursued and carried out in which empirically derived mathematical relations between geotechnical parameters and seismic inversion derived elastic moduli were established for two areas in Campos Basin, Southeastern Brazilian Margin. The generation of predicted or pseudo-logs of Su and qnet on arbitrary locations within the seismic volume enabled comparisons with real geotechnical logs, and the results may be considered good enough (at least for the elastic moduli related to S-wave such as μ and *E,* whose results are generally very similar) since the major natural geotechnical contrasts could be satisfactorily reproduced. However, since the mathematical relations here obtained are not really analytical, but otherwise empirically derived, its validity should be regarded as rather local to the investigated area under consideration, and expected to gradually lose its applicability as one departs away. Nevertheless, our work proceeds towards further developments and refinements.

The quantitative approach discussed here relies on first extracting elastic moduli from seismic data (preferentially good quality high-resolution and/ or multicomponent) and calibrating them with *in situ* measurements of Vs and density, obtained from special geotechnical boreholes. Thus our method assumes the existence of geotechnical boreholes having this kind of information (the so called ”GS boreholes”). To extend this method’s application elsewhere, in the absence of this kind of information one should argue to obtain Vs (or Vp) from other sources, and this could be the case of multi-sensor core logger data (MSCL), frequently acquired as a complement of geotechnical campaigns, where Vp and density data (among other medium’s physical properties) are obtained from geological samples (cores).

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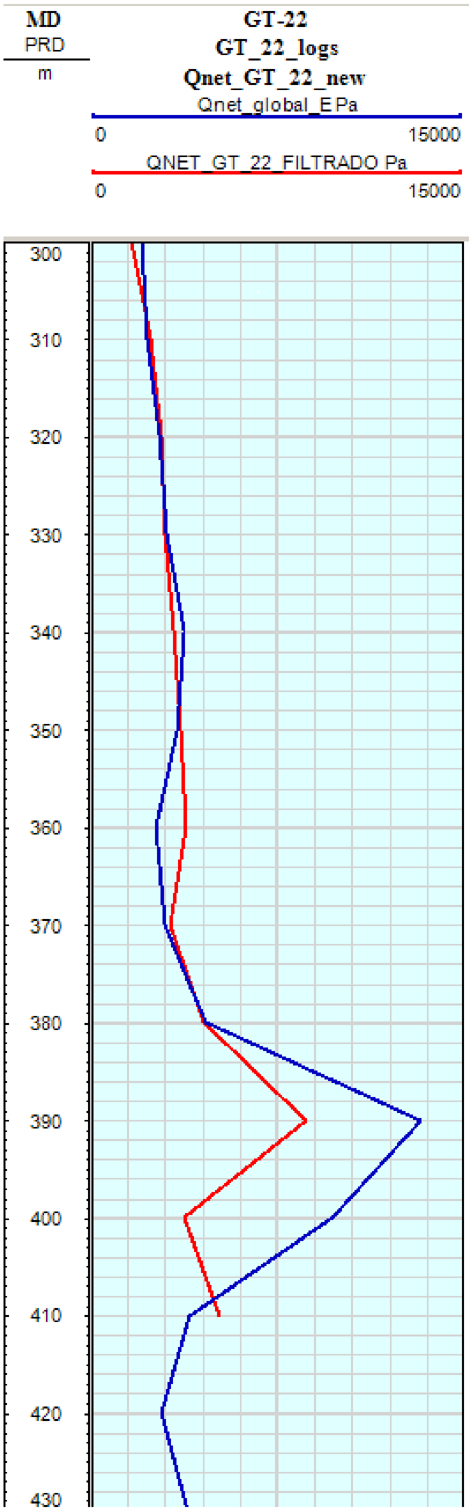

Figure 5 - Example for Albacora area: real qnet log (high cut filtered) from geotechnical borehole GT-22 (in red) and pseudo-qnet log (in blue) empirically derived through power law fit based on crossplot between qnet and Young modulus, with global adjustment (in this case, using two geotechnical boreholes); vertical scale is depth below sea level and ranges from 300 to 430 meters, and horizontal scale ranges from 0 to 15,000 Pa

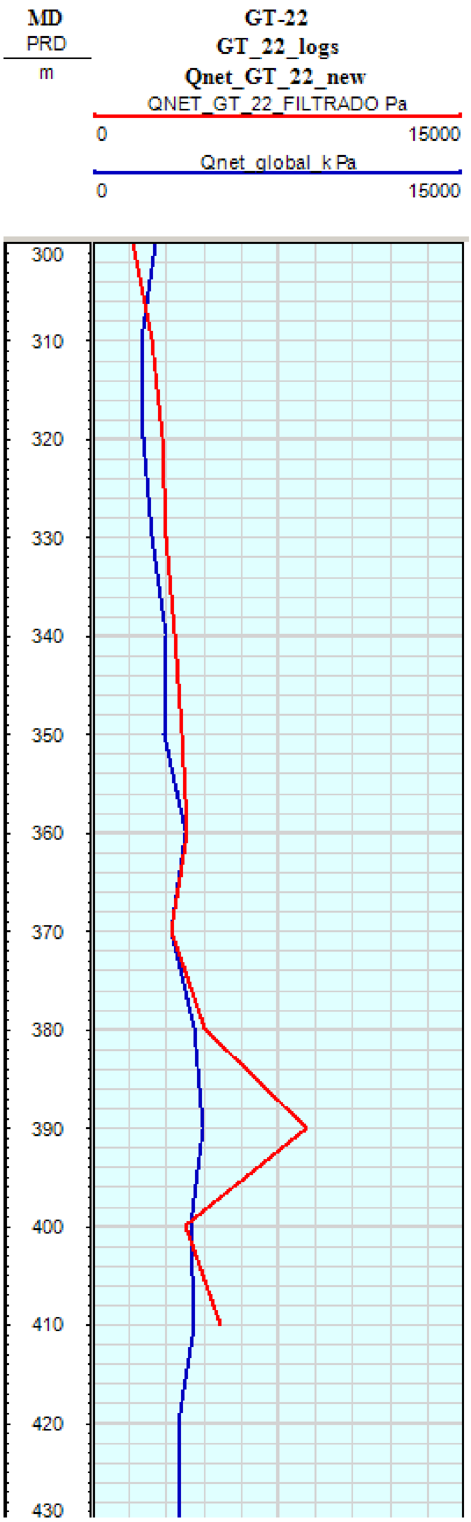

Figure 6 - Example for Albacora area: real qnet log (high cut filtered) from geotechnical borehole GT-22 (in red) and pseudo-qnet log (in blue) empirically derived through power law fit based on crossplot between qnet and bulk modulus, with global adjustment (in this case, using two geotechnical boreholes); vertical scale is depth below sea level and ranges from 300 to 430 meters, and horizontal scale ranges from 0 to 15,000 Pa

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