Relationship Between Shear Wave Velocity and Piezocone Penetration Tests on the Brazilian Continental Margin

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Abstract. A detailed characterization of the shear wave velocity profile is an essential tool in the resolution of a variety of seismological and geotechnical engineering problems. The main objective of this study is to present equations capable of providing reliable shear wave velocity profile estimations based on CPTu parameters. The results of a series of pioneering in-situ seismic piezocone penetration tests on the Brazilian continental margin are presented in this paper. A complete geological and geotechnical characterization of multiple sites was performed. Multiparameter and single parameter correlations were proposed between the measured shear wave velocity and the piezocone penetration test parameters. The suitability of the proposed correlations was evaluated by means of a statistical analysis and compared to the performance of previously published correlations using the test data parameters as input. The results show that the study was successful in presenting equations with superior performance for local soil conditions. Furthermore, this study yielded new reliable correlations that will benefit future projects in similar offshore environments.

Keywords: correlations, offshore geotechnical investigation, piezocone penetration tests, shear wave velocity.

1. Introduction

The shear wave velocity (V_s) is a fundamental property of soil, rock, concrete, steel, and other civil engineering materials. For geotechnical problems, the evaluation of the shear wave velocity is especially important in the definition of small-strain soil stiffness and is generally expressed in terms of the maximum shear modulus (G_{max}). Shear wave velocity is also useful in site response analysis, evaluation of liquefaction potential (Robertson & Wride, 1998; Youd *et al.*, 2001), soil classification, unit weight estimation, stratigraphy definition, as well as foundation settlement analysis (Andrus & Stokoe II, 2000; Schneider *et al.*, 2001; Andrus *et al.*, 2004; Mayne, 2007; Long & Donohue, 2010; Akin *et al.*, 2011; Chang *et al.*, 2011; Omar *et al.*, 2011). In Brazil, for example, the use of SCPT testing has mostly been limited to the identification of on-shore tropical sites (Giachetti *et al.*, 2006) due to limited availability of equipment (Vitali *et al.*, 2012).

Shear wave velocity measurements in soils can either be obtained in the laboratory, using resonant column tests or bender elements, or in-situ, using geophysical techniques. Compared to laboratory methods, in-situ techniques are advantageous since the soil is tested in its natural environment under anisotropic stress with minimal disturbance effects, which is important in the study of offshore environments. In this context, traditional CPTu combined with seismic measurements makes the Seismic Cone Penetration Test (SCPTu) the most cost-effective way to measure shear wave velocity (Schnaid, 2008).

A substantial number of studies have been conducted since the early 1980s to develop and evaluate empirical correlations between small-strain elastic properties, especially the shear wave velocity or the maximum shear modulus in soils, and the data from cone or piezocone penetration tests (*e.g.*, Rix & Stokoe II, 1991; Hegazy & Mayne, 1995; Mayne & Rix, 1995; Andrus *et al.*, 2007; Long & Donohue, 2010; McGann *et al.*, 2015; Zou *et al.*, 2017; Tong *et al.*, 2018). These studies have shown that cone resistance, sleeve friction, confining stress, depth, and the behavior and geological age of the soil influence the correlations.

Data scatter is a factor to be considered for this type of correlation (Wair *et al.*, 2012), and in order to minimize its influence, correlation studies are usually separated into three categories:

- Correlations for clay - undrained behavior (*e.g.*, Mayne & Rix, 1995; Long & Donohue, 2010; Taboada *et al.*, 2013; Zhang & Tong, 2017);
- Correlations for sands - drained behavior (*e.g.*, Baldi *et al.*, 1989; Hegazy & Mayne, 1995; Taboada *et al.*, 2015);
- Correlations for soils in general (*e.g.*, Hegazy & Mayne, 1995, 2006; Robertson, 2009; McGann *et al.*, 2015).

The use of empirical correlations is an easy and straightforward method for estimating shear wave velocity profiles for numerous applications based on parameters obtained through in-situ tests, or more simply, from vertical

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effective stresses. Nevertheless, the quality of the correlations is directly linked to the data used, which may not be appropriate for local conditions. Thus, it is important to validate available equations or develop new ones with local data whenever possible. The increasing number of engineering projects in this field, however, makes it vital to properly assess the agreement between measured and predicted values. According to Zhang & Tong (2017), this assessment can be done in terms of simple statistical descriptive parameters (*i.e.*, coefficient of determination, variable coefficient) or with a more complete statistical analysis (*e.g.*, Onyejekwe *et al.*, 2016).

Direct shear wave velocity V_s measurements are always preferable to estimates based on correlations with cone or piezocone penetration tests. However, such estimates can be particularly useful for projects where it is not possible or economically feasible to obtain local V_s measurements.

The main objective of this study is to provide new and reliable correlations that relate CPTu parameters with V_s values for the Brazilian offshore environment. The present research makes use of the first and only dataset from available deep seismic piezocone penetration tests conducted across the Brazilian continental margin between the years 1991 and 1992. Initially, these test results were compared to correlations found in the literature, both for datasets with similar geological conditions as well as general conditions. Statistical correlations were then developed to estimate the shear wave velocity in the soil deposits of these test sites using the parameters from the piezocone penetration tests. Finally, the results for both sets of correlations were evaluated using the statistical approach described by Zhang &

Tong (2017), in order to properly describe the agreement between the measured and predicted shear wave velocities.

2. Site Characterization

The piezocone (CPTu) tests were performed in two sedimentary basins, Campos and Santos, on the Brazilian continental margin (Fig. 1). There was a total of 10 study points (4 in the Campos Basin and 6 in the Santos Basin) on the continental slope, each of which is an oil and gas production development field, as shown in Fig. 1.

These tests were performed during the site investigation campaign to characterize geohazards and support the foundation design of fixed and floating oil and gas production platforms to be installed in these areas.

2.1. Offshore CPTu testing

A geological and geotechnical site investigation was performed by Fugro-McClelland Marine Geosciences, Inc. for the Brazilian oil company Petrobras from October 1991 to March 1992. The geotechnical boreholes were performed in water depths ranging from -110 m (located in the Tubarão Field) to -502 m (in the Voador-2 Field), and the penetration depths varied between 50 m and 151 m below the seafloor.

The Fugro-McClelland WISON® MkIII cone penetration test system was used, enabling in-situ soil properties to be measured from the base of the borehole (Lange, 1991) and extraction of in-situ samples. The piezocone penetration tests were performed with a standard cone tip (0.001 m² cone base area; 60° apex). The probe was pushed into the seabed at a constant rate of about 0.02 m/s, providing a semi-continuous record of the cone tip resistance (q_c), sleeve

Figure 1 - Location of Campos and Santos basins with respective investigated fields.

ve friction (f_s) and pore pressure generated during the penetration (u_2).

The downhole technique was used, which allowed sample collection and in-situ vane tests between successive probe pushes. This technique consisted of performing the CPTu, removing the probe and pushing the sample extractor and vane device for 1 meter, then reinitiating the CPTu. The intervals of sampling varied according to the depth, ranging from 3 m to 10 m. Because of the length of the borehole dedicated to sample extraction, the profiles obtained do not have a continuous shape, as can be seen in Fig. 2.

The shear velocity measurements were made by means of a set of biaxial geophones arranged orthogonally

in the horizontal plane, approximately 0.4 m above the cone tip. A shear wave hammer was used as the seismic source and activated multiple times until a satisfactory signal/noise ratio was obtained. Travel times were computed using the characteristic points approach.

2.2. Geological description

The geomorphology of the Campos and Santos basins on the continental margin was largely controlled by the underlying salt tectonics and the depositional geometry of the Upper Miocene. Its current form results from variations in the sea level, contour-current action, sediment remobilization through mass movements, structural geology, imple-

Figure 2 - Albacora Field CPTu profile.

mentation of turbidity systems associated with fluvial systems on the continent, and the control of this drainage by salt tectonics. Systematic sampling and dating of the seabed with piston corers determined that this geomorphology is representative of the end of the Pleistocene and that the subsequent sea level rise during the Holocene interrupted almost all the active processes in the area (Kowsmann *et al.*, 2000; Vicalvi & Kowsmann, 2006).

Some of the piezocone penetration tests in the study area exceeded 100 m in depth below the seafloor, and the paleoclimate curves constructed for the recovered stratigraphic sequences show that they reached a maximum age of 145,000 to 150,000 years B.P., placing them in the Upper Quaternary. The observations made by Vicalvi (1999) regarding the samples recovered from the study area indicate that the Holocene/Pleistocene boundary is always characterized by mud, at variable depths, but relatively close to the seafloor.

2.3. Geotechnical description

The laboratory characterization consisted of index tests such as Atterberg limits, particle size distribution, carbonate concentration, as well as oedometer and triaxial tests. Table 1 presents a summary of soil properties for the Campos and Santos basins.

Figure 3 shows the plasticity chart for the fine-grained samples from both basins. As observed, most of the samples retrieved during the campaign can be classified either as CH or CL in the Unified Soil Classification System (USCS). In fact, 86 % of the samples fall into those categories.

For the Campos Basin, the typical geotechnical profile consists of a shallow silty/sandy layer, and layers of silty clay with a few interbedded layers of clayey silts and/or fine sand. Additionally, the presence of organic material, biotite, and bioclasts was detected in all the layers, with an OCR profile varying from normally to slightly overconsolidated clays.

The characteristic profile for the Santos Basin can be described as silty clay with a coarse-grained top layer and interbedded silty/sandy layers. As in the Campos Basin, all the boreholes at this location have a high presence of organic material, biotite, and bioclasts, and the OCR profiles indicate normally to slightly overconsolidated clays.

2.4. Data analysis

Due to the large number of boreholes, Fig. 2 shows the deepest CPTu profile (located in the Albacora Field), which is typical in terms of soil characteristics. Note that the parameter profiles do not appear continuous in Fig. 2 due to the necessary interruptions to run sample extraction and in-situ vane tests.

Complementary to the measured parameters (q , f , u_2 and V_s), the Soil Behavior Type Index (I_c) (Robertson & Wride, 1998) was calculated according to Eq. 1.

Table 1 - Summary of the soil properties.

Basin	Field	Code	Max depth (m)	Number of samples	CL-CH (%)	Unit Weight (kN/m ³)	Water content (%)	I_p (%)	C_c	CaCO ₃ (%)
Campos	Albacora	GS08	151	24	75	17.3-19.0	27.1-39.6	9-52	0.4-0.6	5.0-35.0
		GS27	120	15	93	14.3-28.3	29.6-34.1	26-45	0.4-0.8	6.4-41.5
	Voador	GS28	118	22	95	16.1-19.4	28.5-64.7	18-44	-	18.0
Santos	Tubarão	GS49	124	20	95	16.7-18.8	29.3-62.3	22-54	0.5-0.9	5.7-35.3
		GS80	51	12	92	16.8-18.0	39.1-55.0	18-61	0.6-1.3	5.0-58.5
	Estrela do Mar	GS90	50	11	81	16.4-18.1	40.4-56.1	33-59	0.3-1.1	8.3-46.0
		GS91	117	18	88	16.6-19.0	35.1-52.6	20-51	0.5-0.9	4.6-30.5
	Coral	GS92	44	13	70	16.7-19.5	28.2-56.2	15-51	0.2-0.8	53.7-68.3
		GS100	75	14	79	17.0-19.5	36.6-66.7	25-49	0.6-1.0	4.2-50.2
		GS101	117	18	83	17.0-19.8	41.3-56.2	31-62	0.8-1.0	4.0-51.6

Figure 3 - Plasticity chart for the fine-grained samples.

$$I_c = [(3.47 - \log Q_{it})^2 + (\log F_r + 1.22)^2]^{0.5} \quad (1)$$

where Q_{it} is the normalized penetration resistance and F_r is the normalized friction ratio.

In order to give a more precise overview of the general behavior of the entire CPTu campaign, the density distributions for shear wave velocity and I_c are presented in Fig. 4. As illustrated in Fig. 4, much of the soil profile can

be classified as clay, according to the Robertson & Wride (1998) classification system. With respect to the shear wave velocity, the density plot in Fig. 4a indicates that most of the points are in the 200-400 m/s interval. Regarding the Soil Behavior Type Index (Fig. 4b), most of the points have I_c values between 2.95 and 3.6, indicating a prevalence of clayey soil behavior. As shown in Fig. 2, and indicated by the significant density in Fig. 4b, sandy and silty layers are also present in most profiles.

Shear wave velocity values are assumed to be constant along the measurement depths. In the CPTu campaign, the V_s measurements coincided with the sampling operation, with intervals ranging from 3 m to 10 m, which is greater than the ideal interval of 0.5 m (McGann *et al.*, 2015). However, two factors must be considered regarding these high sampling interval values. The first is related to the fact that the data was collected long before this analysis, precluding any such control. Secondly, with sampling depths of up to 150 m and a uniform Soil Behavior Type Index distribution for most of the profiles, the sampling intervals are likely to have a lower impact on data quality.

The total number of V_s data points is 258. In order to compare these V_s measurements with those of the CPTu data, the midpoint depth for each sampling interval is used and the other parameters are averaged, as recommended by Tonni & Simonini (2013) and Andrus *et al.* (2007). This

Figure 4 - Distribution of: (a) shear wave velocity and (b) soil behaviour type index.

procedure attenuates the effects of using long intervals for shear wave velocity measurements and the subsequent comparison with CPTu data. Even though it may be argued that this procedure could associate two layers with very different characteristics, it is still better than considering the midpoint approach for all CPTu parameters. The latter could introduce a localized condition with a respective V_s value and thereby misrepresent the entire layer (McGann *et al.*, 2015).

3. Previous Published CPTu- V_s Correlations

CPTu- V_s correlations have long been an object of study. Different methodologies and equations have been proposed for various site conditions. On the one hand, it is necessary to understand the nature of the database that generated soil-type specific equations, before applying them to site-specific CPTu data. On the other hand, generic correlations (Robertson, 2009; McGann *et al.*, 2015; McGann *et al.*, 2018; Tong *et al.*, 2018) can be applicable for all soil types as they introduce parameters that can account for differences in behavior, such as I_c and B_q (McGann *et al.*, 2015).

In this study, four relatively recent published correlations are analyzed using the local CPTu data: two generic correlations (Robertson, 2009; Tong *et al.*, 2018), and two for specific soil types (Long & Donohue, 2010; Taboada *et al.*, 2013). This selection was based on a preliminary fit analysis for the generic correlations and for the correlations with similar offshore conditions for the specific soil type. A brief discussion of the chosen correlations is made before the description of the statistical analysis used to fit the data.

3.1. Generic correlations

Robertson (2009) presented a CPTu- V_s correlation based on a large dataset comprising 1,035 points. The variable I_c was introduced to account for the soil type variability, and the initial vertical stress (σ_{v0}) is subtracted from the corrected cone tip resistance (q_t) and normalized by the atmospheric pressure (p_a). Equation 2 shows the general form of the equation proposed by Robertson (2009).

$$V_s = \left[10^{(0.55 I_c + 1.68)} \left(\frac{q_t - \sigma_{v0}}{p_a} \right) \right] \quad (2)$$

Tong *et al.* (2018) developed multiple regression forms based on 14 CPTu tests performed in Holocene floodplain deposits in Nanjing, China, with heterogeneous stratigraphy profiles. The main characteristic of these deposits is related to the presence of silt and sand mixtures, with thinly interbedded layers of various materials. Following the recommendations of Wair *et al.* (2012), Eq. 3 represents the chosen analyzed correlation.

$$V_s = 215 q_t^{0.122} f_s^{0.172} \sigma_{v0}'^{0.172} \quad (3)$$

3.2. Soil-type specific correlations

Long & Donohue (2010) proposed correlations between V_s and CPTu data for ten Norwegian marine soft clays based on previous characterization studies. The database included high-quality in-situ measurements and laboratory tests, in order to minimize uncertainties and improve accuracy. Equation 4 shows the relationship from Long & Donohue (2010) based only on the parameter q_t .

$$V_s = 2.944 q_t^{0.613} \quad (4)$$

Following the general formula proposed by Simonini & Cola (2000), where the normalized pore pressure B_q defined in Eq. 5 is used to substitute for the use of the initial void ratio e_0 , Long & Donohue (2010) proposed a correlation relating shear wave velocity to the parameters q_t and B_q , as shown in Eq. 6.

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} = \frac{\Delta u}{q_{net}} \quad (5)$$

$$V_s = 1.96 q_t^{0.579} (1 + B_q)^{1.202} \quad (6)$$

They suggest that both formulas (Eqs. 4 and 6) can be used without any prejudice to the estimated V_s profile. However, in a preliminary fit quality analysis for the data presented in this work, the second form of regression provided the best set of parameters and, therefore, Eq. 6 was chosen for further analysis.

Taboada *et al.* (2013) analysed P-S logging data for the Bay of Campeche, Mexico, aiming to evaluate the geohazards involved in offshore petroleum exploration. Their study can be directly related to the present work, as it was developed under similar site conditions. The water depths varied from 14 m to 102.3 m with a maximum penetration depth of 121.9 m. The soil profile was composed of soft clay deposits at shallow depths, reaching a maximum of 25 m in the north-eastern portion of the study area. After the top clay layer, a sequence of stiff to hard clays and medium-dense to very-dense sand was found. The correlations that were developed focused on using data from the clay layer, providing soil type-specific correlations. Among the proposed formulae, there are three correlations that included the CPT parameters available in the dataset of the present study, and only one (Eq. 7) with a multiple variable approach which presented the best preliminary agreement between measured and estimated V_s values.

$$V_s = 14.4 q_{net}^{0.265} \sigma_{v0}'^{0.137} \quad (7)$$

where q_{net} is the net cone resistance obtained from Eq. 8.

$$q_{net} = q_t - \sigma_{v0} \quad (8)$$

3.3. Statistical methods for validation of correlation equations

In order to obtain a good match between predicted and measured shear wave velocity values, many authors

(e.g., Onyejekwe *et al.*, 2016; Zhang & Tong, 2017; Tong *et al.*, 2018) have used a more complete analysis with the evaluation of four indexes: Prediction Bias (K), Ranking Index (RI), Ranking Distance (RD) and Root Mean Square Error ($RMSE$).

The Ranking Index K is the ratio between the estimated and measured V_s . According to Onyejekwe *et al.* (2016), the mean of K usually represents the level of accuracy, whereas its standard deviation indicates the precision of the proposed correlation. The optimum value for the mean value of K is 1, indicating no underestimation or overestimation. The Ranking Index can be expressed by Eq. 9.

$$K = \frac{V_{se}}{V_{sm}} \quad (9)$$

where V_{se} is the estimated shear wave velocity and V_{sm} is the measured value (Briaud & Tucker, 1988).

The Ranking Index was proposed to provide a better estimate for correlation quality. The Ranking Index RI is defined by Eq. 10.

$$RI = |\mu_{\ln|K|} + \sigma_{\ln|K|}| \quad (10)$$

where μ and σ are the mean and standard deviation of the data, respectively.

Another parameter to evaluate the fitness of the measured to the estimated data is the Ranking Distance (RD), originally proposed by Cherubini & Orr (2000). On a plot with mean (μ) values on the x-axis and standard deviation (σ) on the y-axis, RD represents the distance from the optimum condition point, where $\mu_K = 1$ and $\sigma_K = 0$, to the point calculated using the correlation (Tong *et al.*, 2018). Equation 11 expresses the Ranking Distance.

$$RD = \sqrt{(1 + \mu_K)^2 + (\sigma_K)^2} \quad (11)$$

The Root Mean Square Error ($RMSE$) is the square root of the squared difference between the estimated and measured shear wave velocities. Large errors produce large $RMSE$ values. Therefore, lower $RMSE$ values indicate better model performance. Equation 12 defines the Root Mean Square Error, where n is the number of data points.

$$RMSE = \sqrt{\frac{1}{n} \sum_1^n (V_{se} - V_{sm})^2} \quad (12)$$

3.4. Comparisons

Figure 5 shows the prediction performance of the four aforementioned correlations from the literature using the dataset of the present study. The measured shear wave velocity values (V_{sm}) were plotted against the estimated values (V_{se}) to show the scatter relative to the 1:1 line. The histogram plots provide an overview of bias distribution showing the mean μ , the standard deviation σ and the Coefficient of Variation CoV . The lower the values of the latter two, the more accurate the estimate.

Among the four correlations selected from the literature, the one proposed by Long & Donohue (2010) was the least applicable, Fig. 5(e, f). The graph shows a large amount of scatter around the 1:1 line, with an R^2 of 0.71 and a mean bias of $\mu = 1.16$, indicating overestimation. This correlation did not yield good results when compared to the other three correlations. The most applicable equation of the four was the one presented by Taboada *et al.* (2013), Fig. 5(g, h). It shows the most accurate mean bias of 0.97, indicating a slight tendency for underestimation, and it provided the highest R^2 , with a value of 0.76. The generic correlations from Robertson (2009), Fig. 5(a, b), and Tong *et al.* (2018), Fig. 5(c, d), showed comparable prediction performance, with a tendency for underestimation. The Tong *et al.* (2018) correlation presented the most precise equation, as indicated by the lowest standard deviation for Prediction Bias K ($\sigma = 0.13$). Table 2 summarizes quantitatively the results of the complete statistical analysis presented in the previous section, thus helping to corroborate the analysis shown in Fig. 5. In summary, the correlation from Taboada *et al.* (2013) was the most accurate and precise equation, with the best prediction performance for the dataset used in this study, and the lowest values of $RMSE$, RI and RD . On the other hand, the Long & Donohue (2010) equation was the least applicable correlation, yielding the highest value for all three parameters.

4. Proposed CPTu- V_s correlations

The data from the in-situ piezocone penetration tests and the estimated shear wave velocity, based on correlations from previous studies, were used to examine trends for the soils in the present study.

In order to obtain more accurate and precise models for the given site conditions, nonlinear regression analyses were carried out to obtain the shear wave velocity profile, by adjusting power function curves to the data from the ten

Table 2 - Statistical parameters from the analysis of the literature correlations.

Correlation	Equation	R^2	K			RI	RD	$RMSE$
			% > 1	μ	σ			
Multiple	15	0.84	51.12	1.01	0.13	0.134	0.131	39.08
Single	16	0.77	58.14	1.01	0.15	0.155	0.148	45.71

Figure 5 - Prediction performance of correlations from the literature using the soil conditions from the present study.

boreholes performed in the region. Two model equations were used to generate the proposed correlations. Equation 13 presents the form suggested by Wair *et al.* (2012), using a multiparameter analysis to obtain the shear wave velocity, which is only applicable when CPTu data are available.

$$V_s = a q_t^b f_s^c \sigma'_{v0}{}^d \quad (13)$$

Equation 14 proposes a single variable analysis using only the vertical effective stress σ'_{v0} .

$$V_s = a \sigma'_{v0}{}^b \quad (14)$$

Equations 15 and 16 were then obtained to estimate V_s in m/s, with q_t , f_s and σ'_{v0} in kPa (258 data pairs in total were used in these regression analyses).

$$V_s = 9.741 q_t^{0.369} f_s^{-0.1402} \sigma'_{v0}{}^{0.1437} \quad (15)$$

$$V_s = 34.641 \sigma'_{v0}{}^{0.342} \quad (16)$$

5. Discussion

Figures 6 and 7 present the prediction performance of the proposed CPTu- V_s correlations, for multiparameter and

single parameter conditions, respectively, with Table 3 summarizing the statistical parameters. As expected, the multiparameter Eqs. 15 (Fig. 6) provided a more applicable correlation, with an R^2 of 0.84 (Fig. 5a), than the single parameter correlation of Eq. 16 (Fig. 7) with an R^2 of 0.77 (Fig. 6a). Equation 15 also had lower values of RI , RD and $RMSE$ (Table 2), corroborating the Coefficient of Determination, R^2 , cited above.

However, the model proposed by Eq. 16 can be used when data from piezocone penetration tests are not available and it has been shown to provide similar shear wave velocity profiles for use in preliminary investigations. In a comparison between the literature correlations (Table 2) and the proposed correlations (Table 3), the last ones exhibited better performance based on all statistical parameters, as expected. Nevertheless, one must be aware that the proposed equations are only valid for similar geological conditions and should not be applied as general correlations.

Figure 8 presents a direct comparison between the proposed and the literature equations with the measured shear wave velocity profile for the Albacora Field. It may be observed that the proposed equations have a better over-

Figure 6 - Performance of the proposed CPTu- V_s correlations for multiparameter correlation.

Figure 7 - Performance of the proposed CPTu- V_s correlations for single parameter correlation.

Table 3 - Statistical parameters from the proposed correlations.

Reference	Equation	R^2	K			RI	RD	$RMSE$
			% > 1	μ	σ			
Robertson (2009)	2	0.74	24.42	0.91	0.15	0.277	0.173	51.614
Tong <i>et al.</i> (2018)	3	0.74	13.18	0.87	0.13	0.304	0.184	62.085
Long & Donohue (2010)	6	0.71	78.40	1.16	0.23	0.352	0.277	79.770
Taboada <i>et al.</i> (2013)	7	0.76	37.99	0.97	0.14	0.188	0.142	44.406

all fit to the measured V_s values than the literature equations. It is also seen that among the literature correlations, the one proposed by Taboada *et al.* (2013) had the best fit, and that proposed by Long & Donohue (2010) the worst fit, as pointed out above. The correlations proposed by Tong *et al.* (2018) and Robertson (2009) ranked intermediately between the other two, with a less satisfactory agreement for depths 0-60 m.

6. Conclusions

The present study made use of an existing database of in-situ measurements of shear wave velocity and piezocone penetration test parameters conducted on the Brazilian continental margin in order to make reliable correlations between CPTu parameters and V_s values. The data were collected at ten borehole locations from five areas during a site

Figure 8 - Shear wave profile comparison - Albacora Field.

investigation campaign performed for the Brazilian oil company Petrobras, for geohazards assessment and foundation design of oil platforms.

With these available data, four published correlations from the literature were evaluated and two new correlations were proposed. The prediction performance of the correlations was measured in terms of multiple statistical parameters. The main conclusions of this work are as follows:

- The correlation presented by Taboada *et al.* (2013) had the best fit, as expected, considering the similar geological background to the one studied here.
- The correlation proposed by Long & Donohue (2010) yielded the worst fit, primarily because it is the more general database, including data from all types of soil profiles;
- Two new correlations were proposed, using multiparameter analysis and single parameter analysis. The multiparameter correlation yielded the best overall agreement with measured data, as expected. However, since the effective vertical stress is an elemental geotechnical variable, the proposed single parameter correlation can be a powerful tool for preliminary studies;
- Particular attention and engineering judgment should be exercised when applying the proposed CPTu- V_s correlations to sites with soil conditions that differ from those of the database used in this work;

- This study yielded new reliable correlations that will benefit future projects in similar offshore environments.

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List of Symbols

- CaCO_3 : calcium carbonate
 R^2 : coefficient of determination
 CoV : coefficient of variation
 C_c : compression index
 q_t : corrected cone tip resistance
 d : depth below mudline
 σ'_{v0} : effective vertical stress
 Δu : excess pore pressure
 u_0 : hydrostatic pore pressure
 G_{max} : maximum shear modulus
 μ : mean
 q_c : measured cone tip resistance
 u_z : measured pore pressure at the position u_z
 q_{net} : net cone resistance
 Q_n : normalized cone resistance
 n : number of samples
 I_p : Plasticity Index
 B_q : pore pressure ratio
 K : prediction bias
 RD : ranking distance
 RI : ranking index
 $RMSE$: root mean square error
 V_s : shear wave velocity
 f_s : sleeve friction
 I_c : soil behavior type index
 σ : standard deviation
 γ : total unit weight
 σ_{v0} : total vertical stress
 s_u : undrained shear strength