XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020
FOZ DO IGUAÇU
PARANÁ – BRAZIL

Variation of Measured CPTu Data of Brazilian Marine Soil

Christiano A. F. Várady Filho[1], Adlehr Gabriele C. Oliveira[1], Aline V. Esteves[1], Beatriz R. Barboza[1], Eduardo Toledo de Lima Júnior[1], João Paulo Lima Santos[1], Rafael Dias[2], Fabio Sawada Cutrim[2]

[1]*Laboratório de Computação Científica e Visualização, Universidade Federal de Alagoas*
Av. Lourival Melo Mota, S/N, CEP 57072-900, Tabuleiro do Martins, Maceió - AL, Brazil
christiano_varady@lccv.ufal.br
[2]*Cenpes - Petrobras*
Av. Horácio Macedo, 950, CEP 21941-915, Cidade Universitária da Universidade Federal do Rio de Janeiro, Rio de Janeiro - RJ, Brazil

Abstract. Soil profiling and estimation of soil parameters (e.g. undrained shear strength) are essential to the design of oil wells. Piezocone Penetration Test (CPTu) is one of the most used tests to characterize geomechanical behavior. Uncertanties regarding CPTu data reflects in transformation models for undrained strength evaluation. Present work assess variability of cone tip resistance and total vertical stress data obtained from CPTu tests in brazillian geological basins and its effect in undrained shear strength transformation model. DNV's recommended practice C207 assess undrained strength characteristc values that are used in conductor casing design, which plays an important role in structural integrity and safety of well operations serving as foundation element, supporting all construction and operation phases. Results shows low levels of uncertanties and good overall repeatability, an indicator of good quality of data.

Keywords: Uncertanties; CPTu; Geomechanics.

1 Introduction

Soil profiling and estimation of soil parameters (e.g. undrained shear strength, specific weight) are essential to the design of oil wells. The Piezocone Penetration Test (CPTu), among the *in situ* test methods, is one of the most used tests to characterize geomechanical behavior due to the fact that is a robust, simple, fast, and economical test that provides continuous soundings of subsurface soil (Abu-Farsakh and Nazzal [1]; Zou et al. [2]).

Furthermore, Abu-Farsakh and Nazzal [1] and Zou et al. [2] also highlight that the best estimates of soil properties are central unbiased estimates with lowest possible standard errors. Best estimates are normally used for assessment of serviceability limit states, i.e. whenever problems are found for which predictions of the expected foundation behaviour are of interest. According to Knuuti and Länsivaara [3], estimation of soil properties always includes some uncertainties arising from different sources i.e. spatial, measurement, statistical, model and transformation variabilities. Moreover, Phoon and Kulhawy [4] demonstrated using statistics that geotechnical variability depends on the site condition, measurement error (which is associated with a field test) and quality of the correlation model adopted to relate the field test to a design property.

Knuuti and Länsivaara [3] and Veritas [5] divide uncertanties in two categories: aleatory and epistemic uncertainties. The aleatory uncertainty is attributed to outcomes that, for practical purposes cannot be either predicted or reduced, as it has been developed over the time through multiple physical processes. Aleatory uncertainty is, therefore, treated as stochastic (e.g., soil strength, varying from point to point throughout a soil volume), whereas epistemic uncertainty consists on measurement uncertainty, statistical uncertainty, transformation uncertainty and model uncertainty and is attributed to missing information or expertise. The epistemic uncertainty, in contrast to the aleatory uncertainty, can be reduced by using more precise testing methods or increasing the number of the tests (Knuuti and Länsivaara [3]).

Measurement uncertainty is caused by the equipment, procedural/operator, and random testing practices (Phoon and Ching [6]). In the literature, measurement errors are ignored in spatial variability analysis for simplification purposes. However, for sensitive soft clays, small measurement errors may have a considerable impact on the measured tip resistance and interpreted soil strength (Mayne [7]). The transformation uncertainty arises when soil properties are indirectly derived. Therefore, the fact that design properties are derived from different correlation and transformation models adds more uncertainty into the design process.

Acoording to Knuuti and Länsivaara [3], the statistical uncertainty is related to random measurement fluctuations. These random fluctuations can occur in measuring devices even when the motion detector is measuring the distance to a stationary object. Random fluctuations can also be a characteristic of the quantity being measured. The model uncertainty, as the name suggests, corresponds to the variability associated to the used model, which carries simplifications inherent to its derivation, either in a rational, empirical or numerical approach. All of these uncertainties are often described as the values of the Coefficient of Variation (COV), which will be discussed in Section 2. In brief, the transformation uncertainty is calculated for both models at each site and the bias factor as well as the COV were evaluated.

DNV-RP-C207 [5] states that soil characteristic values are used to represent properties such as soil undrained shear strength (S_u). Regarding lower and upper bounds values, soil reports often specify them to be adopted as characteristic values in well design. Lower bounds are usually meant for design against the ultimate limit state where low strengths are unfavourable and upper bounds are usually meant for considerations where large strengths are unfavourable. For instance, the evaluations of skirt penetration resistance for installation of skirted foundations and pile driving resistance for installation ability of piles by means of particular pile driving hammers. For design of structures subjected to cyclic loading or influenced by dynamic behaviour, it may be necessary to perform sensitivity studies for both lower and upper bound values for relevant soil properties for the supporting foundation soils.

Phoon and Kulhawy [4] affirm that the direct measurement from a geotechnical test is not directly applicable to design. Instead, a transformation model is needed to relate the test measurement to an appropriate design parameter. One example is undrained strength transformation model that uses cone tip resistance q_T, total vertical stress σ_{v0} and cone factor N_{kt}

$$S_u = \frac{q_T - \sigma_{v0}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \tag{1}$$

also, q_{net} is total cone resistance.

The present work assesses CPTu data uncertainties that are used in an undrained shear strength S_u transformation model. It is also important to say that numerous correlations for cone factors are presented in literature to evaluate S_u for site-specific soil conditions. However, the cone factors used in this study has been directly provided by the company's geotechnical analysis report for each basin.

Moreover, the used data consists of CPTu boreholes from brazilian geological basins. Following the geotechnical analysis report for these basins, only soft clay layers from the CPTu profiles were taken into the calculations in order keep the soil homogeneity. The crust layer on the top of the soft clay and the denser layer at the bottom of the clay were excluded. It is worth mentioning that when the soil strata at nearby locations is required during a design process, the results at the existing location generally cannot be used directly due to the significant variability of natural soils (Lloret-Cabot et al. [8]). The stratification of natural soil may change greatly within a small horizontal distance of, nearly, 15m (Das and Sobhan [9]).

2 Soil statistics

Statistical analyses are commonly used to investigate the variability in the measured data or a single parameter. In the field of marine engineering, the sample size is usually very limited and the quality of the data may vary significantly. According to Knuuti and Länsivaara [3], the biased estimates are not fully representative of the real data distribution, but they are often more useful for standard design applications than complicated probability distributions. Furthermore, the calculation of first two statistical moments (sample mean μ and standard deviation σ), are sufficient for most geotechnical design cases as the complexity and error increases at higher moments.

The amount of soil property uncertainty x is usually represented by COV, which is a dimensionless ratio between the standard deviation σ and the mean value μ of the property

$$COV_x = \frac{\sigma_x}{\mu_x} \tag{2}$$

Knuuti and Länsivaara [3] highlight that usually a large COV value indicates large uncertainties, but these are not entirely comparable. The uncertainties arising from different sources discussed on Section 1 can be combined as the sum of different uncertainty components to a single value using

$$COV_X^2 = COV_{spat,X}^2 + COV_{err,X}^2 + COV_{trans,X}^2 + COV_{stat,X}^2 + COV_{mod}^2 \tag{3}$$

where $COV_{spat,X}$, $COV_{err,X}$, $COV_{trans,X}$, $COV_{stat,X}$ and COV_{mod} are for spatial, measurement, transformation, statistical and model uncertainty. Also, COV_X is the total uncertainty related to parameter X (Phoon [10]).

Another important factor analysed is the bias factor b, which is the sample mean of the measured value divided by the mean value for the global data points

$$b = \frac{1}{n}\sum_{i=1}^{n}\frac{x_i}{\mu_i} \tag{4}$$

where the measured value x_i indicates property value at a certain depth i and the property mean value (μ_i) at the same depth i. The b value may vary significantly but values next to 1 indicate that the measured values from each point are close to the mean value, representing a good overall repeatability. On the other hand, values far away from 1 represent a poor data repeatability, meaning that data varies a lot in a short interval.

In the end, the parameter variability ε was used in order to validate the results

$$\varepsilon = \frac{measured\ value}{b \times mean\ value}\,. \tag{5}$$

The product of constant b and the mean value leads to unbiased estimation on the average and variability ε has a mean of 1 by definition.

3 Evaluation of Measured CPTu Data

This section details the main properties of the analysed test sites and how the CPTu tests were executed. Due to the company's privacy policy, all data was decharacterized. Four clay test sites were considered in this study: Test site A to D. Maximum penetration depths for CPTu boreholes at each site were 8m at A and C and 10m at B and D.

The CPTu tests results are available on company's geotechnical analysis reports executed using API RP 2GEO standard [11] in evaluation of the axial load of the conductor casing. Design teams follow this kind of report to assess the number of joints to be applied in wells and to analyze structural behavior of Subsea Wellhead System (SWS) for fatigue life evaluation.

The statistical mean values μ and the standard deviation σ of cone tip resistance q_T and total vertical stress σ_{v0} were calculated for each site. There are three boreholes for each site and measurements were taken each 2 cm. Statistical analysis is performed in the following way: for each CPTu borehole, the bias factor b and its COV are calculated at each depth with Equations 4 and 2, respectively. After that, COV is also calculated for the combination of the CPTu boreholes, that is, for the test site as a whole, considering all data as a single sample. In the end, Eq. 5 is used to ensure the results reliability.

The data uncertainty related to Eq. 1 arises from multiple factors. In this study, only the inherent variability and the measurement uncertainty are taken into account, as we aim to evaluate the uncertainty of the transformation models itself. The inherent and the measurement uncertainty within a soil volume will be subtracted in order to obtain the actual transformation uncertainty, following Eq. 6, derived from Eq. 3.

$$COV_{trans}^2 = (COV_{spat} + COV_{err} + COV_{trans})^2 - (COV_{spat} + COV_{err})^2 \tag{6}$$

where $COV_{spat} + COV_{err} + COV_{trans}$ corresponds to S_u (Eq. 1) COV value for each site, since this value includes the measurement inherent variabilities of the parameter and $COV_{spat} + COV_{err}$ is basically related to q_T COV value because σ_{v0} and N_{kt} uncertanties were very low.

3.1 Cone Tip Resistance

Examples of CPTu results from the test sites are presented in Figure 1 along with the calculated statistical mean value μ. Generally, the results (Table 1 and Figure 2) show that the variation of cone tip resistance q_T vary a lot among the analysed sites. The repeatability of CPTu seems to be very good at Test Sites A and B. The obtained

COV-values vary between 0.039 and 0.060, which indicate small uncertainty within the measurements. Also, for both test sites, the bias factor is 1, indicating that the measured values from each point are close to the mean value μ.

On the other hand, at test sites C and D, although bias factor values ranged from 1 to 1.002, the COV-values ranged from 0.074 to 0.091, indicating a slightly higher level of uncertainities. The deviating results can be explained by many factors. One of those is technical failure or human error, which may cause large spikes on results. Another plausible explanation regards to the soil heterogeneity, since its properties values vary throughout its depth. Moreover, Eq. 5 was used to ensure the results reliability and succeeded. The mean value of the variability ε was equal to 1 for each CPTu borehole, as expected.

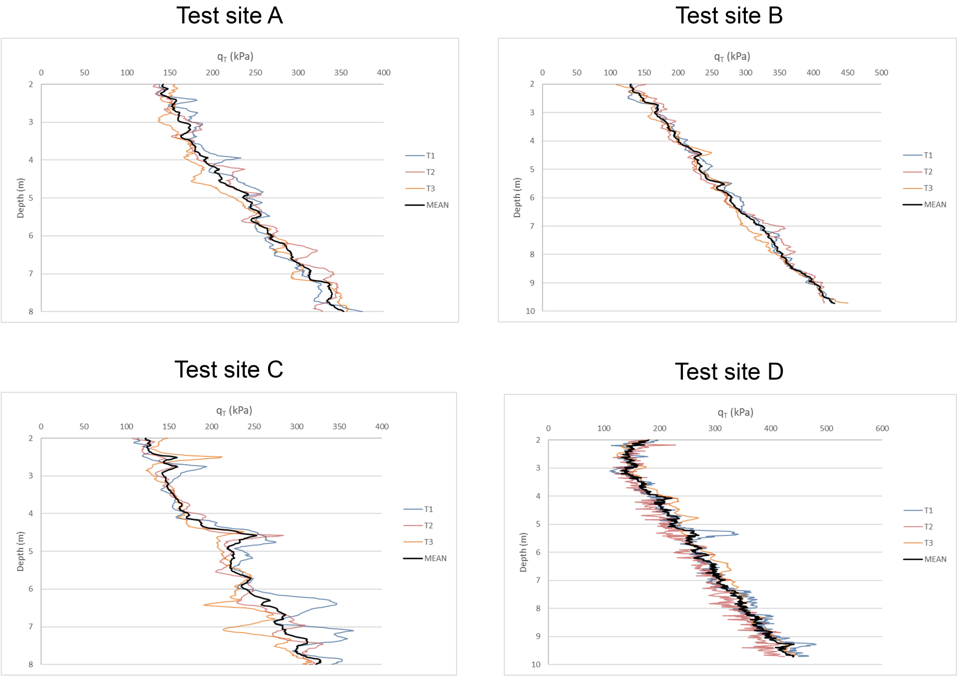

Figure 1. The measurement results of cone tip resistance (q_T) at each site.

3.2 Total Vertical Stress

Results of the total vertical stress measurements are presented in similar way. The results from statistical analyses are available on Table 2 and on Figure 4. Examples of CPTu results and its mean values along the depth are presented in Figure 3.

The results on Table 2 show that the variation of total vertical stress σ_{v0} is very low in all analyzed test sites, unlike the cone tip resistance results. Overall repeatability of CPTu seems to be very good. The obtained COV-values varies between 0.008 and 0.044, which indicate little uncertainty within the measurements. Also, the bias factors ranging from 1 to 1.002 indicate that the measured values from each point are close to the mean value μ.

Once again, Eq. 5 was used to ensure the results reliability and succeeded. The variabilty ε mean for each CPTu borehole was equal to 1, as expected.

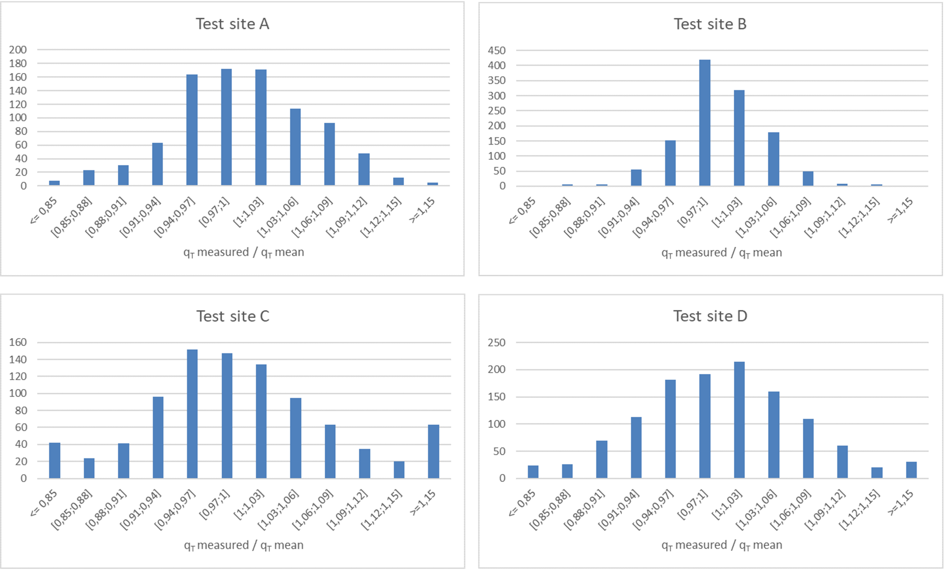

Figure 2. Histograms of measured and mean corrected cone tip resistances (q_T) at each site.

Table 1. Number of data points (n), bias factor (b) and COV of cone tip resistance at each site.

Test site A				Test site B			
Borehole	n	b	COV	Borehole	n	b	COV
T1	300	1.020	0.057	T1	400	1.007	0.034
T2	300	1.014	0.046	T2	400	1.009	0.041
T3	300	0.966	0.062	T3	400	0.982	0.036
All	900	1.000	0.060	All	1200	1.000	0.039

Test site C				Test site D			
Borehole	n	b	COV	Borehole	n	b	COV
T1	300	1.053	0.093	T1	400	1.009	0.077
T2	300	0.987	0.053	T2	400	0.960	0.072
T3	300	0.960	0.094	T3	400	1.036	0.058
All	900	1.000	0.091	All	1200	1.002	0.074

3.3 Undrained Shear Strength

The statistical results for interpreted undrained shear strength based on the net cone resistance (Eq. 1) are presented in Table 3. The comparison between the interpreted S_u value and S_u mean is shown on Figure 5. The statistical results show that the uncertainty related to S_{uNET} (Eq. 1), transformation model based on net cone resistance, is low. The COV values range from 0.046 to 0.105 and the bias factors are 1.0. These COV values are considered low due to the fact that they include, besides the actual transformation model uncertainty, the measurement uncertainty and the inherent variability as well. The actual transformation model (COV_{trans}) uncertainty will be calculated later.

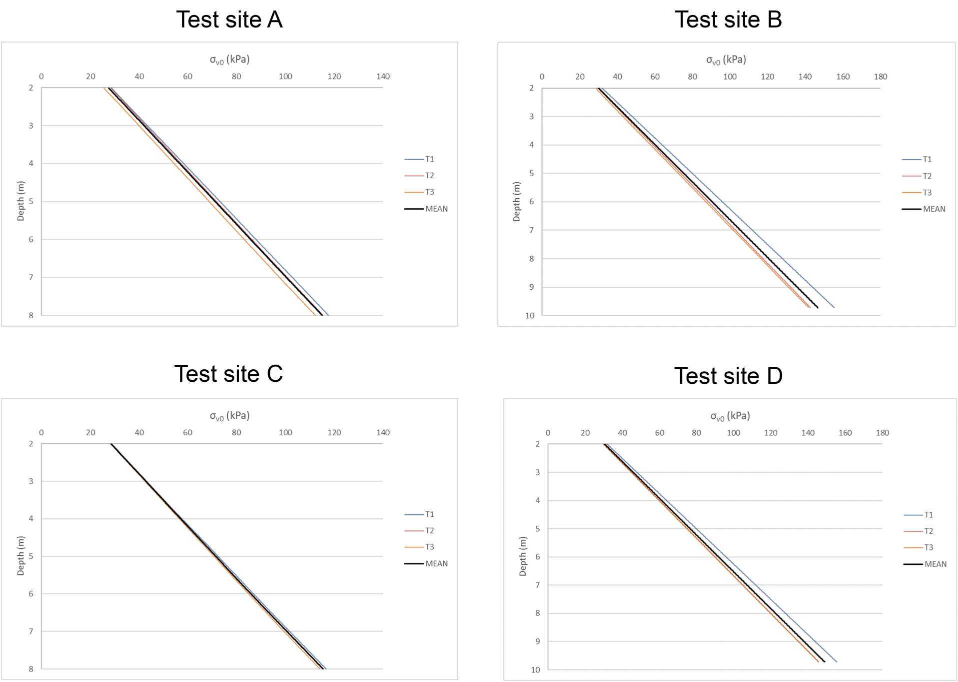

Figure 3. The measurement results of total vertical stress (σ_{v0}) at each site.

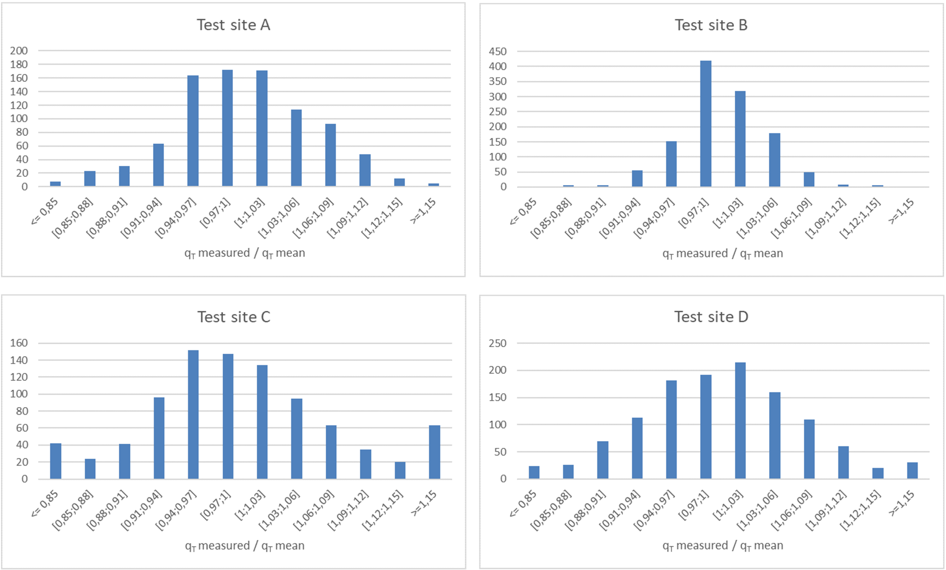

Figure 4. Comparison between measured and mean total vertical stress (σ_{v0}) at each site.

3.4 Transformation Model Uncertainty Related to Correlation Model

As specified earlier, the calculated transformation model uncertainties in Table 3 include also the measurement inherent variabilities of the parameter. The transformation model uncertainty related to the correlation model (1) is calculated using Eq. 6. The calculation parameters and the results are shown in Table 4. The calculation considered the whole test site. The results indicate that the transformation model uncertainties are very low.

Table 2. Number of data points (n), bias factor (b) and COV of total vertical stress σ_{v0} at each site.

Test site A				Test site B			
Borehole	n	b	COV	Borehole	n	b	COV
T1	300	1.028	0.004	T1	400	1.060	0.001
T2	300	1.010	0.007	T2	400	0.978	0.004
T3	300	0.962	0.011	T3	400	0.961	0.005
All	900	1.000	0.029	All	1200	1.000	0.044

Test site C				Test site D			
Borehole	n	b	COV	Borehole	n	b	COV
T1	300	1.010	0.003	T1	400	1.025	0.000
T2	300	1.000	0.001	T2	400	0.967	0.000
T3	300	0.990	0.002	T3	400	1.015	0.000
All	900	1.000	0.008	All	1200	1.002	0.031

Table 3. Number of data points (n), bias factor (b) and COV of undrained shear strength (S_u) at each site.

Test site A				Test site B			
Borehole	n	b	COV	Borehole	n	b	COV
T1	300	0.995	0.068	T1	400	1.015	0.041
T2	300	0.989	0.049	T2	400	1.003	0.058
T3	300	1.016	0.065	T3	400	0.982	0.048
All	900	1.000	0.062	All	1200	1.000	0.046

Test site C				Test site D			
Borehole	n	b	COV	Borehole	n	b	COV
T1	300	1.052	0.110	T1	400	1.013	0.083
T2	300	1.009	0.062	T2	400	0.966	0.077
T3	300	0.938	0.102	T3	400	1.021	0.066
All	900	1.000	0.105	All	1200	1.000	0.075

Table 4. Calculated transformation model uncertainties for transformation model (Eq. 1).

Uncertainties	Test site A	Test site B	Test site C	Test site D
$COV_{spat} + COV_{err} + COV_{trans}$	0.062	0.046	0.105	0.075
$COV_{spat} + COV_{err}$	0.060	0.039	0.091	0.074
COV_{trans}	0.014	0.024	0.052	0.010

4 Conclusions

We used data from different oil field basins to assess uncertanties from different locations and equipments. The applied method aids in assessing quality data acquired from experimental tests regarding marine soil charac-

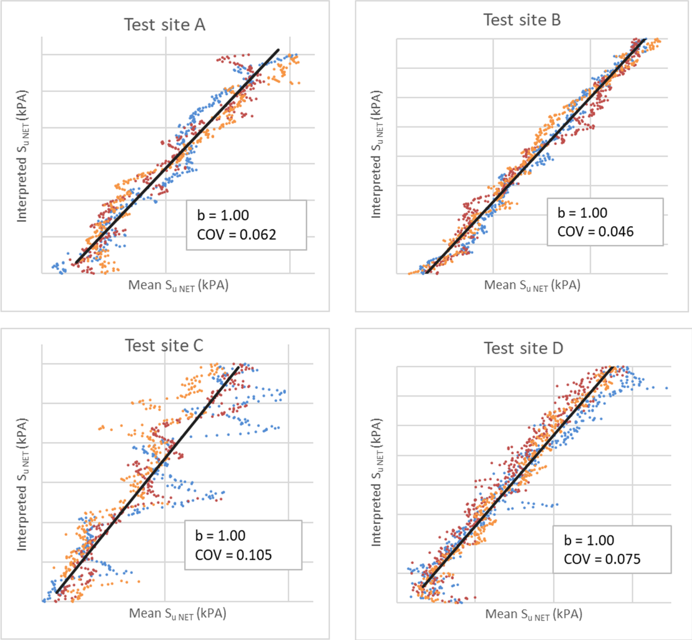

Figure 5. Comparison between the interpreted and mean S_u values using net cone resistance correlation model.

terization. It is important to remark that the datasets used comes from actual tests for oil extraction in marine soil. Therefore, logistical and execution problems must be taken into account in results.

Results show very low levels of uncertanties for every CPTu borehole in A and B sites. There were some differences observed between sites but overall repeatability of CPTu is considered satisfactory. The low variabilty reflects in undrained shear strength transformation model. As showed in results, we achieved small amounts of uncertanty for the combined data. This shows that execution of the test, however difficult, was well done and application of transformation models gives reliable results.

Acknowledgements. The authors would like to acknowledge Petrobras technical and financial support.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Abu-Farsakh, M. Y. & Nazzal, M. D., 2005. Reliability of piezocone penetration test methods for estimating the coefficient of consolidation of cohesive soils. *Transportation research record*, vol. 1913, n. 1, pp. 62–76.

[2] Zou, H., Cai, G., Bheemasetti, T., Liu, S., & Puppala, A., 2016. Assessment of measurement errors of piezocone penetration test in soft clay. *Geotechnical Testing Journal*, vol. 39, n. 5, pp. 721–741.

[3] Knuuti, M. & Länsivaara, T., 2019. Variation of measured cptu data. In *Proceedings, 7th International Symposium on Geotechnical Safety and Risk, Research Publishing*, pp. 11–13.

[4] Phoon, K.-K. & Kulhawy, F. H., 1999. Characterization of geotechnical variability. *Canadian geotechnical journal*, vol. 36, n. 4, pp. 612–624.

[5] Veritas, D. N., 2012. Dnv-rp-c207: Statistical representation of soil data. *Det Norske Veritas, Høvik, Norway*, vol. 1.

[6] Phoon, K. & Ching, J., 2012. Beyond coefficient of variation for statistical characterization of geotechnical parameters. *Keynote lecture of Geotechnical and Geophysical Site Characterization*, vol. 4, pp. 113–130.

[7] Mayne, P. W., 2007. *Cone penetration testing*, volume 368. Transportation Research Board.

[8] Lloret-Cabot, M., Fenton, G. A., & Hicks, M. A., 2014. On the estimation of scale of fluctuation in geostatistics. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, vol. 8, n. 2, pp. 129–140.

[9] Das, B. M. & Sobhan, K., 2013. *Principles of geotechnical engineering*. Cengage learning.

[10] Phoon, K., 1997. *Reliability-based design of foundations for transmission line structures.* PhD thesis, Cornell University.

[11] API, R., 2014. 2geo - geotechnical and foundation design considerations. *American Petroleum Institute, Washington, DC, USA*.