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Correlations between SPT and CPT data for a sedimentary tropical silty sand deposit in Brazil

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ABSTRACT: This study aims at presenting correlations between the SPT blow count number (N_{SPT}) and results of CPT tests (tip resistance, q_c, and sleeve friction resistance, f_s) for a sedimentary silty sand deposit. Correlations were obtained for 88 SPT tests and eight CPT tests carried out in the construction site of the new football stadium of the City of Natal, situated on the Northeast region of Brazil. Field test data were analyzed using a simplified geostatistic approach. Correlations between SPT and CPT data were developed using semivariograms for defining influence zones at the site. The range calculated with the semivariograms was used in the selection of appropriate SPT boreholes to correlate with a specific CPT borehole. SPT data outside this range were discarded. Correlations between q_c and N_{60} with coefficients of determination larger than 0.7 were obtained following this methodology. A representative ratio q_c/N_{60} of 0.39 MPa was found for the investigated soil.

1 INTRODUCTION

The standard penetration test (SPT) is still the most commonly used in situ test for obtaining the required geotechnical parameters for foundation analysis and design in Brazil. A reason for that may be because of the lack of local availability of other better tests. Geotechnical engineers in Brazil are likely to request CPT tests only for moderate to high-risk projects. Because CPT tests are seldom requested in ordinary practice, local contractors do not offer them, and vice-versa. Robertson (2012) highlights the need of breaking such a cycle. Moreover, the low cost is also taken as another strong argument for choosing the SPT test.

Since in most situations only SPT data is available, the search for new SPT-CPT correlations is necessary. However, most of the available SPT-CPT correlations in Brazil have been established for soils of southern regions of the country. New local correlations for other soil types are therefore necessary.

This paper aims at presenting correlations between the SPT resistance number (N_{SPT}), cone tip resistance (q_c) and sleeve friction resistance (f_s) for a sedimentary tropical silty sand deposit in the Northeast Region of Brazil. The correlations were devised from the results of 88 SPT tests and eight CPT tests, which reached a maximum depth of 35 m in the subsoil.

2 CPT-SPT CORRELATIONS

Studies on correlations for estimating cone tip resistance (q_c) and sleeve friction resistance (f_s) from SPT data using statistical approaches have been conducted for a large variety of soil types (Schmertmann & Palacios 1979, Robertson & Campanella 1983, Kasim et al. 1986, Chan et al. 1988, Danziger & Velloso 1995, Politano 1999, Akca 2003, Kara & Gündüz 2010, Shahri et al. 2014). Statistical correlations based on linear regressions have been widely used, particularly for granular materials (Alonso 1980).

Table 1 presents a compilation of values of k = q_c/N_{SPT} proposed for soils of southern regions of Brazil. It should be noted that some correlations in Table 1 were proposed using non-corrected N_{SPT} values for 60% energy.

Amongst the available correlations published in the literature, very few studies attempt to describe the statistical methods used for developing their proposed SPT-CPT correlations. Geostatistical concepts have been incorporated in more recent investigations. For instance, Akca (2003) presents a study conducted in the United Arab Emirates, which included results from 65 SPT borings and 101 CPT borings. SPT data were divided into two large groups according to their proximity from the CPT boreholes. For those SPT boreholes within a distance of 30 m from a specific CPT borehole, representative N_{60} values were calculated from the arithmetic mean of the data. The inverse distance weighting (IDW) method was employed in the analysis of the data from the SPT boreholes beyond this range.

Table 1. Values of k for Brazilian soils.

Reference	Soil	k (MPa)
Aoki & Velloso (1975)*	Sand	1.00
	Silty sand	0.80
	Clayey sand	0.60
	Silt	0.40
	Sandy silt	0.55
	Sandy clay	0.35
	Clayey silt	0.23
	Clay	0.20
Barata et al. (1978)*	Sandy silty clay	0.15 – 0.25
	Clayey silty sand	0.20 – 0.35
Danziger & Velloso (1986, 1995)	Silt, sandy silt, sandy clay	
	Sandy-clayey silt, clayey-sandy silt, silty-sandy clay,	0.48
Danziger et al. (1998)	sandy-silty clay	0.38
	Clayey silt	0.30
	Clay, silty clay	0.25
	Sand	0.57
	Silty sand, silty clay	0.5 – 0.64
	Clayey silt	0.31
	Sandy clay	0.18 – 0.35
	Clay	0.45

*N_{SPT} not corrected for 60% efficiency

3 METHODOLOGY

3.1 *Site location and Geology*

The field data used as part of this research were collected from standard penetration tests (SPT) and cone penetration tests (CPT) conducted to investigate the subsoil for the project of the new football stadium of the City of Natal, Brazil. Situated in the Northeast Region of Brazil, Natal was one of the 12 host cities of the 2014 Football World Championship. Figure 1 shows the location of the investigated site.

Figure 1. Location of the investigated site.

The subsoil of Natal and neighboring areas is composed of colluvium and alluvial tertiary deposits of unconsolidated sand, clayey sand, and silty sand sediments with some laterization. Overlying the tertiary deposits are quaternary deposits of eolian sediments composed of quartz sands with fine to coarse grain sizes (Angelim 2006).

3.2 *Site investigation*

Eighty-eight SPT borings and eight CPT borings were carried out in an area of 45,100 m^2 where the stadium was constructed. Figure 2 shows the distribution of the CPT boreholes on the site within the limits of the stadium. The SPT borings are also distributed within the limits of the stadium.

The SPT boreholes reached maximum depths ranging from 15 m to 26 m. The N_{SPT} blow count number was collected within each meter below ground surface, and corresponds to the number of blows required to drive in the soil the last 300 mm of a 450-mm-long sampler. The SPT tests were performed in accordance with Brazilian Standard NBR 6484. SPT blow count numbers were corrected for 60% efficiency (N_{60}).

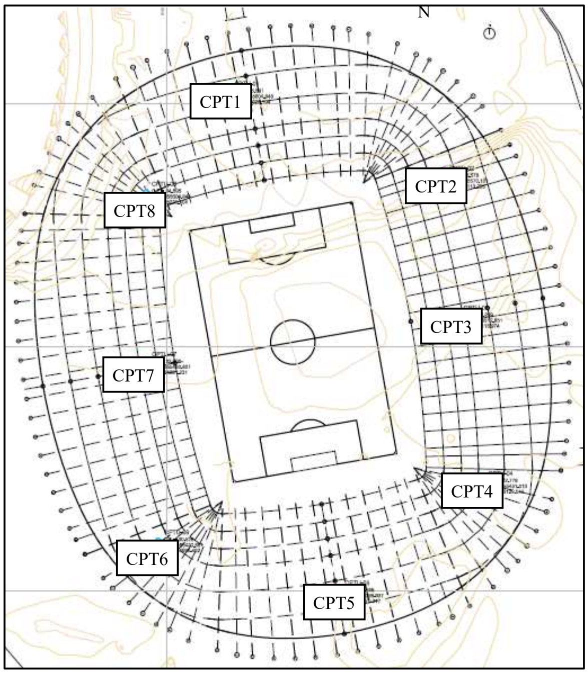

Figure 2. Location of the CPT boreholes.

The CPT boreholes reached maximum depths between 22 m to 35 m. In order to allow comparisons with the SPT results, average cone tip resistance (q_c) and average sleeve friction resistance (f_s) were calculated from the CPT profiles at the same depth interval of determination of the N_{SPT} number within the soil. The CPT tests were carried out following Brazilian Standard NBR 12069.

3.3 *Subsoil characteristics*

Figure 3 shows a simplified profile of the experimental site as well as the results of the eight CPT tests. Measurements of the cone tip resistance, q_c, and sleeve friction, f_s, obtained with the CPT tests, are plotted with depth. The subsoil is composed of a surficial layer of pure sand with thickness of about 3 m. This is a medium uniformly graded quartz silica sand that classifies as SP according to the Unified Soil Classification System. Underneath the sand layer is a silty sand deposit with non-plastic fines. CPT based soil behavior type (SBT) charts were used to classify the soil (Robertson, 2010). The soil layers in the profile were classified into SBT zone 6 (clean sand to silty sand).

Figure 4 shows the plots of N_{SPT} number with depth for all 88 boreholes. The mean N_{SPT} and the range of deviation of N_{SPT} from the mean are also shown in Figure 4 (thick line and dashed lines, respectively). Figure 4 provides a good indication of the large spatial variability of the investigated subsoil. The large dispersion of the data shows the need of portioning the subsoil into zones of influence for the SPT tests, in order to derive consistent correlations with the CPT results, instead of using all SPT results at once.

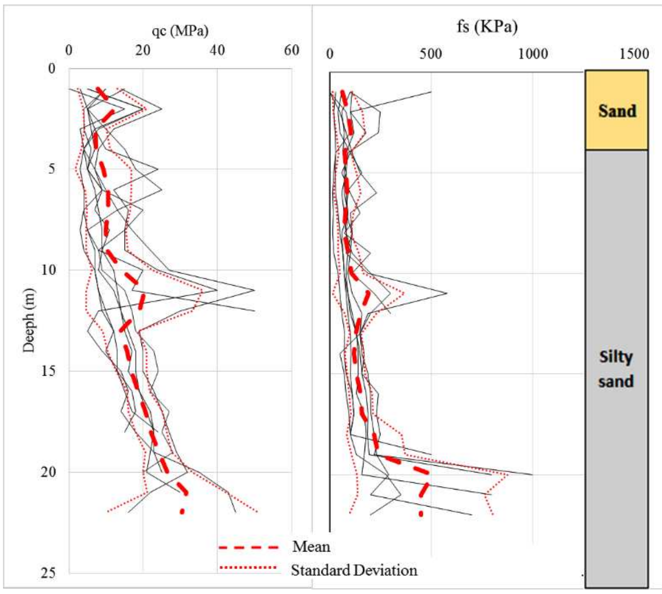

Figure 3. Soil profile at the experimental site and results of CPT tests.

4 VARIOGRAPHIC ANALYSIS

The zones of influence of the sampled values (zones with non-zero correlation) were determined using a semivariogram-based approach using data from CPT boreholes 1 to 8. Data from CPT 4 were excluded from this analysis due to lack of correspondence of soil type with the SPT data within its zone of influence. Semivariograms of the samples were calculated using Equation 1 for the field data collected in the ground at the following selected depths (z): 1 m, 5 m, 10 m, and 15 m.

$$\gamma(h) = (1/2N(h)) \sum_{i=1}^{N(h)} [Z(x+h) - Z(x)]^2 \tag{1}$$

where: h = distance vector between observed pairs; n = number of pairs; Z(x+h) and Z(x) = random variables at locations x+h and x, respectively.

The empirical semivariogram was fitted with a theoretical semivariogram of a spherical semivariance model, according to Equation 2:

$$\gamma(h) = \begin{cases} C_0 + C\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right], h < a \\ C_0 + C \qquad\qquad\qquad\qquad , h \geq a \end{cases} \tag{2}$$

where: a = range; C_0 = nugget effect; C = spatial variance.

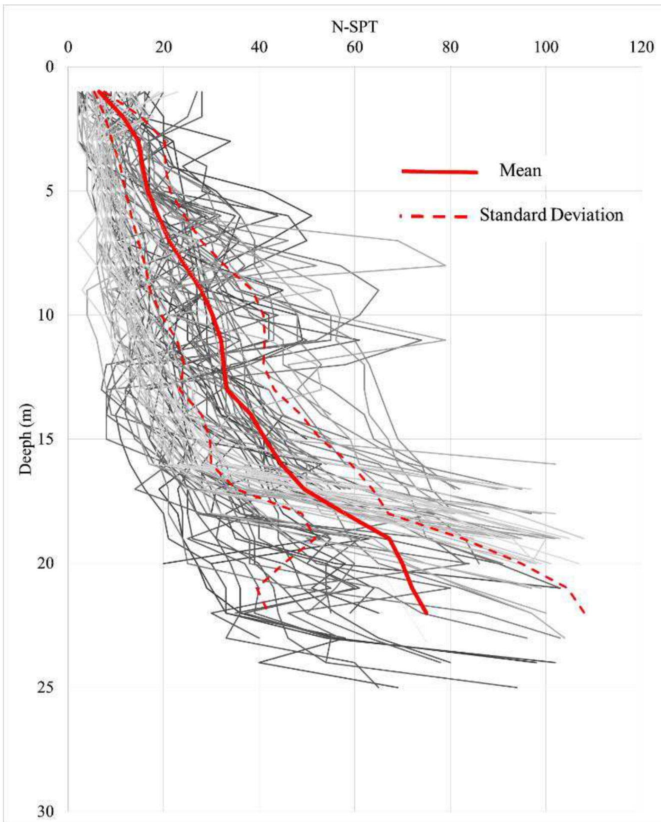

Figure 4. Variation of N_{SPT} with depth.

As an example, Figure 5 presents the empirical semivariogram and the corresponding theoretical fitting (dashed line) obtained for the data collected at depth z = 1 m. The range *a* of the variogram, i.e., the distance beyond which the SPT data fail to correlate adequately, was obtained from the fitted curve. In the semivariogram, this range was assumed as the lag distance for which the fitted curve begins to divert from its initial trend of linear increase of the semivariance with distance.

Among all investigated depths, the shortest range was found for z = 1 m, and measured 32 m. This distance was therefore used to limit the influence zone around the CPT boreholes. In other words, only SPT boreholes within a distance of 32 m were used for a given a CPT borehole.

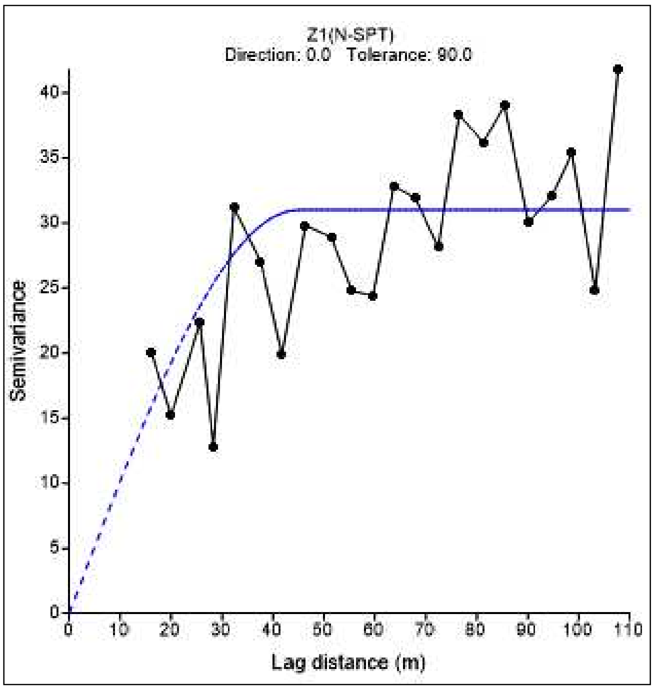

Figure 5. Semivariogram for depth z = 1 m.

5 RESULTS AND DISCUSSION

5.1 *Arithmetic mean approach*

In a first approach, a correlation between SPT and CPT results was achieved by calculating the arithmetic mean of the values. In this simple approach, all data were used regardless the distance from the CPT boreholes. No attempt was made to pick specific SPT data. 402 pairs of q_c – N_{60} values were combined, resulting in an average q_c/N_{60} ratio (k) of 0.6 (with standard deviation of 0.4) for the silty sand deposit. No correlation between q_c and N_{60} was found with this methodology.

5.2 *Correlations of q_c and N_{60}*

In an attempt to reduce the influence of soil spatial variability, the CPT results were correlated with N_{60} values collected within the zone of influence of each CPT borehole, defined by a circle with ray equal to the smallest range found in the variographic analysis, i.e. 32 m (see Section 4). Soil mass was thus divided into eight distinct zones of influence, and eight different CPT-SPT correlations were established for those zones.

Figure 6 shows the relationship between q_c and N_{60} for Zones 1 to 8. The experimental data points of each influence zone were adjusted using a linear fitting passing through the origin. Table 2 presents k = q_c/N_{60} ratios found from the linear fittings for Zones 1 to 8. The found coefficients of determination (R^2), as indicated in Table 2, show the good agreement achieved between the correlated variables.

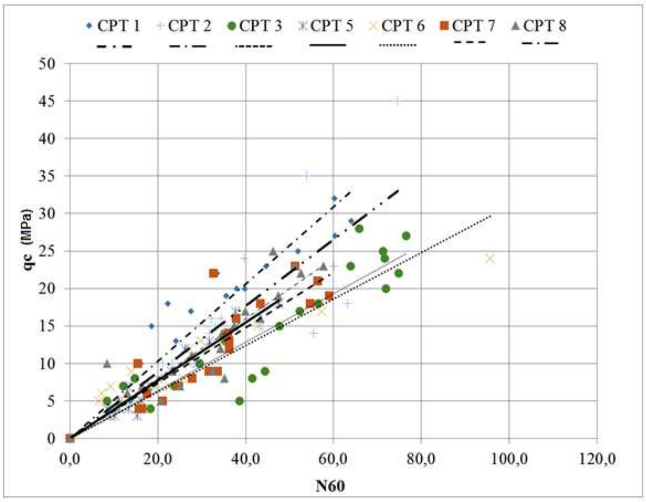

Figure 6. Correlations between q_c and N_{60} assuming distinct zones of influence for the SPT boreholes at the site.

Table 2. Values of k for the influence zones.

CPT Zone	k (MPa)	R^2
1	0.51	0.863
2	0.44	0.701
3	0.32	0.848
5	0.39	0.919
6	0.31	0.761
7	0.37	0.766
8	0.40	0.822

Figure 7 shows the correlation of q_c and N_{60} obtained using the data points from all eight zones, and selected according to the variogram-based approach previously described. A k ratio of 0.39 MPa was obtained for the soil according to this analysis. This value is lower than the range reported by Danziger et al. (1998) for residual silty sand deposits in Brazil, which is in the range of 0.5 – 0.64.

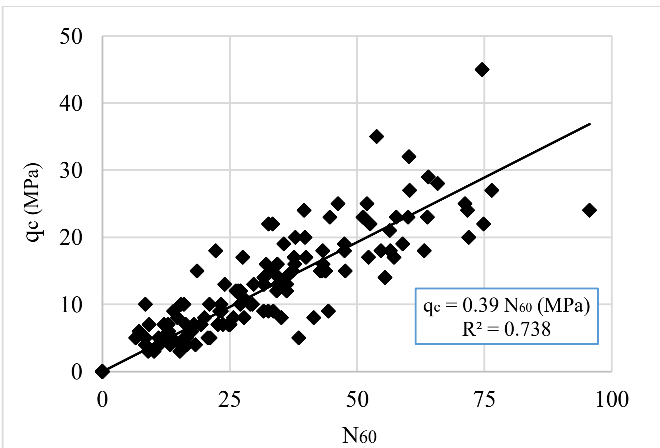

Figure 7. General correlation between q_c and N_{60} for the investigated soil.

5.3 *Correlations of f_s and q_c/N_{60}*

Figure 8 shows the sleeve friction f_s as a function of $(q_c/p_a)/N_{60}$ for Zones of influence 1 to 8. The cone tip resistance q_c is normalized by the atmospheric pressure p_a (p_a = 100 kPa). A linear regression passing through the origin was fitted to the experimental data points. Table 3 presents the ratio $fs{\cdot}N_{60}/(q_c/p_a)$ found with the linear fittings, for Zones 1 to 8. Except for Zones 1 and 6, the coefficients of determination (R^2) found according to this analysis are relatively high.

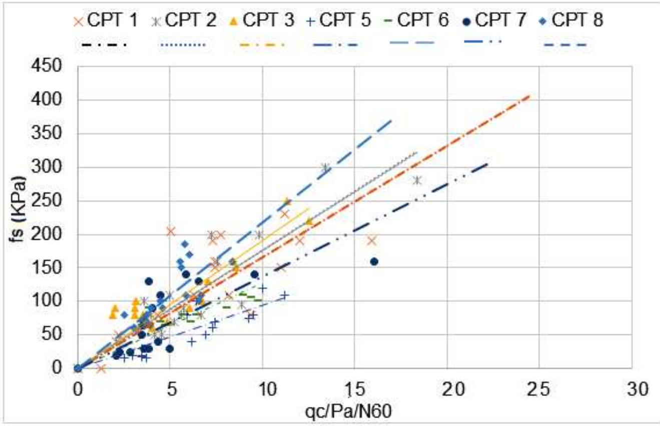

Figure 8. Correlations between f_s and $(q_c/p_a)/N_{60}$ assuming distinct zones of influence for the SPT boreholes at the site.

Table 3. Values of $fs{\cdot}N_{60}/(q_c/p_a)$ for the influence Zones.

CPT Zone	$fs{\cdot}N_{60}/(q_c/p_a)$	R^2
1	16.63	0.468
2	17.61	0.807
3	19.03	0.795
5	9.40	0.790
6	12.79	0.441
7	13.75	0.507
8	21.81	0.658

Figure 9 shows the correlation between f_s and $(q_c/p_a)/N_{60}$ obtained using the data points from all zones, selected according to the variogram-based approach previously described. A value of 16.01 found for the ratio $fs{\cdot}N_{60}/(q_c/p_a)$ for the investigated soil.

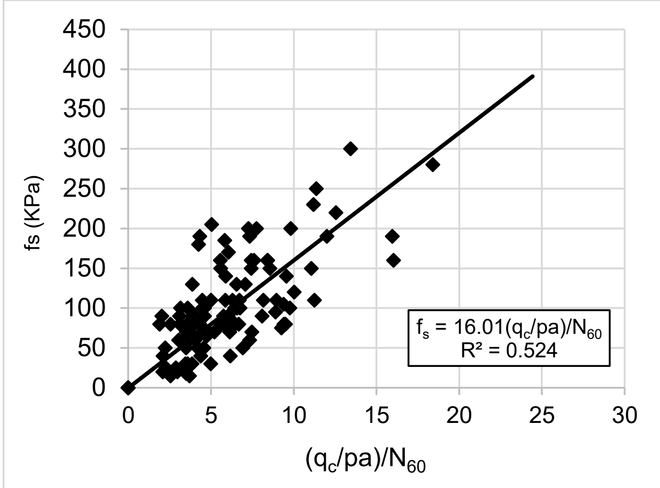

Figure 9. General correlation between f_s and $(q_c/p_a/N_{60})$ for the investigated soil.

6 SUMMARY AND CONCLUSIONS

Analyses on correlations between SPT and CPT data for a sedimentary silty sand deposit in the Northeast Region of Brazil were presented in this paper. The investigation included results of 88 SPT borings and eight CPT borings. Data were selected using a variogram-based approach.

A preliminary analysis consisted of finding a relation between cone tip resistance (q_c) and the N_{SPT} blow count number corrected for 60% efficiency (N_{60}) by calculating the arithmetic mean of the variables. Because of the large dispersion of the values caused by soil spatial variability, no correlation between q_c and f_s was found with this approach.

In an attempt to reduce the effect of soil spatial variability, a zone of influence for each CPT borehole was defined using a variographic-based approach. Only N_{60} values within a range of 32 m were picked to correlate with data from a specific CPT borehole. This approach led to good correlations with comparatively high coefficients of determination. A representative ratio k = q_c/N_{60} of 0.39 MPa was found for the silty sand deposit. This ratio is below the range reported in the literature for silty sand deposits of residual origin in Brazil.

Geostatistics is an essential tool for the achievement of more refined SPT-CPT correlations, and its use should be more disseminated.

7 ACKNOWLEDGEMENTS

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