The Influence of the Relative Density of Sands in SPT and CPT Correlations

J.M.S. Souza, B.R. Danziger, F.A.B. Danziger

Abstract. Correlations between CPT and SPT in sands are presented in this paper for different sand densities. Such proposition is based on the experience obtained with the use of piezocone whose penetration in sands occurs commonly under drained condition. The SPT penetration, on the other hand, is much faster, occurring under a partially drained condition. Due to the high loading velocities, much higher than that of the CPT, the SPT test can generate positive excess pore pressures in loose sands and negative excess pore pressures in dense sands. In this way, the *N* value may be higher than if the test were carried out in a drained condition, for dense sands, and smaller for loose sands. The same does not occur for the q_c value of CPT. So, the trend would be of greater q_c/N_{60} ratio for loose sands than for dense sands with the same grain size distribution. The results confirm distinct correlations for different sand densities. The q_c/N_{60} ratio of 0.5 MPa/blows/0.30 m for sands, obtained from Danziger & Velloso (1995) regardless of the sand density, is consistent with the value obtained in the present research for the whole data, if no distinction of density is made. For distinct sand densities, the q_c/N_{60} ratio was found to be 0.7; 0.5; and 0.4 MPa/blows/0.30 m, respectively for loose, medium and dense sands. While most of the correlations in the literature depend only on grain size, the results presented in this paper show that the sand density is of fundamental importance and should also be considered to interpret CPT and SPT correlations.
Keywords: SPT, CPT, correlations, sands, relative density.

1. Introduction

CPT and SPT correlations have practical applications in many geotechnical areas, especially in foundation design.

The existing correlations between cone tip resistance, q_c, and SPT *N* value in sedimentary sands are usually based solely on soil grain size (Fig. 1).

In fact, the suggestion of Robertson *et al.* (1983) is quoted extensively in the literature. This is shown in Fig. 1, together with data obtained by Politano *et al.* (1998, 2001) and Viana da Fonseca & Coutinho (2008) for residual soils. The figure shows that the data obtained in residual soils do not follow the trend shown by Robertson *et al.* (1983).

Mitchell & Brandon (1998) emphasized that the ratio q_c/N_{60} does not correlate uniquely with mean grain size (D_{50}). They suggest that site specific determinations should be developed if a q_c/N_{60} value is needed so that it results can be used with N_{60} value property correlations, or vice versa. Mitchell & Brandon (1998) quoted Kulhawy & Maine (1990), as shown in Fig. 2, with a rather broad band when a large number of data points from tests at many sites are examined.

Mitchell & Brandon (1998) pointed out that the q_c/N_{60} based on mean particle size may involve significant uncertainty. They suggested that site specific q_c/N_{60} values based on median values for relatively thick homogeneous layers may be more reliable.

The use of the piezocone, instead of the CPT, brings a new feature to the correlation analysis, since the pore pressure is also measured. In fact, it is generally accepted that the piezocone tests in sands occur in a drained condition, which is easy to verify with the pore-pressure measurement. On the other hand, the much faster velocity in the SPT procedure, even in sands, results in a test condition usually considered as partially drained (*e.g.* Youd *et al.*, 2001).

The main objective of the present paper is to show an alternative interpretation of CPT and SPT correlations by taking into account distinct sand densities.

The SPT is more influenced by the change in shear stresses than normal stresses. Due to a much higher loading velocity, the SPT generates positive excess pore pressures in loose sands and negative excess pore pressures in dense sands. As a result, the *N* value may be higher than if the test were carried out in a drained condition, for dense sands, and smaller for loose sands. The same does not occur for the q_c value of CPT. Therefore, the trend would be of greater q_c/N_{60} ratio for loose sands than for dense sands with the same grain size distribution. Taking these points into consideration, the paper presents and discusses the correlations obtained in sedimentary sandy layers of variable relative densities. The data have been selected from sites where the database has been extracted from layers of high thickness and a satisfactory soil characterization has been available.

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The data from the tests in layers of small thickness or containing sandy soils with high percentage of fines have been discarded. The inclusion of these data could compromise the quality of the analysis, which aimed to determine the influence of relative density of pure sands or sands with low fines content in the correlations.

In fact, Mitchell & Brandon (1998) also reported that the presence of layers of different density and strength within a soil profile may have a significant influence on the measured values of cone penetration resistance. According to them, the cone "senses" the presence of a different underlying layer when it reaches a few diameters of the layer boundary. The layer effect is likely to be conservative in that the measured resistance of dense layers will be lower than its real value, whereas that measured in loose layers will be reasonably close to the correct value. The authors also pointed out that the layer effect could lead to incorrect soil identification if tip and friction ratio based classification charts are used.

Depending on the SPT equipment, the actual energy delivered by the rods may also influence the test results. Faster automatic equipments may present different conditions from manual equipments routinely used.

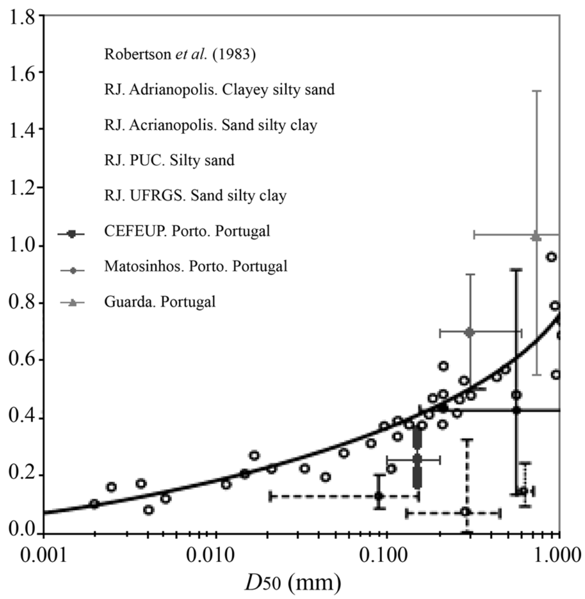


Figure 1 - q_c/N_{60} and D_{50} relationship from Roberson *et al.* (1983) with data from residual soils, extracted from Politano *et al.* (1998, 2001) and Viana da Fonseca & Coutinho (2008).

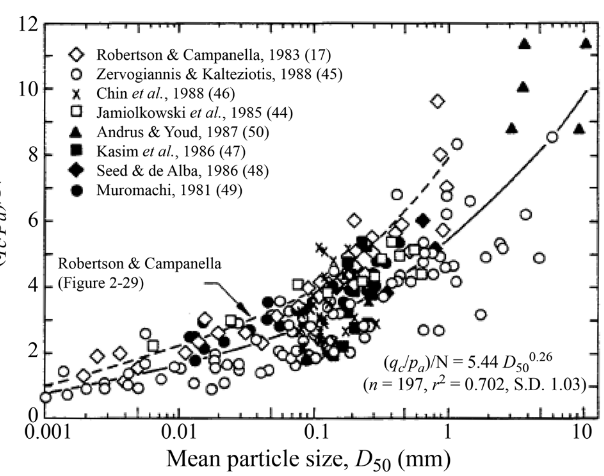


Figure 2 - q_c/N correlations based on mean particle size from Kulhawy & Mayne (1990), as quoted by Mitchell & Brandon (1998).

2. Geotechnical Characterization of the Test Sites

Most interpretations of the soil stratification profile have been based on soil classification from SPT samples or obtained indirectly from the piezocone results. It is worth emphasizing that Robertson & Campanella (1983) reported that tests conducted by Schmertmann (1978) in calibration chambers showed that the cone tip senses an interface region between 5 and 10 cone diameters ahead and behind the tip. Robertson & Campanella (1983) called attention to the fact that if the sandy layer has a thickness less than about 70 cm and is located between two soft clay deposits, the cone penetration resistance may not reach its full value within the sand because of the close proximity of the adjacent interfaces. In fact, Mitchell & Brandon (1998) also reported that the presence of layers of different density and strength within a soil profile may have a significant influence on the measured values of cone penetration resistance. According to them, the cone "senses" the presence of a different underlying layer when it reaches a few diameters of the layer boundary. In the present analysis all data from layers with thickness smaller than 1 m has been discarded. Table 1 lists the locations of the sites whose data have been included in the database.

Table 1 - Sites from the database.

Region	Site
Brazil	Port of Açu - São João da Barra, Rio de Janeiro
	Presidente Dutra Highway km 36 - Queimados, Rio de Janeiro
	Industrial Construction in Rio de Janeiro West Zone
	Presidente Dutra Highway, km 163 to 165 Jacareí, São Paulo
USA	University of Florida
	San Francisco Bay
Canada	Mildred Lake Settling Basin - Syncrude
	Massey and Kidd - Fraser River Delta
	J-Pit - Syncrude
	LL Dam and Highmont Dam - HVC Mine

2.1. Port of Açu - RJ

The Port of Açu is located in São João da Barra, 30 km from Campos dos Goytacazes, in the State of Rio de Janeiro. The Port of Açu will have an important role to export Brazilian ore.

Several SPT test and nine piezocone tests have been performed in part of the site. The soil profile in this region shows a thick superficial layer of sand, up to 10 to 15 m deep, over a layer of organic clay of low strength with 5 m thick. Underlying the clay occur layers of high density sands.

2.2. President Dutra Highway, km 36 - Queimados - RJ

This area of the highway is located in the town of Queimados, nearly 40 km from the City of Rio de Janeiro.

Five vertical adjacent SPT and CPT tests have been performed. No laboratory tests have been available to better characterize the investigated soils.

The geotechnical profile consists of a superficial low strength clay layer, 2.5 m thick, overlying a sandy deposit of medium to high density 14 m thick. Below that depth residual soils can be found. In some borings small layers of very soft clay are present, between the sandy layers.

2.3. Industrial construction in the Rio de Janeiro West Zone

The soil profile in this site consists of a sedimentary superficial soft clay deposit of low consistency, nearly 14 m thick, over the sandy stratum with thicknesses ranging from 6 to 20 m. Small lenses of very soft clay are present, within the sand deposit.

2.4. President Dutra Highway - Jacareí - SP

In the President Dutra highway, close to the city of Jacarei, State of São Paulo, CPTU tests have been performed in the central region of the highway and at each side, forming 4 transversal sections to the axis of the highway. A total of eight CPTU tests have been included in the database.

The tests aimed at characterizing the quaternary sediments presented at the site. Adjacent to the CPT tests, SPT tests have also been performed. The SPT blow counts were obtained every 0.5 m depth. Some samples collected by the surveys were submitted to grain size tests. It has been possible, then, to verify the low content of fines in the sandy soil away from the boundary of the neighboring layers.

The CPTU tests have been performed in previously leveled ground next to the SPT tests. Therefore, the reference depths were the same both for the CPTU and SPT tests.

Figure 3, extracted from Danziger *et al.* (1998), illustrates the local geotechnical profile and compares SPT 17 and CPTU 6. The soil of the upper sand layer, between 7.5 to 8 m depth, is composed of 34% of soil passing through 200 # sieve, 56% of fine sand and 10% of medium sand. However, even with the great predominance of the sandy fraction, excess pore-pressure has been developed, including negative pore-pressure, indicating undrained or partially drained behavior. The second layer of sand, on the other hand, between 8 to 10 m depth, presented a drained behavior. The grain size distribution of the material shows only 2% passing through 200 # sieve, 12% of fine sand, 71% of medium sand and 15% of coarse sand. The drained behavior is therefore fully justified.

This figure helps to explain the importance of verifying carefully the data points before including them in the database, as the authors intended to do.

2.5. University of Florida - USA

These data were obtained by Palacios (1977) at three sites on the campus of the University of Florida. Palacios' research accounted for energy measurements in SPT tests.

In the three sites the soil profile indicated superficial sandy layers of great thickness. Atterberg limits and grain size analyses were performed with indication of soil classification by the unified system. In the three sites the most superficial layer was classified as SP, which corresponds to a sandy soil with less than 5% of fines, poorly graded. The underlying sandy layer, on the other hand, was classified as SC - SP in sites A and B. This means that there are parts of sandy clay, SC, with more than 12% of fines and parts of sand with less than 5% of fines, poorly graded. On site C the whole soil profile is sandy, with the lower layer containing sands classified as SC, with more than 12% of fines.

Palacios (1977) performed CPT tests, not CPTU tests. Moreover, Palacios (1977) did not include, for the whole database, the grain size characteristics of the sandy soil. It was not possible to discard the data from sands containing high fines content. An aspect that motivated the authors to analyse Palacios (1977) data was the fact that the SPT have been performed with the sampler with liner removed. With the removal of the liner, the internal friction in the sample is smaller, resulting in a lower N value. The authors expectation was that the ratio q_c/N_{60} would be greater with the use of the sampler with the liner removed. The authors decided to analyze the data from Palacios (1977) in order to verify if the higher values of the ratio q_c/N_{60} would be also sensitive to the relative density of the sand. However, data from Palacios (1977) were not included in the global analysis, as is further emphasized in the paper.

2.6. San Francisco Bay - USA

The soil profile where Kasim *et al.* (1986) conducted their experiments consisted of a deposit of sand from a recent hydraulic landfill (pumped 16 years before), 5.5 m thick, overlying a deposit of natural Pleistocene sand. The hydraulic fill was classified as SM, silty sand, with nearly 10% of fines. The natural sand deposit was classified as SM, silty sand, and occasionally as SM-SC, clayey silty sand, with fine content of the order of 20%.

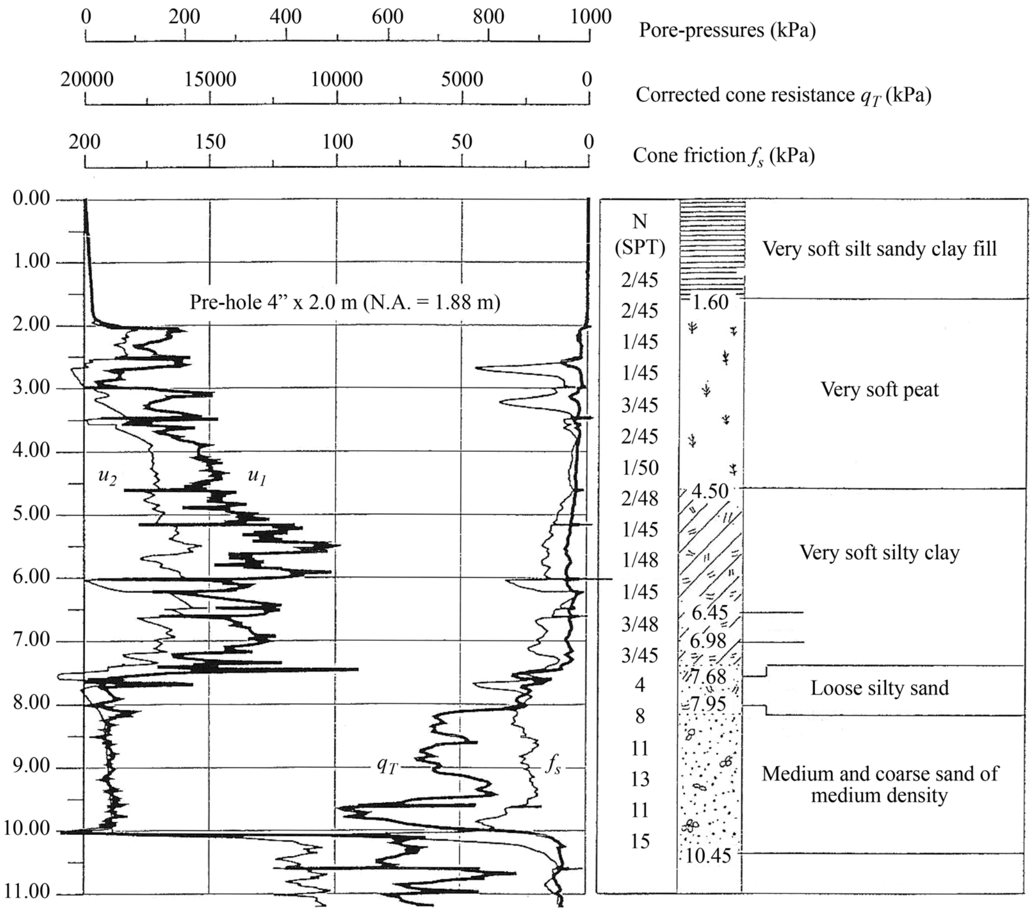


Figure 3 - Comparison between the SPT-17 test and CPTU 6 (Danziger *et al.*, 1998).

The tests have been performed with electrical cone, without the measurement of pore-pressure.

It should be emphasized that the authors have found the same trend of Robertson & Campanella (1983): the reduction of q_c/N_{60} with D_{50}, as in Fig. 1, but with a large dispersion. The authors attributed the large dispersion to the variability found in the penetration tests and also in other soil properties not completely defined by grain size. The soil properties not completely defined by grain size distribution also support Mitchell & Brandon (1998) feelings. It also justifies the idea that motivated the main objective of this paper: to investigate the effect of relative density in the q_c/N_{60} correlation in sands.

2.7. Canlex - Canadá

Wride *et al.* (2000) and Robertson *et al.* (2000) summarize the Canlex project (The Canadian Liquefaction Experiment), a research project developed over a period of 5 years, whose main objective was to study the phenomenon of liquefaction of soil, likely to occur in saturated sandy soils, characterized by a large shear strength and soil stiffness loss resulting in significant deformation.

Canlex research project was divided into phases, each phase representing a new location or a different purpose. Each phase included a series of activities, with many field and laboratory tests being performed. Only the data of interest to the present analysis have been obtained from the Canlex reports and included in the database.

The deposits of sand covered in the Canlex research project are from the Holocene (less than 11,000 years old). The age of the deposits ranges from 2 months to 4,000 years. Table 2 illustrates the different ages of the deposits analyzed. They consist of normally consolidated sands without cementation, composed mainly of quartz grains with small amount of feldspar and mica. They are

Table 2 - Ages of each deposit of CANLEX research (Robertson *et al.*, 2000).

Phase	Location	Site	Deposit Age
I	Syncrude	Mildred Lake	12 years
II	Fraser River delta	Massey	200 years
		Kidd	4,000 years
III	Syncrude	J-Pit	2 months
IV	HVC Mine	LL Dam	5 years
		Highmont Dam	15 years

uniform sands, with D_{50} ranging from 0.16 to 0.25 mm and generally containing percentage of fines less than 15%, with some samples showing fines content less than 5%.

Table 3, taken from Robertson *et al.* (2000), illustrates the main characteristics of the various deposits, allowing the observation that it consists, in general, of deposits with low fines content.

Energy measurements have been performed in SPT tests. The energy measured in the 6 sites of the research ranged from 50 to 80%.

The ISSMFE (1989) has established 60% of the theoretical potential energy as the international reference. Once performed the SPT test, the N value must be converted to N_{60} by the expression:

$$N_{60} = N \frac{E}{E_{60}} \tag{1}$$

where E = measured energy corresponding to N value and E_{60} = 60% of the theoretical potential energy of 474 J (ISSMFE, 1989).

Energy correction has been made from the efficiency obtained from each N value included in the database.

3. Description of the Criteria for Data Selection

3.1. Grain size

The authors discarded the soil data with finer content higher than 12%. According to Souza Pinto (2000), the behavior of sands with finer content of this order is determined by the contact between grains. On the other hand, sands with higher percentage of fines usually have their behavior most influenced by the clay fraction, and their behavior is much more similar to that of clays.

3.2. Layer thickness

Data obtained from layers of sands of low thickness were not considered appropriate. In such cases the data are influenced by adjacent layers, mainly in presence of thin soils, especially soft clays, as quoted by Mitchell & Brandon (1998) and Robertson & Campanella (1983), already cited. Horizons of small thickness were present in most sites. In such situations, the presence of higher fines content is evident, indicating an undrained behavior in the piezocone test.

3.3. The B_q parameter

In the absence of the characterization tests for most data, the pore-pressure parameter B_q from the piezocone is an important tool in verifying the soil behavior.

Senneset & Janbu (1984) have a proposal for soil classification based on the corrected cone resistance, q_T, and the pore-pressure parameter B_q. This proposal is based on the fact that the generation of excess pore-pressure is an excellent indication of the type of soil penetrated.

The authors made use of the B_q parameter (Eq. 2) in cases where grain size analyses were not available in order to decide if the results would be incorporated into the database. The authors made use of the classification procedure from Senneset *et al.* (1989) and also that from Robertson *et al.* (1986), Figs. 4 and 5.

$$B_q = \frac{u - u_0}{q_T - \sigma_{v0}} \tag{2}$$

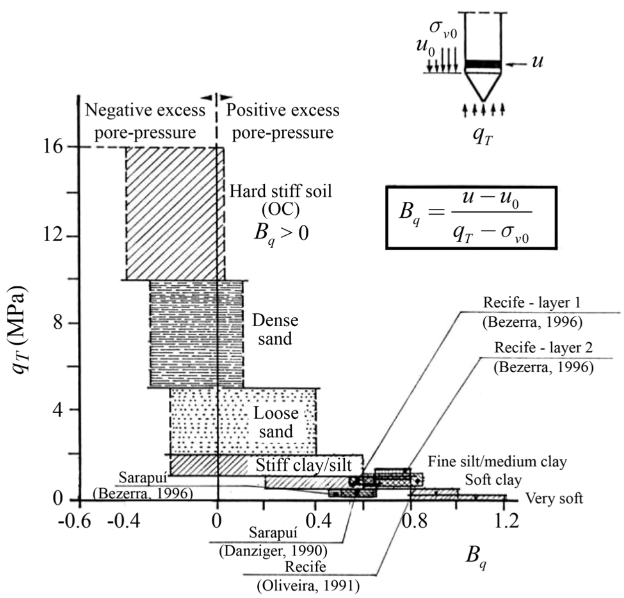
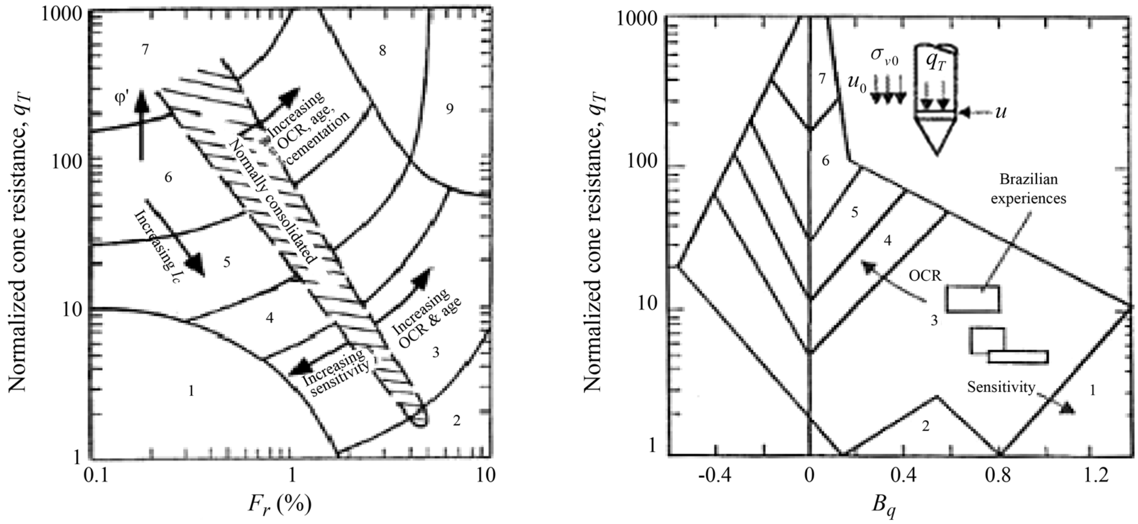


Figure 4 - Soil classification by Senneset *et al.* (1989), including data from Bezerra (1996) and Oliveira (1991), as quoted by Danziger & Schnaid (2000).

Table 3 - Index properties of CANLEX deposits (Robertson *et al.*, 2000).

Local	e_{max}	e_{min}	G_s	D_{50} (mm)	C_u (D_{60}/D_{10})	% fines < # 200 mm
Mildred Lake	0.958	0.522	2.66	0.15	2.22	≈10
Massey	1.100	0.700	2.68	0.20	1.57	< 5
Kidd	1.100	0.700	2.72	0.20	1.78	< 5
J-Pit	0.986	0.461	2.62	0.17	2.50	≈15
LL Dam	1.055	0.544	2.66	0.20	2.78	≈8
Highmont Dam	1.015	0.507	2.66	0.20	4.00	≈10



$$Q_t = \frac{q_T - \sigma_{v0}}{\sigma'_{v0}} \qquad B_q = \frac{u - u_0}{q_T - \sigma_{v0}} \qquad F_r = \frac{f_s}{q_T - \sigma_{v0}} \times 100\%$$

1. Sensitive fine-grained soil
2. Organic soil
3. Clay
4. Silty clay to clay
5. Clayey silt to silty clay
6. Sandy silt to clayey silt
7. Silty sand to sandy silt
8. Sand to silty sand
9. Sand
10. Sand to gravelly sand
11. Very stiff fine-grained soil
12. Overconsolidated or cemented sand to clayey sand

Figure 5 - Proposal for classification of soils from Robertson *et al.* (1986), including the Brazilian experience, as cited by Schnaid (2000).

where u is the pore-pressure measured at the base of the cone, u_0 is the hydrostatic pressure and σ_{v0} is the total vertical stress (see Fig. 4).

Meireles (2002) reports that Robertson & Campanella (1983) consider the determination of the soil profile as the main application of the CPTU data. The authors commented that traditionally the soil classification has been related to the tip resistance, q_c, and friction ratio, (f_s/q_c) * 100%, f_s being the side friction. Several charts have been developed based on the fact that sandy soils usually present high tip resistance and low friction ratio, while clayey soils often present low tip resistance and high friction ratio.

Robertson *et al.* (1986) proposed the simultaneous use of two diagrams for soil classification, Fig. 6. The first is a graph of corrected cone tip resistance *vs.* friction rate, (f_R/q_T), f_R being the corrected lateral friction. The second is a graph of corrected cone tip resistance *vs.* pore-pressure parameter, B_q. According to the authors, occasionally a particular soil can be classified in different ways in both graphs. In fact, in such circumstance a more appropriate analysis is necessary in order to classify the soil in a satisfactory way. The authors reported that both the rate and the way in which the excess pore-pressure dissipates during an interruption in the penetration are of help in soil classification.

In the present paper the authors discarded the B_q values outside the interval (-0.1, +0.1) in order to assure a drained behavior for the soil under analysis.

According to Meireles (2002), Robertson (1991) modifies the second graph in order to incorporate more negative values of B_q, Fig. 7. According to the author this modification provides a better fit for many of the prior experience. The author also included in the same graph the Zone 2 for organic soil and peat, which was missing in the original published graph.

4. The Correspondence of the Two Tests

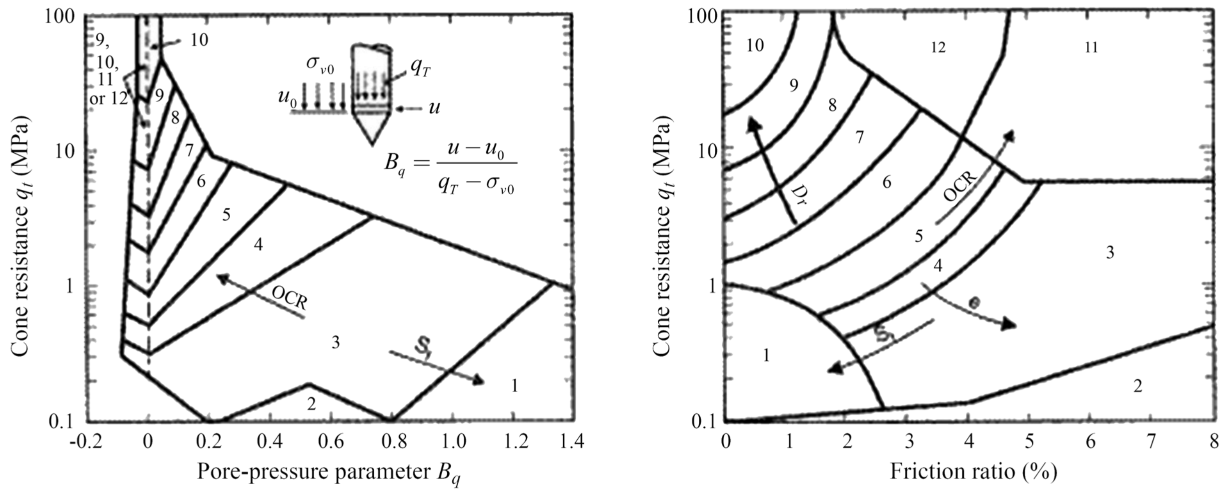
Using the same procedure adopted by Politano (1999) and Politano *et al.* (1998, 2001), aiming at analyzing the values of q_T and N in the same depths, the q_T were taken at each meter depth plus 0.30 m. This follows from the fact that the N values are measured between the depths of A +0.15 m and A +0.45 m, being A an entire number corresponding to a given depth, *i.e.* N corresponds to an average depth of A +0.30 m, as shown in Fig. 8.

At this way, the N value for the last 0.30 m of penetration (N) was obtained directly from the boring report, while in the piezocone tests the values of q_T were considered corresponding to A +0.30 m depth, following the trend of the q_T curve, avoiding the use of discrepant results.

5. Data Handling

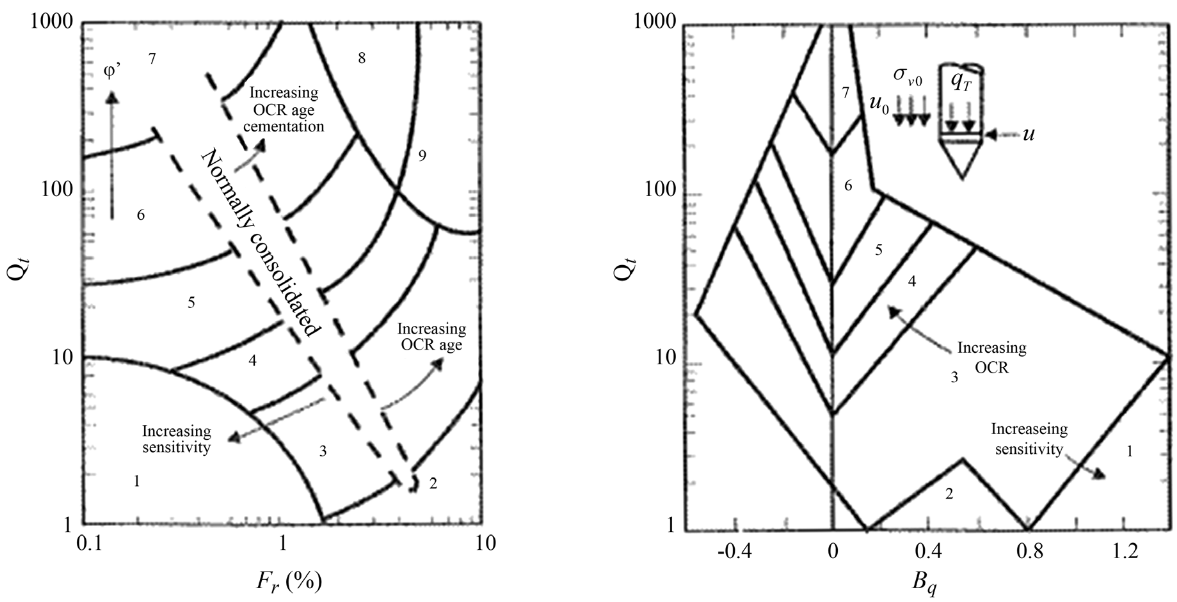
The data were grouped according to the relative density of the sand.

The relative density was estimated considering the influence of the vertical effective stress. First, the value of N_{60}, the number of blows related to the standard energy of 60% of the theoretical potential energy, was estimated from the Eq. 3. For the Brazilian data, the value of 1.37 in Eq. 3 is an average value based on energy measurements carried



1. Sensitive fine-grained soil
2. Organic soil
3. Clay
4. Silty clay to clay
5. Clayey silt to silty clay
6. Sandy silt to clayey silt
7. Silty sand to sandy silt
8. Sand to silty sand
9. Sand
10. Sand to gravelly sand
11. Very stiff fine-grained soil
12. Overconsolidated or cemented sand to clayey sand

Figure 6 - Proposal for soil classification. Robertson *et al.* (1986).



$$Q_t = \frac{q_T - \sigma_{v0}}{\sigma'_{v0}} \qquad B_q = \frac{u - u_0}{q_T - \sigma_{v0}} \qquad F_r = \frac{f_s}{q_T - \sigma_{v0}} \times 100\%$$

1. Sensitive, fine grained
2. Organic soil - peats
3. Clays - silty clay to clay
4. Silt mixtures - clayey silt to silty clay
5. Sand mixtures - silty sand to sandy silt
6. Sands – clean sand to silty sand
7. Gravelly sand to dense sand
8. Very stiff sand to clayey sand*
9. Very stiff, fine grained*

*Heavily overconsolidated or cemented

Figure 7 - Proposal for soil classification - Robertson (1991).

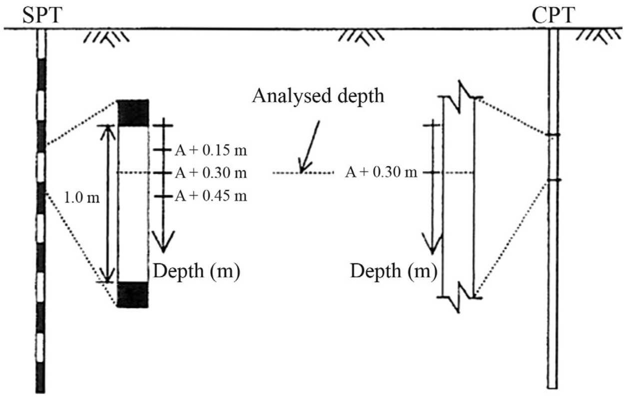


Figure 8 - Illustration showing how the data have been obtained (extracted from Politano (1999) and Politano *et al.* 1998, 2001).

out in equipments used routinely in Brazil (*e.g.*, Belincanta, 1985, 1998, Cavalcante, 2002, Odebrecht, 2003, Odebrecht *et al.*, 2005).

$$N_{60} = 1.37 N_{SPT} \tag{3}$$

From N_{60}, the value of $(N_1)_{60}$ were estimated, which means the value of N_{60} normalized for a vertical effective stress of 100 kPa, through Eq. 4:

$$(N_1)_{60} = C_N N_{60} \tag{4}$$

where C_N is given by Eq. 5, from Seed & Idriss (1982). Kaeyn *et al.* (1992) recommend that the value of C_N should not exceed 1.7.

$$C_N = \frac{2.2}{\left(1.2 + \sigma'_{v0}/p_a\right)} \tag{5}$$

In Eq. 5, σ'_{vo} is the vertical effective stress and p_a is a reference pressure of 100 kPa. After the estimation of $(N_1)_{60}$, the relative density D_r is obtained from Eq. 6 from Kulhawy & Mayne (1990).

$$\frac{(N_1)_{60}}{D_r^2} = 60 + 25 \log D_{50} \tag{6}$$

The value of D_{50} for use in Eq. 6 was based on results of particle size distribution, when available. In cases where there was no information on the soil particle size, the value of D_{50} was estimated as 1 mm.

It should be noted that the Eq. 6 refers to a normally consolidated and not aged deposit. The second term of the expression represents the factor C_p, relative to the size of the particles.

Some investigations have been made by conducting some analysis including an equation that contains the age of the deposit, also reported by Kulhawy & Mayne (1990). As this information was not available in most of the database, a sensitivity analysis has been made in order to verify the influence of the age on relative density. The influence of the age is given by the factor C_A, which must be applied according to the Eq. 7, the factor C_{ov} in Eq. 8 being related to over consolidation and the factor C_p due to the particle size.

$$C_A = 1.2 + 0.05 \log\left(\frac{t}{100}\right), t \text{ in years} \tag{7}$$

$$D_r^2 = \frac{(N_1)_{60}}{C_A \cdot C_p \cdot C_{ov}} \tag{8}$$

Considering a deposit with ages ranging from 1 to 10^8 years, in comparison to a not aged deposit, the results are shown in Table 4. The difference in the estimation of relative density for a value of $(N_1)_{60} = 20$ is also shown in Table 4. It can be observed that a change in age from 1 to 10^8 years represents an increase of 36% in the C_A factor, resulting in a reduction of only 0.08, or 8%, on the relative density. Although these changes, if incorporated into the database, would cause a small increase in the number of data of sands with lower relative density and a small reduction in the number of data corresponding to sands of greater relative density, its influence in the q_c/N_{60} ratio is not significant at all. For the deposits with age information available, its influence has been considered in the determination of the relative density.

With the value of the relative density determined by Eq. 8, the data were classified according to Table 5, obtained from Terzaghi & Peck (1967).

Table 4 - Sensitivity analysis of the influence of the factor C_A in D_R.

t (years)	C_A	D_R^2
1	1.10	0.30
10	1.15	0.29
10^2	1.20	0.28
10^3	1.25	0.27
10^4	1.30	0.26
10^5	1.35	0.25
10^6	1.40	0.24
10^7	1.45	0.23
10^8	1.50	0.22

Table 5 - Relative density of the sands (Terzaghi & Peck, 1967).

Relative density	D_R (%)
Very loose	0 a 15
Loose	15 a 35
Medium	35 a 65
Dense	65 a 85
Very dense	85 a 100

6. Testing Data

6.1. For each site

In establishing the correlations 41 SPT tests and 41 CPTU have been considered, including 319 data points (N_{60}, q_T), N_{60} being the corrected N value for an efficiency of 60% and q_T the corrected cone resistance. In most cases these data corresponded to metric intervals, since this is the usual practice in Brazil. It should be noted that the value of $q_{T,}$ in the case of sands is almost equal to q_c. For this reason, the designation q_c is also used in the present paper.

A linear correlation passing through the origin was initially established. According to Bussab (1988), the equation that determines the angular coefficient K_c of the linear correlation passing through the origin is given by:

$$K_c = \frac{\sum N_{60} q_c}{\sum (N_{60})^2} \tag{9}$$

In cases of small number of data (less than 9 data sets) the correlation has not been established. It has been preferred to calculate only the average value of the statistical distribution of the ratio q_c/N_{60}, designated as K_m. Souza (2009) presented the results in tables and graphs. In the present paper the results are only shown graphically. In Figs. 9 to 15 the values of K_c and K_m are presented for each density range and data site.

6.2. For all sites

The results of University of Florida from Palacios (1977) showed the great influence of the liner removal on the measured

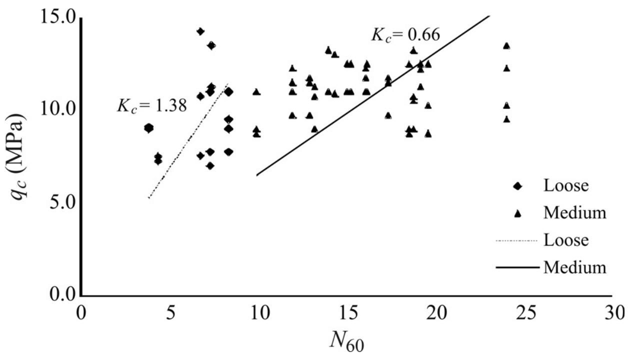


Figure 11 - University of Florida, K_c values for loose and medium sands.

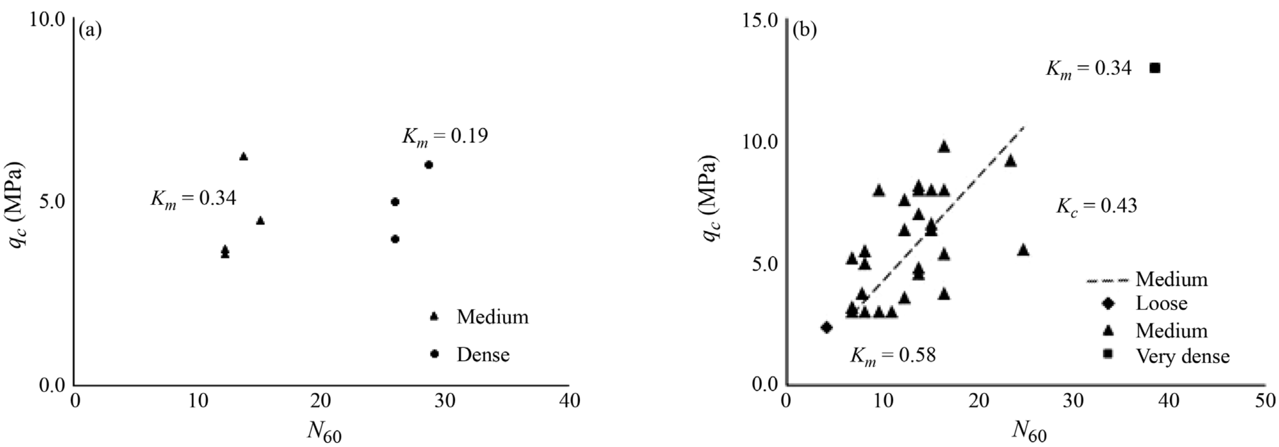


Figure 9 - K_m and K_c values for loose, medium, dense and very dense sands. (a) Port of Açu. (b) President Dutra, Queimados.

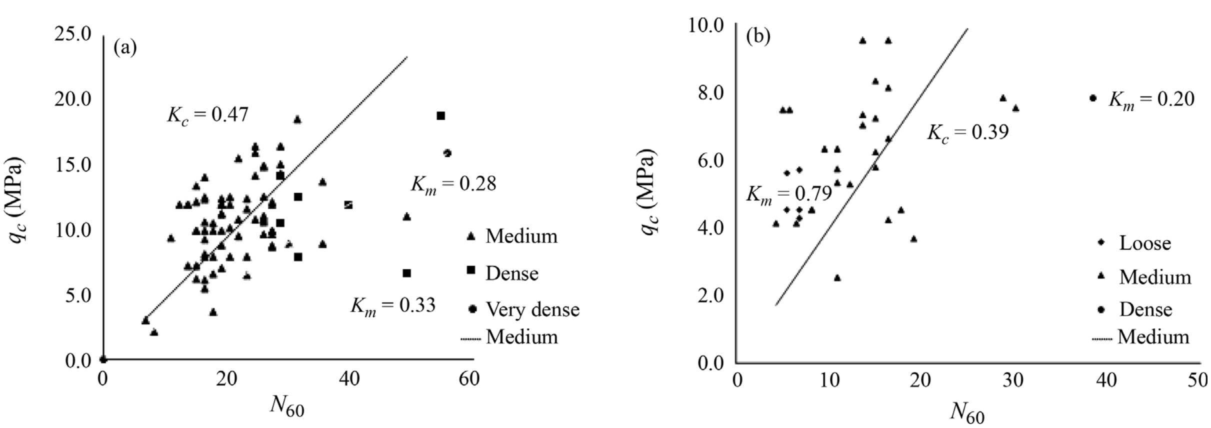


Figure 10 - K_m and K_c values for loose, medium, dense and very dense sands. (a) Industrial construction in the West Zone of Rio de Janeiro. (b) Banhado do Jacareí.

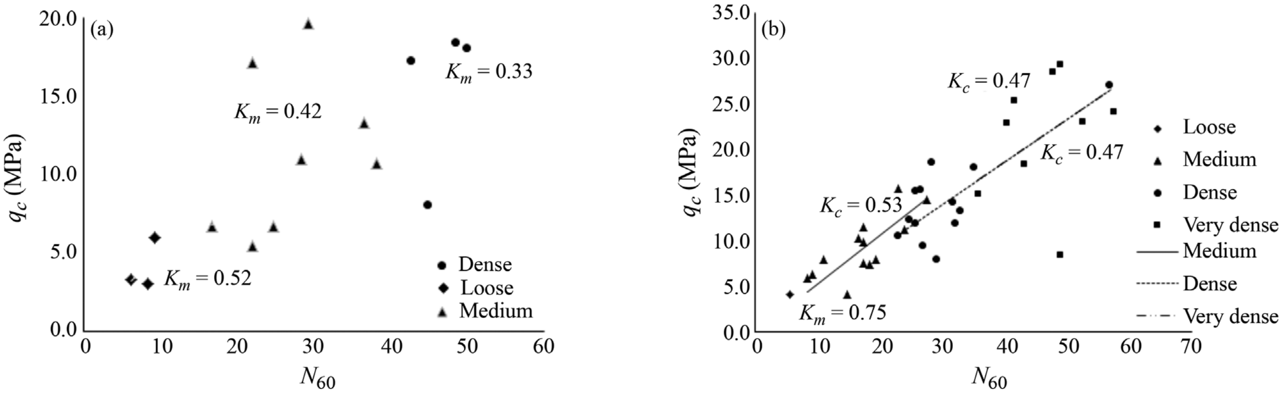


Figure 12 - K_m and K_c values for loose, medium, dense and very dense sands. (a) Natural sand from San Francisco Bay. (b) Hydraulic Fill from San Francisco Bay.

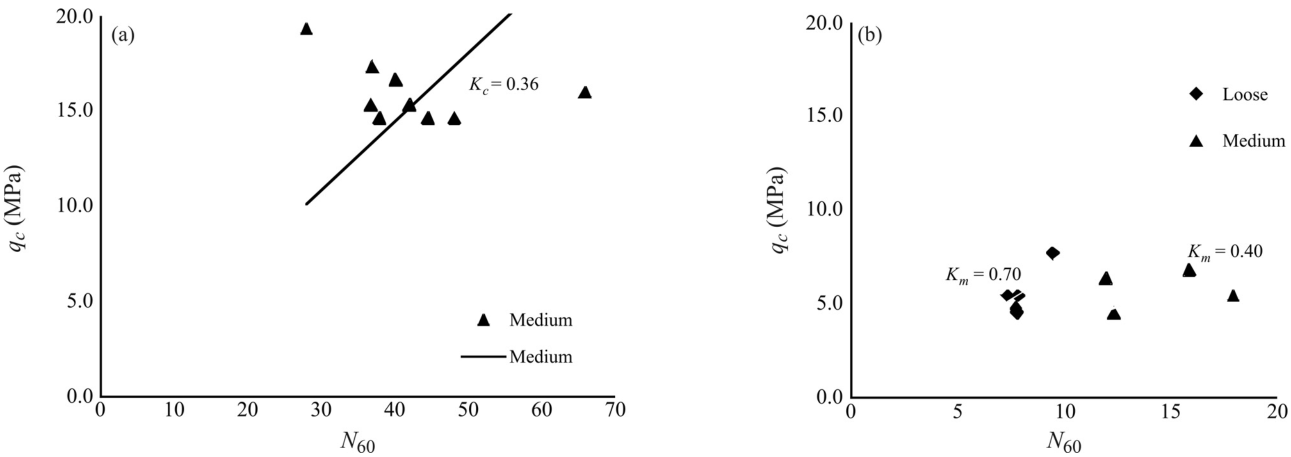


Figure 13 - K_c and K_m value for loose and medium sands. (a) Canlex, Mildred Lake. (b) Canlex, Massey.

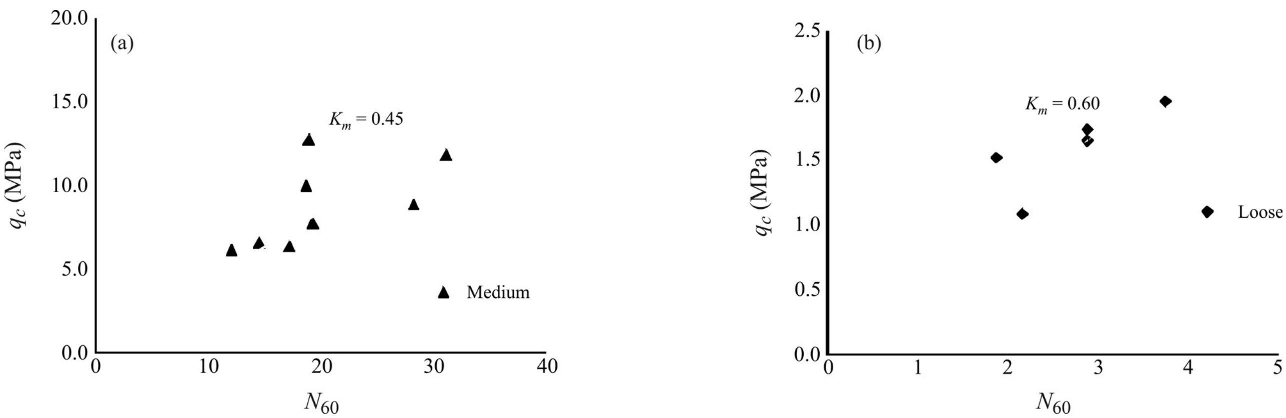


Figure 14 - K_m value for loose and medium sands. (a) Canlex, Kidd. (b) Canlex, J-Pit.

N values. In fact, Fig. 11 shows the higher values of K_c compared to the other data. For that reason, the results from University of Florida were excluded from the "all sites" database. The remaining data, including 255 data points (N_{60}, q_c) were grouped for a comprehensive analysis, with results summarized in Table 6. In this table, the numbers of data included in each correlation is also shown in parentheses. The last column in Table 6 corresponds to the median *K* value, representing the value with 50% of the data with $q_c/N60$ inferior and 50% superior to it.

For very dense sands the data points are very few and the K_c value in Table 6 should be considered with caution. The corresponding Figs., 16 to 19, are shown below.

For the whole database an analysis was also made using a potential correlation, for all the density range. Based

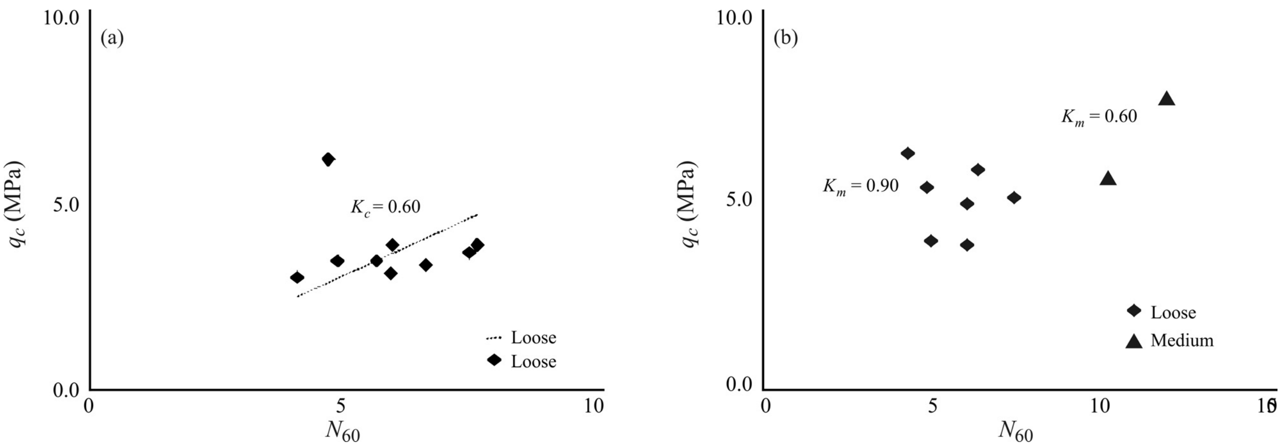


Figure 15 - K_c and K_m value for loose and medium sands. (a) Canlex, LL Dam. (b) Canlex, Hightmont Dam.

Table 6 - Analysis of the whole database.

Sand density	K_c (MPa)	K_m (MPa)	K_{median} (MPa)
Loose (37)	0.69	0.72	0.66
Medium (179)	0.44	0.46	0.44
Dense (28)	0.36	0.37	0.37
Very dense (11)	0.40	0.44	0.43
Whole database (255)	0.41	0.51	0.50

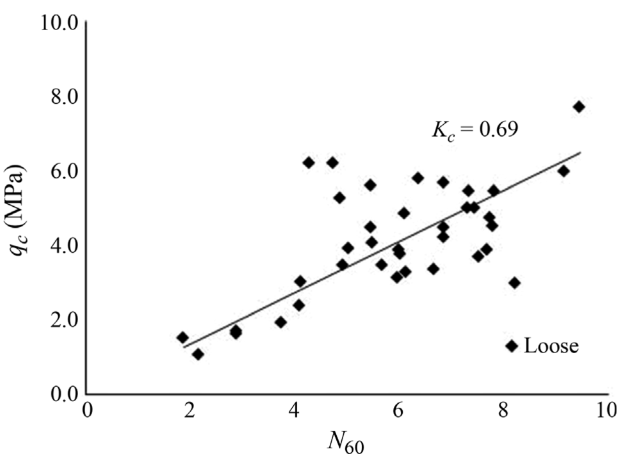


Figure 16 - K_c value for loose sands, whole database.

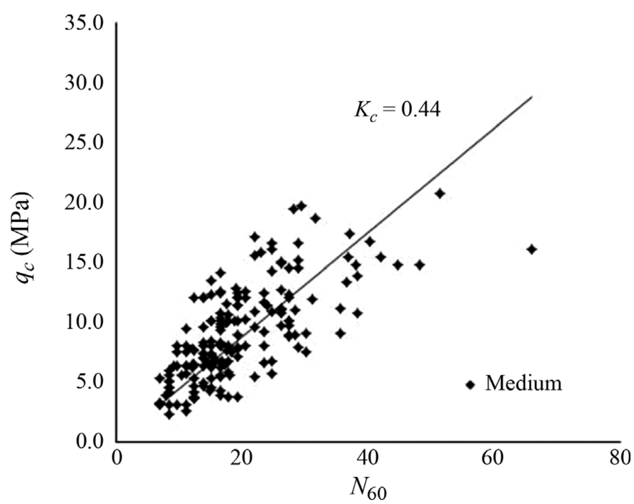


Figure 17 - K_c value for medium sands, whole database.

on 255 data points, the following expression has been obtained:

$$q_c = 1.06 N_{60}^{0.71} \tag{10}$$

q_c given in MPa, Figs. 20 and 21.

7. Data Interpretation

7.1. Relative density

The expectation of the authors, highlighted in the introduction, was that the SPT test is more influenced by the increases in shear stress (due to the unplugged behavior in sands in most of the length of the sampler) than by increases in normal stress. Given the high rate of loading, much higher than in the CPT, the SPT test can generate positive excess pore-pressures in loose sands and negative excess pore-pressures in dense sands. Thus, the N_{60} must be greater than it would be if the test was performed in drained conditions, in the case of dense sands, and lower in the case of loose sands. The same is not true for the values of q_c from the CPT (or CPTU). Therefore, the tendency would be for

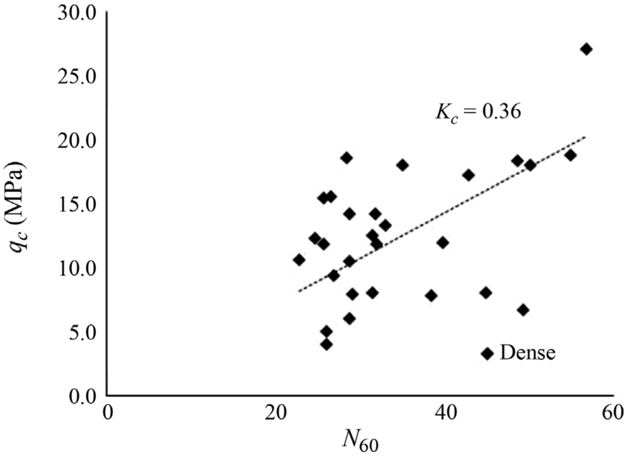


Figure 18 - K_c value for dense sands, whole database.

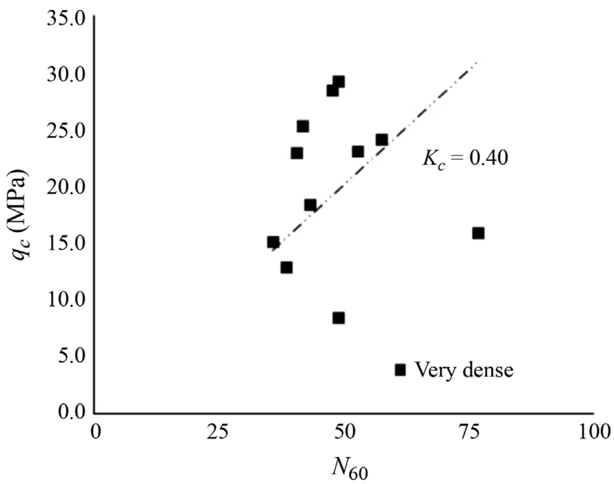


Figure 19 - K_c value for very dense sands, whole database.

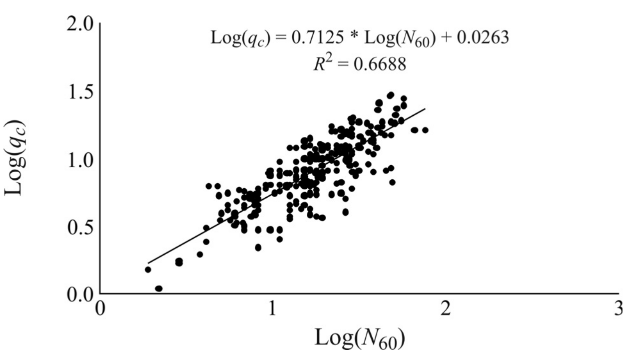


Figure 20 - Linearization of the potential correlation for the whole database.

higher values of the q_c/N_{60} in loose sands and lower values in dense sands for the same grain size.

Schmertmann (1976), as cited by Palacios (1977), found that the sampler penetration velocity could vary from about 4.60 m/s to 0.45 m/s, with an average of 1.20 m/s. On the other hand, the CPT penetration rate is 1.20 m/min, a factor of 60 slower. The author noted that in some soils, the

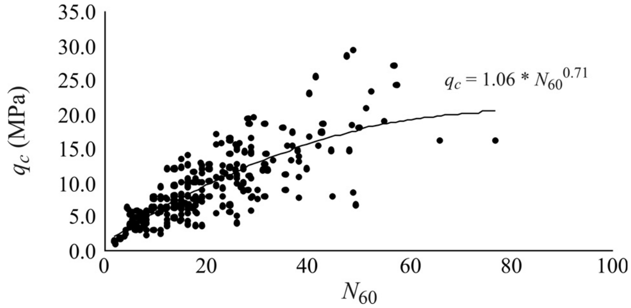


Figure 21 - Potential correlation for the whole database.

different pore-pressure effects due to these different rates of penetration will cause errors; the most serious are likely to occur in loose saturated sands, where the SPT might liquefy the soil, and yield a very low blow count in relation to q_c. That is precisely what Table 6 shows, not only for loose sands, but also for the other density ranges. The q_c/N_{60} ratio is strongly influenced by the density, and not only by the grain size as the existing correlations illustrated. Figures 9 to 15 have also shown that this behavior has been observed in all sites.

In fact, Table 6 shows that the value of $K = q_c/N_{60}$ decreases with increasing density. It is interesting to note that this same behavior has been observed in all the deposits from the database, not only for K_c but also for K_m.

7.2. Liner removal

Only on the deposit of the University of Florida, whose data were obtained from Palacios (1977), the database included measurements of the SPT *N* values with the liner removed. In Brazil the use of the liner is not usual. Schmertmann (1979) observed that the liner removal reduces the relative importance of lateral friction, showing experimental results which confirmed his theory. It should be noted that the results of the q_c/N_{60} of the deposit studied by Palacios (1977), with the liner removed, were nearly twice those of the other deposits, where the liner was not removed. As the removal of the liner practically eliminates internal resistance, the value of N_{60} with the liner removed should be lower than that obtained with the use of the liner, with the sampling unplugged. Consequently the value of *K* should be greater, with the removal of the liner, when compared to the value of *K*, for the same soil. One should note that this was exactly what happened with the database of Palacios (1977), Fig. 11, when compared to the rest of the database analyzed in this paper.

7.3. The analysis of the global database

Excluding the results presented by Palacios (1977), which showed the great influence of the liner removal in the measured values of N_{60}, all the other results, including 255 data points (N_{60}, q_c) were grouped for a global analysis, for each density range. The results, presented in Table 6, confirmed the trend observed in individual deposits: a reduction of K has been observed with increasing soil density.

A value of K in MPa/blows/0.30 m close to 0.7 has been obtained for loose sands, 0.5 for medium sands, 0.4 for dense and very dense sands and 0.5 for the whole database, regardless its density.

7.4. The potential correlation

From Eq. 10, and based on the average N_{60} of each density range suggested by the Brazilian Code, ABNT (2001), which presents 5 density ranges, one can obtain the values of Table 7.

The values obtained by the potential correlation expressed by Eq. 10 are close to those obtained with the linear correlation for each density range. The advantage of the potential correlation is that a single equation can represent the tendency of distinct K values for the various densities.

The authors suggest the direct use of the potential equation in future applications of correlations between the CPT and SPT in sands.

7.5. The consequences for foundation design

The results obtained in the present paper have a great impact in foundation design. In fact, some design methods use direct correlations between the results of SPT and CPT. While in the traditional correlations the values of q_c/N_{60} depend solely on grain size, the results observed show that the density is of fundamental importance in correlations and should therefore be considered.

In particular, the analysis indicate that the value of K equal to 0.7 MPa/blows/0.30 m for sands, as commonly used in Brazil in the Aoki & Velloso (1975) method for estimating bearing capacity of piles, is more characteristic of loose sands. In fact, Danziger & Velloso (1995) found a K value of 0.5 MPa/blows/0.30 m for an extensive database covering all density ranges. It is interesting to note that the value of K, obtained from Table 6 for the overall analysis, is equal to 0.5 MPa/blows/0.30 m. The results presented herein also indicate that the value of K of 0.5 MPa/blows/ 0.30 m for sands found by Danziger & Velloso (1995) is consistent with the overall analysis shown in the present paper. In the case of a pile driven through a sedimentary low consistency deposit and embedded into an underlying dense sand, with a K value in the order of 0.4, according to the present paper, the use of a K value of 0.7, as suggested in Aoki & Velloso (1975) method, would lead to a very unsafe design.

The comparison made also reinforces the experience that the tip resistance of the mechanical cone is similar to corresponding values of the electrical cone test (and piezocone). Indeed, the correlations established by Costa Nunes & Fonseca (1959), which served as the basis for Aoki & Velloso (1975) bearing capacity method and the correlations of Danziger & Velloso (1995), were both based on data from the mechanical cone, while the present correlations consider the CPT and piezocone, equivalent to the electrical cone.

8. Conclusions

The present paper presented the analysis of nearly 319 data points (q_c, N_{60}) from cone tip resistance (mainly CPTU) and dynamic SPT in sands. The main purpose of the analysis was to investigate the influence of the relative density of the sand in the establishment of correlations between q_c and N_{60}. The results confirmed the author's initial expectation that relative density has a great influence on the correlations. The main conclusions are:

i) The value of $K = q_c/N_{60}$ decreases with increasing relative density of the sand. In the overall analysis, including the database from all sand deposits, an approximate value for K, in MPa/blows/0.30 m of 0.7 has been obtained for loose sands, 0.5 for medium sands and 0.4 for dense and very dense sands. The analysis with all database indicated 0.5 for K regardless the relative density.

ii) Data from Palacios (1977), who registered the N_{60} with liner removed, indicated the same trend of reduction of the K value with relative density. However, the K values were almost twice those found in other deposits, where the N_{60} have been obtained without the liner removal.

iii) The results have great impact on foundation design, as long as some design methods of bearing capacity estimation use q_c *vs.* N_{60} correlations. While traditional correlations of q_c/N_{60} are based solely on grain size, the results shown in the present paper illustrate that the relative density is of fundamental importance and should therefore be considered. The tests performed indicate that the value of K equal to 0.7 MPa/blows/0.30 m for sands, as used in Aoki & Velloso (1975) method for pile bearing capacity estimation

Table 7 - Values of K obtained from Eq. (10).

Density	N_{SPT}	N_{60}	q_c (MPa)	$K = q_c/N_{60}$
Loose	2 (≤ 4)		2.2	0.79
Low density	6 (5 to 8)		4.7	0.58
Medium	13 (9 to 18)	1.37 x N_{SPT}	8.2	0.46
Dense	30 (19 to 40)		14.9	0.36
Very dense	> 40		> 18.0	< 0.34

is more characteristic of loose sands. For piles in sands with higher density, the use of smaller values of K is suggested. As an alternative, a potential correlation is presented, which allow with a single expression the estimation of q_c for the whole density range.

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