Journal of GeoEngineering, Vol. 18, No. 4, pp. 225-238, December 2023
http://dx.doi.org/10.6310/jog.202312_18(4).6

SPT AND CPT CORRELATIONS FOR JOLSHIRI AREA OF DHAKA RECLAIMED BY DREDGED RIVER SEDIMENTS

Asef Israk Arnob [1], Mohiuddin Ahmed [2], and Khondaker Sakil Ahmed [3*]

ABSTRACT

Correlations between standard penetration test (SPT) and cone penetration test (CPT) are often crucial because the very common and cost-effective SPT may reliably predict the expensive CPT-based layer-wise bearing strength of the soil. This study intends to establish correlations between SPT-N_{60} values to different CPT parameters such as cone tip resistance (q_c), sleeve friction (f_s), soil behavior type index (I_c), fines content (F_c%), and mean grain size (D_{50}) for various soil types of Jolshiri Area of Dhaka City. In this study, four types of soil are identified from the dredged river sediments namely, poorly graded sand (SP), clayey silt (ML), silty sand (SM), and silty clay (CL). Both statistical and arithmetic approaches are followed to develop the correlation equations. Primarily, this study finds a linear relationship between SPT-CPT parameters for various soil types. Initially, a total of 638 data pairs are selected to develop correlations between SPT-N_{60} and q_c for each soil type. A reasonably good correlation is observed between q_c and N_{60} with regression coefficients greater than 0.70 for each soil type except silty sand (SM). Afterward, data filtration is performed to determine more accurate correlations for each soil type. The relationships between SPT-N_{60} and CPT-f_s for each soil type demonstrate moderate correlations between them. In this study, an improved correlation between q_c/N ratio and mean grain size (D_{50}) is also proposed. A linear relationship is also developed to capture the correlations between q_c/N ratio, soil behavior type index (I_c), and fines content (F_c%).

Key words: SPT, CPT, correlations, fines content, sleeve friction, tip resistance, dredged sediment.

1. INTRODUCTION

The two in situ tests most frequently used to define soil strata and ascertain the geotechnical engineering properties of subsurface soils are the standard penetration test (SPT) and the cone penetration test (CPT). The SPT was the most often performed field test to evaluate the geotechnical parameters of granular materials due to its simplicity, low cost, and several well-established SPT-based geotechnical design approaches in the literature. Several geotechnical design properties like bearing capacity, skin friction, or end bearing can be determined using SPT-N values (Tarawneh 2014). Standard penetration test (SPT) is a widely used in-situ test for geotechnical investigations in Bangladesh. Foundations in Bangladesh are typically designed using SPT-N values and lab test data. On the other hand, the cone penetration test (CPT) is gaining popularity worldwide as an in-situ test for site investigation and geotechnical design. The CPT has been viewed as an alternative to the SPT because of its dependability, repeatability, and standardization. CPT tests are primarily conducted in Bangladesh for major projects only because of their high cost and not available for routine practice, *i.e.,* local contractors do not offer them (Arifuzzaman and Anisuzzaman 2022). As a result, only in a few selected construction projects, the findings of static cone penetration tests are utilized for final design and construction quality control. In contrast, standard penetration test results are used to calculate soil properties during the preliminary design stage or vice versa (Alam *et al.* 2018).

The CPT is achieving prominence in subsoil investigation due to its speedy and convenient way of measuring continuous soil stratigraphy. There are a good number of researches where SPT-CPT correlations were investigated in the literature (Jamiolkowski *et al.* 1985; Seed and De Alba 1986; Kulhawy and Mayne 1990; Jefferies and Davies 1993; Stark and Olson 1995; Suzuki *et al.* 1998; Baez *et al.* 2000). In those works, the researchers worked with the parameters like SPT-N_{60} value, cone tip resistance (q_c), the q_c/N ratio, the mean grain size (D_{50}), the fines content (F_c) of the soil, and the soil behavior index (I_c). It was suggested by some researchers that a ratio $n = q_c/N$ (q_c in MPa) for different soil types can be a stable parameter that can be used for design applications (Schmertmann 1970). In that particular study, the author recommended N-values as 0.2 MPa; for clean, fine-to-medium sand and slightly silty sand, 0.3-0.4 MPa; for coarse sand and sand with little gravel, 0.5-0.6 MPa; and for sandy gravel, and 0.8-1.0 MPa for gravel. Another study on the SPT-CPT correlation claimed that a better correlations between f_s (sleeve friction) and N-value may be created, particularly for cohesive soils, in place of the correlation of q_c with N-value. Among the different areas, SPT-CPT parameters were correlated for Brazilian soil (Danziger and Velloso 1995). The values obtained by their findings were within the same range that was suggested by Schmertmann (1970).

The q_c/N ratio was established by Robertson *et al.* (1983) as a function of the mean grain size, D_{50}. This study conducted the cone penetration test considering pore pressure measurement tests (CPTU) and also proposed a soil behavior type classification. Jefferies and Davies (1993) presented a soil categorization chart that estimated N values, and Lunne *et al.* (1997) agreed with their work.

Manuscript received April 27, 2023; revised August 9, 2023; accepted September 22, 2023.

[1] BSc Student, Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh.
[2] Associate Professor, Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh.
[3*] Associate Professor (corresponding author), Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh. (e-mail: drksa@ce.mist.ac.bd).

Using a piezo-cone, this innovative idea evaluates q_c by accounting for pore water pressure (u) and overburden stress (σ'_{vo}). Ismael and Jeragh (1986) developed a correlation for clean, fine to medium sands and slightly silty sands in Kuwaiti calcareous deserts and compared it to values with that proposed by Schmertmann (1970). They found higher correlation values than Schmertmann. They also found a close relationship between the q_c/N ratio and D_{50}, as developed by Robertson *et al.* (1983).

Table 1 summarizes the previously developed correlations as found in the existing literature. The existing correlations could be divided into three distinct groups (Shahien and Albatal 2014). They are based on (A) median grain size, D_{50}; (B) fines content, F_c%; and (C) soil behavior type index, I_c. In the majority of the correlations, the variable is a ratio of $(q_c/P_a)/N_{ER}$, where, q_c is the CPT tip resistance, P_a is the atmospheric pressure, and N_{ER} is the SPT-N value with the energy ratio of the hammer used in the field test. In some correlations, no ER value is shown, meaning the energy ratio for those correlations is unknown. According to the majority of previous research, an approximate, more or less average relationship was found. The majority of them excluded correlation coefficients or standard deviation. However, recent studies have shown that applying statistical methods would significantly help to improve correlations and indicate the reliability of the developed correlations (Akca 2003). In this study, both statistical and average arithmetic approaches are used to develop required correlations.

As many soil parameters are related to the SPT-N value, and only SPT data is typically available in most cases, the correlation of CPT data with the SPT-N value is very effective. Unfortunately, there is very limited study on the SPT-CPT correlation, particularly on reclaimed land from dredged sediments. To accommodate a large 20 million population, Dhaka city is expanding towards its outer periphery as happened to the Jolshiri area. Recently, this area has been reclaimed by the dredged sediments of the nearby river. This study aims to explore the SPT-CPT correlation of the Jolshiri Area of Dhaka.

2. SITE SELECTION AND FIELD TEST

Jolshiri Abasion area is made up of a soft organic layer that is between 3 and 6 meters thick, a layer of soft silty soil that is between 25 and 35 meters deep, and a layer of dense silty sand that is very deep. The area of the depression has recently been raised, primarily through hydraulic fill made of dredging silty sand gathered from neighboring rivers. The selected study area is shown in Fig. 1, located in the extension of Dhaka city. The figure shows the CPT location and the nearby SPT locations of the Jolshiri area.

Primarily, standard penetration tests (SPT) were carried out following ASTM D 1586 at 1.5 m intervals to identify relative density/consistency and classify soil at various elevations, including collecting disturbed soil samples from each interval following the specifications of the engineer. The cone penetration test (CPT) is the most effective in-situ method for evaluating soil stratigraphy and geotechnical properties of soil (Duan *et al.* 2018). Using a special mobile penetrometer rig propelled by water pressure, the cone descends to ground level without using a borehole (Clayton 1995). Most modern penetrometers can use an electronic pressure transducer to measure the pore water pressure. These penetrometers are called "piezocones". It measures the equilibrium value (called u_o) or piezometric level at that depth when porewater pressure becomes constant.

Table 1 Summary of Existing SPT-CPT Correlations (Shahien and Albatal 2014)

No.	Reference	Correlation	Comment
(A) Correlations based on median grain size, D_{50}			
	Muromachi and Kobayashi (1982)	$(q_c/p_a)/N = 5.48 + 1.36 \log_{10} D_{50}$	
	Robertson *et al.* (1983)	$(q_c/p_a)/N_{55} = 7.5\ (D_{50})^{0.26}$	
	Burland *et al.* (1985)	$(q_c/p_a)/N = 8.0\ (D_{50})^{0.30}$	
	Seed and De Alba (1986)	$(q_c/p_a)/N_{60} = 6.0\ (D_{50})^{0.24}$	
	Andrus and Youd (1989)	$(q_c/p_a)/N_{60} = 4.95\ (D_{50})^{0.168}$	
	Kulhawy and Mayne (1990)	$(q_c/p_a)/N = 5.44\ (D_{50})^{0.26}$	
	Suzuki *et al.* (1998)	$(q_c/p_a)/N = 11.1\ (D_{50})^{0.261}$ $(q_c/p_a)/N = 8.4\ (D_{50})^{0.225}$ $(q_c/p_a)/N = 6.0\ (D_{50})^{0.165}$	$0 \le N < 10$ $10 \le N < 30$ $30 \le N, F_c \le 20$
(B) Correlations based on fines content, F_c%			
	Jamiolkowski *et al.* (1985)	$(q_c/p_a)/N_{64} = 4.90 - 0.03 \times F_c$ (%)	
	Chin *et al.* (1988)	$(q_c/p_a)/N_{55} = 4.70 - 0.05 \times F_c$ (%)	
	Kulhawy and Mayne (1990)	$(q_c/p_a)/N = 4.25 - 0.024\ F_c$ (%)	
	Suzuki *et al.* (1998)	$(q_c/p_a)/N = 0.0026\ F_c^2 - 0.263F_c + 12.34$ $(q_c/p_a)/N = 0.00085\ F_c^2 - 0.120F_c + 8.733$ $(q_c/p_a)/N = 0.0001\ F_c^2 - 0.059F_c + 5.59$	$0 \le N < 10$ $10 \le N < 30$ $30 \le N, F_c \le 20$
(C) Correlations based on soil behavior type index, I_c			
	Jefferies and Davies (1993)	$(q_c/p_a)/N_{60} = 8.5\ (1 - I_c/4.75)$	
	(Lunne *et al.* 1997)	$(q_c/p_a)/N_{60} = 8.5\ (1 - I_c/4.6)$	Modified definition of I_c based on Robertson and Wride (1998)
	Robertson (2012)	$(q_c/p_a)/N_{60} = 10^{(1.1268 - 0.2817 I_c)}$	
	Suzuki *et al.* (1998)	$(q_c/p_a)/N = 31.25 \exp(-0.68 I_c)$ $(q_c/p_a)/N = 18.60 \exp(-0.54 I_c)$ $(q_c/p_a)/N = 10.21 \exp(-0.35 I_c)$	$0 \le q_t < 5$ $5 \le q_t < 15$ $15 \le q_t$
(D) Correlations based on other variables or other forms			
	Idriss and Boulanger (2006)	$(q_{c1}/p_a)/(N_1)_{60} = (2.092 D_r + 2.224)^{3.788}/46(D_r)^2$ $D_r = 0.478(q_{c1}/p_a)^{0.264} - 1.063$, $(q_{c1}/p_a > 21)$ or $D_r = ((N_1)_{60}/46)^{0.5}$	q_{c1} and $(N_1)_{60}$ are q_c and N_{60} respectively, corrected for σ'_{vo}
	Hayati and Andrus (2009)	$(N_1)_{60CS} = 0.356(q_{c1-CS})^{0.851}$	Holocene sand, $F_c < 20\%$ $I_c < 2.25$
	Souza *et al.* (2012)	$(q_c/p_a) = 10.6(N_{60})^{0.71}$	$F_c < 10\%$

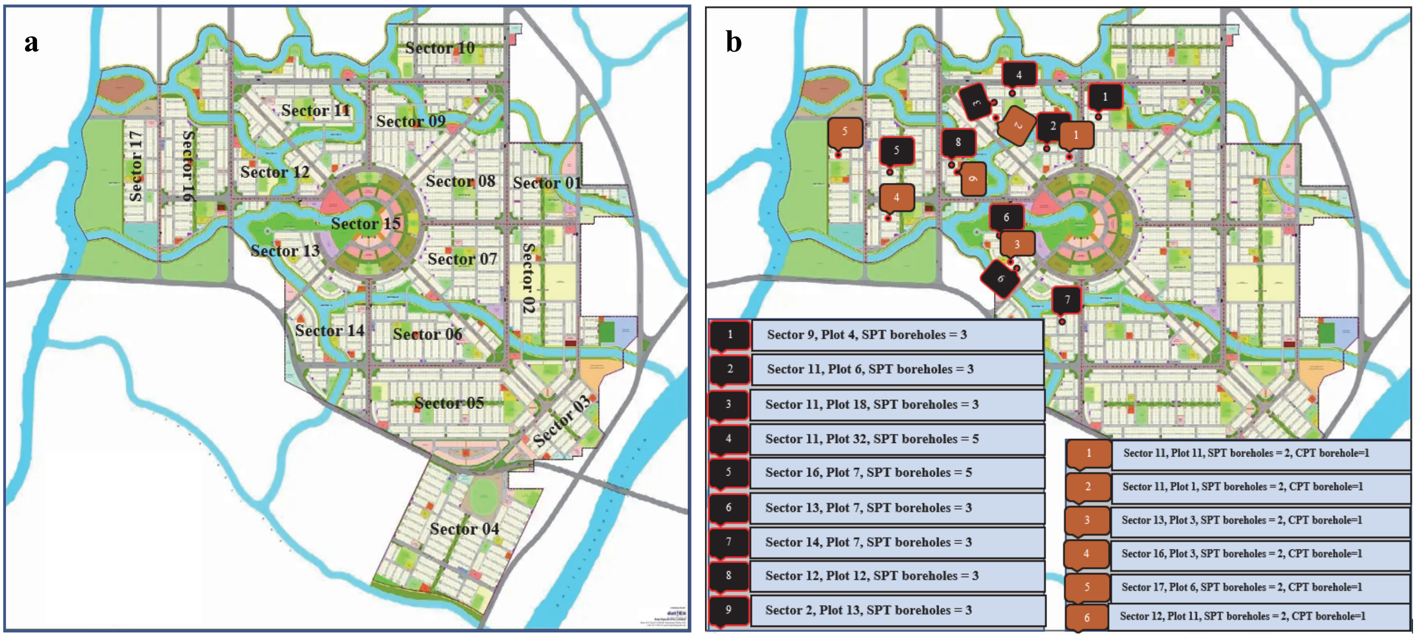


Fig. 1 Maps of (a) the Jolshiri area, the nearby river, sectors, and (b) SPT-CPT plot locations

In this study, a penetrometer tip with a conical point, a 60° apex angle, and a cone base area of 10 or 15 cm^2 were pushed into the soil at a constant rate of (20 ± 5) mm/s. Electrical methods were used to determine the force needed to penetrate the soil at least every 50 millimeters on the conical point (cone). Cone resistance, q_c, was obtained by dividing the measured force (total cone force) by the cone base area. At least every 50 mm of penetration, a friction sleeve was present on the penetrometer just behind the cone tip, and electrical methods measured the force acting on the sleeve. Sleeve resistance, f_s, was calculated by dividing the recorded axial force by the friction sleeve's surface area. Figure 2 shows that the cone penetration test was conducted for this study.

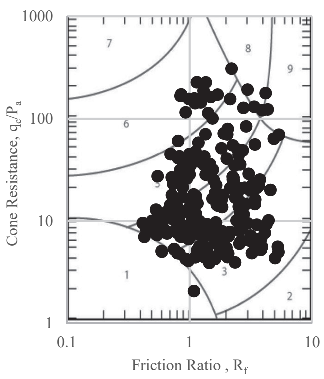
(a) Instrumentation for the CPT test (b) Data collection at the site

Fig. 2 Cone penetration test at soil site

3. SUBSOIL CHARACTERISTICS OF THE STUDY AREA

A total of fifteen residential plot area was selected for the data collection. Among them, six plots where both SPT and CPTs are conducted. In the remaining nine plots, only SPT tests were performed. Using friction ratio (R_f %), soil types can be identified from the SBT chart developed by Robertson (1990) and Robertson (2010). Different soil types in this study are determined using the chart as shown in Fig. 3. It can be shown from Fig. 3 that the majority of soil types from this study fall in zones 3, 4, 5, and 6, where zone 3 is silty clay to clay, 4 is clayey silt to silty clay, 5 is silty sand to sandy silt, and 6 is clean sand to silty sand. Considering laboratory tests, soil behavior type (SBT) chart, and field identification of soil types of SPT, mainly four (4) types of soil are found in these areas: fine sand (SP), clayey silt (ML), silty clay (CL), silty sand (SM). Besides, silty-clayey sand (SC-SM), sandy silt (MS) & CL-ML are also found at very few depths. The samples were taken during SPT testing, and the soil particle percentages were determined based on laboratory tests, as shown in Table 2.

Similar soil types are evidenced in the majority of the borehole locations where subsoil comprises a layer of fine sand of about 1.5 m to 10.5 m. Among them, two plots are identified where fine sand is found from 28.5 m to 36 m in depth. Clayey silt is generally found in the depths of 9 m to 37.5 m of the majority of plot locations. However, clayey silt is also found in some scattered depths at a few plots. On the other hand, silty sand is found from 39 m to 45 m. In the case of silty clay, no general range of depth can be identified. Silty clay is found in scattered depths and varies from plot to plot. The soil characterization also revealed that fine



Zone	Soil Behaviour Type (SBT)
1	*Sensitive fine-grained*
2	*Clay - organic soil*
3	*Clays: clay to silty clay*
4	*Silt mixtures: clayey silt & silty clay*
5	*Sand mixtures: silty sand to sandy silt*
6	*Sands: clean sands to silty sands*
7	*Dense sand to gravelly sand*
8	*Stiff sand to clayey sand**
9	*Stiff fine-grained**

** Overconsolidated or cemented*

Fig. 3 Identifying soil types of the Jolshiri area using the SBT chart (Robertson 2010)

Table 2 Percentages of sand and fines content in the site soil

Soil types	No. of tests	Percentage of soil particles	
		% sand	fines content
Poorly graded sand (SP)	17	78% - 98%	2% - 22%
Clayey silt (ML)	55	1% - 45%	55% - 99%
Silty sand (SM)	37	54% - 94%	7% - 46%
Silty clay (CL)	10	20% - 45%	55% - 80%

sand and silty sand usually contain over 80% sand and 60% sand particles, respectively. The clayey silt and silty clay consist of over 55% of the fines content that may reach up to 99%.

4. FIELD DATA

Fifteen (15) individual plots were selected to conduct the field tests and collect data. In those plots, a total of six CPTs and 43 SPTs were performed in the Jolshiri Area. Two SPTs were performed nearby each CPT test location, totaling 12 SPTs (out of 43) that were used as direct correlations. The locations of CPT tests and nearby SPT test locations are presented in Fig. 1. SPT N_{60} - CPT and q_c graphs with depth are shown in Figs. 4 and 5. The maximum depth of the bore log from the existing Ground Level was 45 m. Table 3 shows the number of plots where only SPT tests are performed and where both SPT and CPT tests are performed. According to laboratory tests (such as grain size analysis, hydrometer analysis, and the Atterberg limits test), the soil profile in each SPT boring log is classified into several soil layers.

SPT data were taken in each 1.5 m interval, whereas CPT parameters were recorded in each 1 m interval (as per soil report). To match the depth, interpolation has been performed for CPT parameters and SPT values. Therefore, the CPT parameters are equivalent to each depth SPT-N value of both SPT boreholes. For example, Fig. 5 shows that at 25.5 m depth, SPT-N values are 14 and 10 for boreholes 1 and 2, respectively. The q_c value obtained from CPT at the same depth is 2.5 MPa. Therefore, at this depth, two unique (N, q_c) data pairs, (14, 2.5) and (10, 2.5) were found. This strategy was followed to find the unique SPT-N-CPT q_c; SPT-N-CPT f_s data pairs at each depth for the plots where both SPT and CPT tests were performed. A total of 300 SPT-N-CPT q_c; SPT-N-CPT f_s data pairs were observed for all soil types from the six SPT CPT plots. It is assumed that the non-CPT plots, of which SPT graphs are quite similar to the reference plot's SPT graph and they have the equivalent cone tip resistance, q_c values. The idea behind this assumption was the source of the reclaimed soil used to fill the studied area. Since the entire area was filled by dredge soil collected from the nearest river bed and the soil parameters of the reference plot are quite close to the other non-CPT plots, the data pair can be approximated from the conducted CPTs.

For the non-CPT zones, the SPT data is very much similar up to 30 m depth for all boreholes (as they are mainly dredged river sediment). Therefore, it can be inferred that up to that depth, the soil properties of the non-CPT plots are identical to the reference plot (nearby the CPT test). Based on this idea, it is assumed that in those non-CPT plots, the cone tip resistance (q_c) and sleeve friction, f_s values up to 30 m depth, are equivalent to the q_c values of the reference plot. Thus, unique SPT-N and CPT q_c; SPT-N and CPT f_s pairs are found for the non-CPT plots. Based on this correlation strategy, a total of 338 data pairs for all soil types was recorded and that makes a total of 638 data pairs.

The basic statistical parameters of all 638 data have been presented in Table 4. It can be seen from Table 4 that the SPT-N_{60} and the CPT q_c vary in a wide range for the fine sand. The SPT-N_{60} of the fine sands has been found in a range of 1-50 with a mean of 8 and a standard deviation of 7.72. Higher values of skin friction are observed for the clayey silt and silty sand. The lowest values of q_c and skin friction have been observed for silty clay. The mean value of D_{50} is 0.103 with a standard deviation of 0.096, whereas the SBT index I_c varies in a range of 1.57-3.86. The soil properties typically reflect the standard dredged river sediments, *i.e.,* alluvial deposition in the rivers of the delta region of South Asia.

4.1 Data Interpretation and Data Matching

In this study, field SPT-N values are further corrected for the field as per standard procedures. Many authors in the literature (Akca 2003; Feda Aral and Gunes 2017; Hore *et al.* 2018; Arifuzzaman and Anisuzzaman 2022) have developed correlations based on N_{60}, where field N value is corrected for 60% of the hammer efficiency. Corrected SPT-N_{60} can be calculated from field SPT-N using the following formula from Das and Sivakugan (2018).

$$\text{SPT-}N_{60} = \frac{E_H \times C_B \times C_S \times C_R \times \mathrm{N}_f}{0.60} \quad (1)$$

where N_{60} = SPT-N value corrected for field procedures; C_B = borehole diameter correction; C_S = sampler correction; C_R = rod length correction; E_H = hammer efficiency (%); N_f = SPT value recorded in the field.

The SPT-N values at the same elevation were compared to the q_c and f_s values. SPT results were collected from 1.5 m intervals, whereas CPT outputs were collected from 1 m intervals. To merge the values from SPT and CPT at the same axis, linear interpolation was performed to find the CPT parameters at the same depth of SPT values, as SPT value intervals are larger than CPT. CPT parameters are correlated by taking SPT-N values as a reference in the plots where only the SPT test is done. According to Jarushi *et al.* (2015), each type of soil from all boreholes is separated and then combined into a single analysis is necessary for the correlation process. The stronger the correlation, the nearer the correlation coefficient to 1 (+ or −). According to Yusof and Zabidi (2018), the relationship between any parameters can be classified as $R^2 < 0.3$ (no correlation), $0.3 < R^2 < 0.499$ (mild correlation), $0.5 < R^2 < 0.699$ (moderate correlation), $0.7 < R^2 < 1$ (strong correlation).

4.2 Data Training (Filtration)

In order to improve the correlation values between SPT and CPT data, a data training process is adopted based on data consistency. Inconsistent data, data away from general trends, are eliminated to make the relationship as accurate as possible. Though 638 data pairs are selected initially for all soil types, data from some depths are eliminated after training due to inconsistency. It is observed from the field data that many of the SPT-N values were recorded much higher than 50. Initially, they were recorded as N values of 50. However, once field SPT-N values were corrected following field procedures (N_{60}), these values showed less consistency with the other data sets, and the correlation between SPT-N_{60} and CPT q_c was less. Therefore, we screened out those data sets. Therefore, SPT-N values of precisely 50 or close to 50 were chosen carefully.

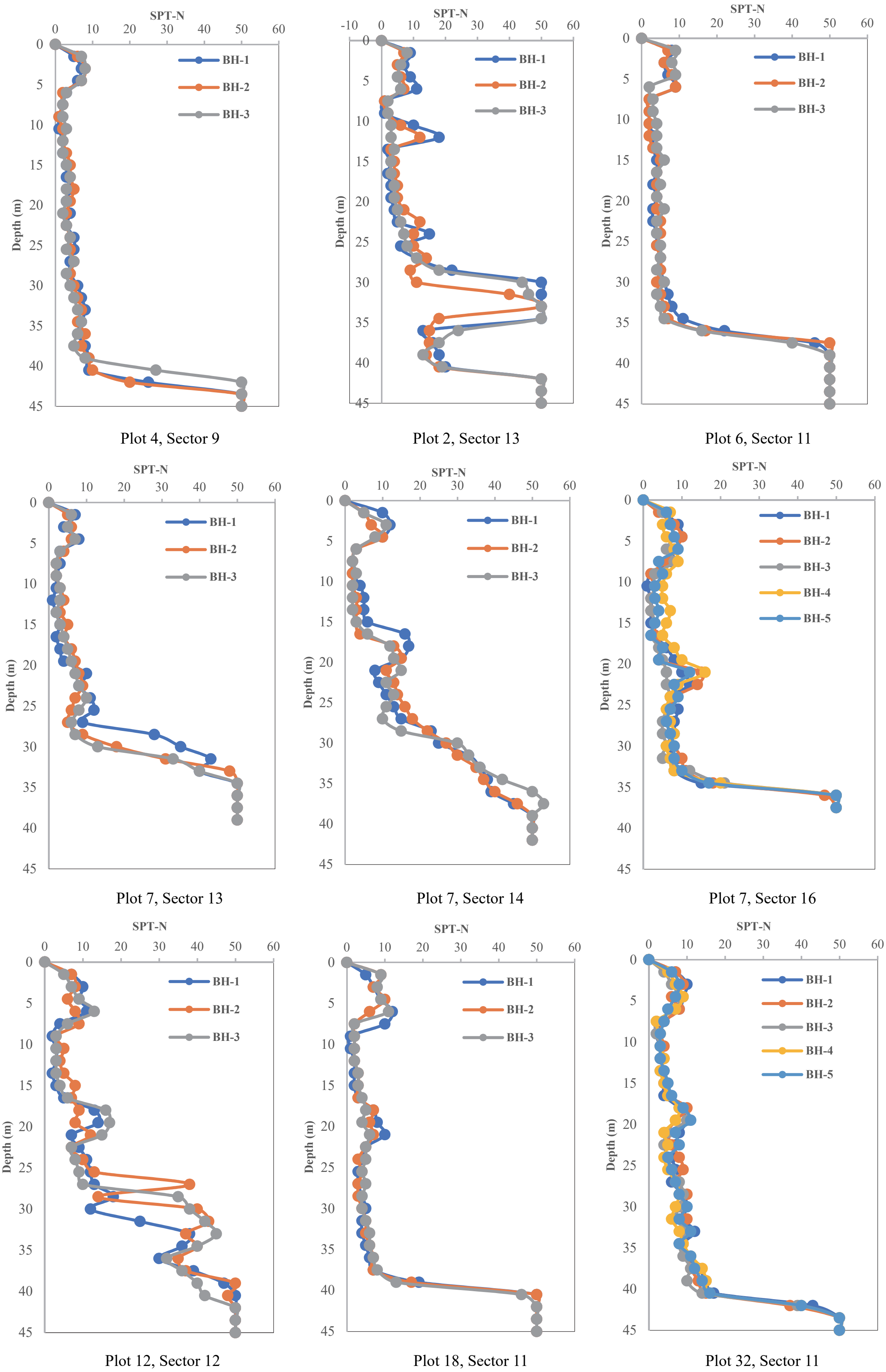


Fig. 4 SPT-*N* values with depth of different boreholes of 9 plots

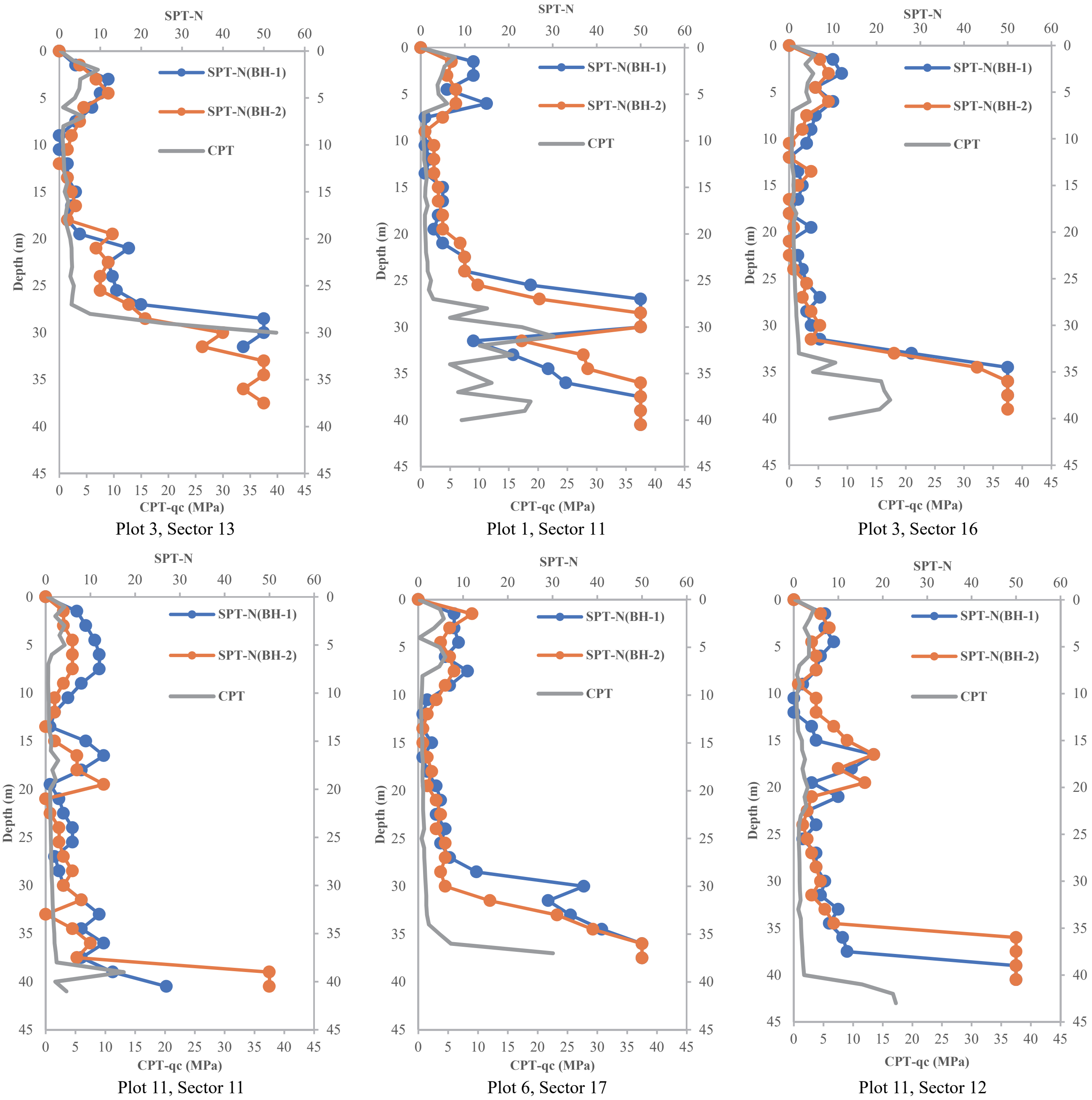


Fig. 5 SPT-N and CPT-q_c with depth of different boreholes of 6 plots

Table 3 Summary of SPT-CPT boreholes

Plot number	Sector number	No. of SPT tests	No. of CPT tests	Penetration depth (m)-SPT	Penetration depth (m)-CPT
4	9	3	None	45	–
18	11	3	None	45	–
32	11	5	None	45	–
6	11	3	None	40.5	–
7	16	5	None	37.5	–
7	13	3	None	39	–
7	14	3	None	42	–
12	12	3	None	45	–
2	13	3	None	45	–
3	13	2	1	37.5	30
1	11	2	1	40.5	40
3	16	2	1	39	40
11	11	2	1	40.5	41
6	17	2	1	37.5	37
11	12	2	1	40.5	43

Besides, it is also observed that some data were deviating from the general data trend. Those data sets were considered as inconsistent data, and they were also screened out. Based on these two criteria, a total of 115 data pairs were screened out for all soil types. Therefore, a total of 523 data pairs (out of 638) are selected after training for all soil types. In the case of D_{50}, 28 values are selected from all soil types. Table 4 shows all data statistics, and Table 5 shows trained data statistics for each soil type. The statistical analysis is performed using SPSS, a statistical computer program.

5. RESULTS AND DISCUSSIONS

Results are presented in terms of the correlations between CPT-q_c and SPT-N (N_{60}), CPT-f_s and SPT-N (N_{60}), q_c and N_{60} with mean grain size, D_{50}, q_c and N_{60} with soil behavior type index, (I_c), q_c and N_{60} with fines content, F_c(%) and q_c/N ratios for different types of soil.

5.1 Correlation between CPT-q_c and SPT-N (N_{60})

Correlation between q_c and N_{60} for all data and trained data are shown in Figs. 6 and 7. Figure 6 shows that except for silty sand, coefficient of determination (R^2) values for other soil types are above 0.7, indicating a strong correlation between the parameters. The non-linear (power) correlation is found higher than the linear correlation for silty sand. Table 6 compares the results for each soil type for all data using linear and non-linear correlation equations.

According to a recent study conducted in Bangladesh by Hore *et al.* (2018), based on reclaimed areas of Dhaka city, proposed correlations are

$$q_c = 1.5538 \times N_{60}^{0.31} \quad (\text{sand}; R^2 = 0.120) \tag{2}$$

$$q_c = 0.3373 \times N_{60}^{0.6284} \quad (\text{silt}; R^2 = 0.314) \tag{3}$$

$$q_c = 0.5637 \times N_{60}^{0.3447} \quad (\text{clay}; R^2 = 0.149) \tag{4}$$

It is to be noted that the correlation found in this study follows a similar pattern as developed by Hore *et al.* (2018). However, a relatively strong correlation is found for every soil type in the present study. In the previous study, only non-linear correlations were developed. However, linear and non-linear both correlations have been developed in this study. In the previous study, ten different locations were used to collect data, and in this study, one large reclaimed area is considered where every borehole is close to each other.

Jarushi *et al.* (2015) developed correlations between SPT-CPT for various soil in Florida. According to this study,

$$q_c = 0.291\, N + 2.43 \quad (\text{fine sand}; R^2 = 0.60) \tag{5}$$

$$q_c = 0.12\, N + 5 \quad (\text{silty sand}; R^2 = 0.35) \tag{6}$$

Table 4 Statistics of all data

Soil type	No. of data	Variables	Mean	Standard deviation	Max.	Min.	Range
Poorly graded sand (SP)	126	N_{60}	8.0	7.72	50	1	49
		q_c (MPa)	3.34	3.73	22.86	0.504	22.360
		f_s (kPa)	41.09	50.42	304	8	296
Clayey silt (ML)	427	N_{60}	5.60	5.69	50	1	49
		q_c (MPa)	1.01	1.41	15.60	0.390	15.215
		f_s (kPa)	15.98	44.50	552	3	549
Silty sand (SM)	32	N_{60}	34.91	19.06	50	1	49
		q_c (MPa)	8.01	6.79	22.86	0.483	22.381
		f_s (kPa)	181.03	176.53	635	4	631
Silty clay (CL)	53	N_{60}	6.25	4.43	17	1	16
		q_c (MPa)	1.04	0.51	2.71	0.504	2.205
		f_s (kPa)	18.91	20.27	81	5	76
All types oφ σoil	28	D_{50} (mm)	0.103	0.096	0.342	0.0083	0.342
	300	SBT index, I_c	2.92	0.52	3.86	1.57	2.29

Table 5 Data statistics for trained data

Soil type	No. of data	Variables	Mean	Standard deviation	Max.	Min.	Range
Poorly graded sand (SP)	105	N_{60}	7.53	7.71	50	1	49
		q_c (MPa)	3.49	4.05	22.864	0.504	22.360
Clayey silt (ML)	347	N_{60}	5.43	5.75	50	1	49
		q_c (MPa)	0.97	1.21	12.544	0.390	12.154
Silty sand (SM)	23	N_{60}	27.04	18.62	50	1	49
		q_c (MPa)	3.58	2.59	8.142	0.483	7.659
Silty clay (CL)	48	N_{60}	6.31	4.49	17	1	16
		q_c (MPa)	1.003	0.48	2.385	0.504	1.881

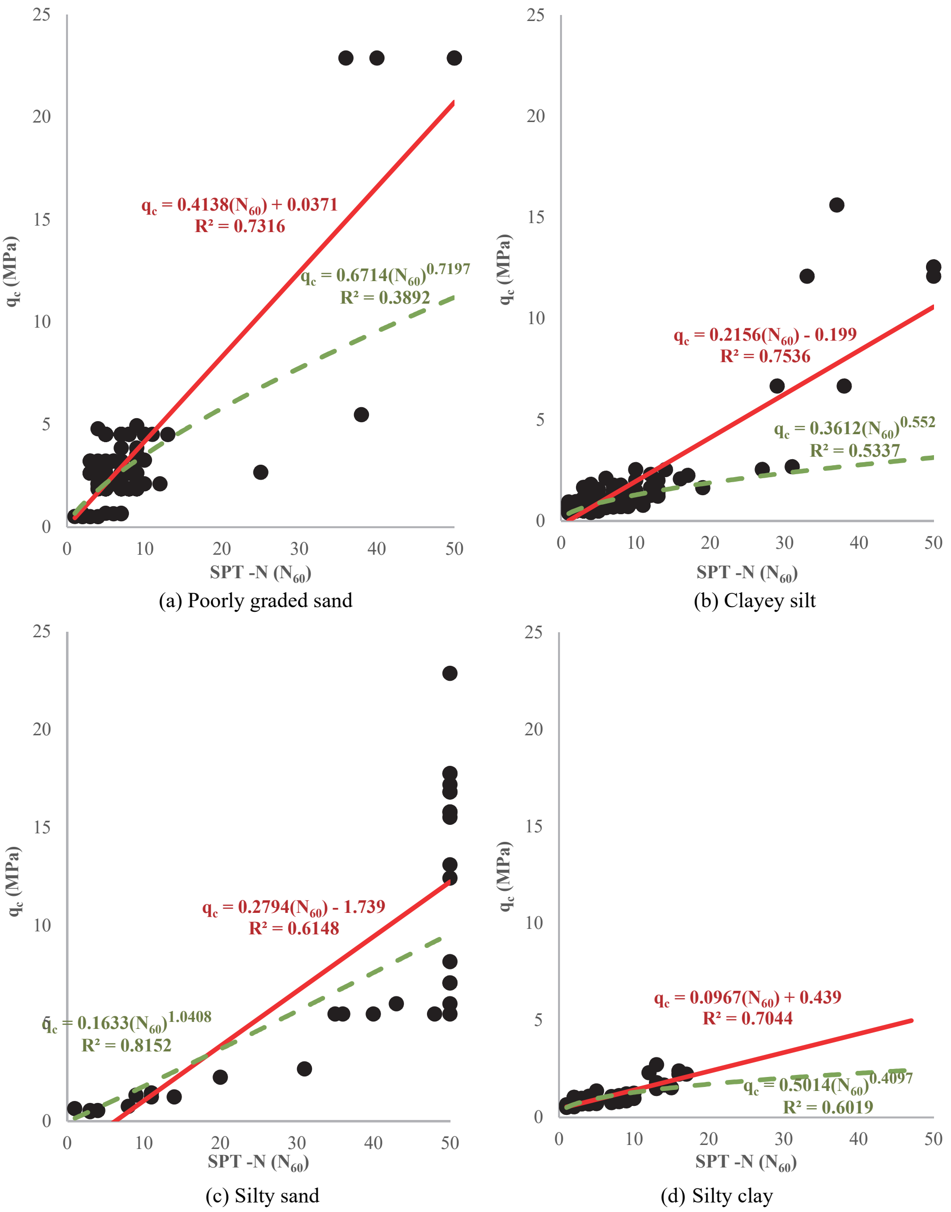


Fig. 6 Correlation between CPT-q_c and SPT-N_{60} for different soil types

The linear correlation observed in this research follows a similar pattern to that established by Jarushi *et al.* (2015). However, there are some dissimilarities in the correlations, which is understandable given the vast array of differences in soil characteristics worldwide. They evaluated the correlations between field tests and soil property using linear equations because they are straightforward and convenient. Following Jarushi *et al.* (2015), the preliminary attempt of this research is also to present the correlations using a linear relationship of the form $y = mx + b$. Non-linear correlations between the soil parameters are also explored.

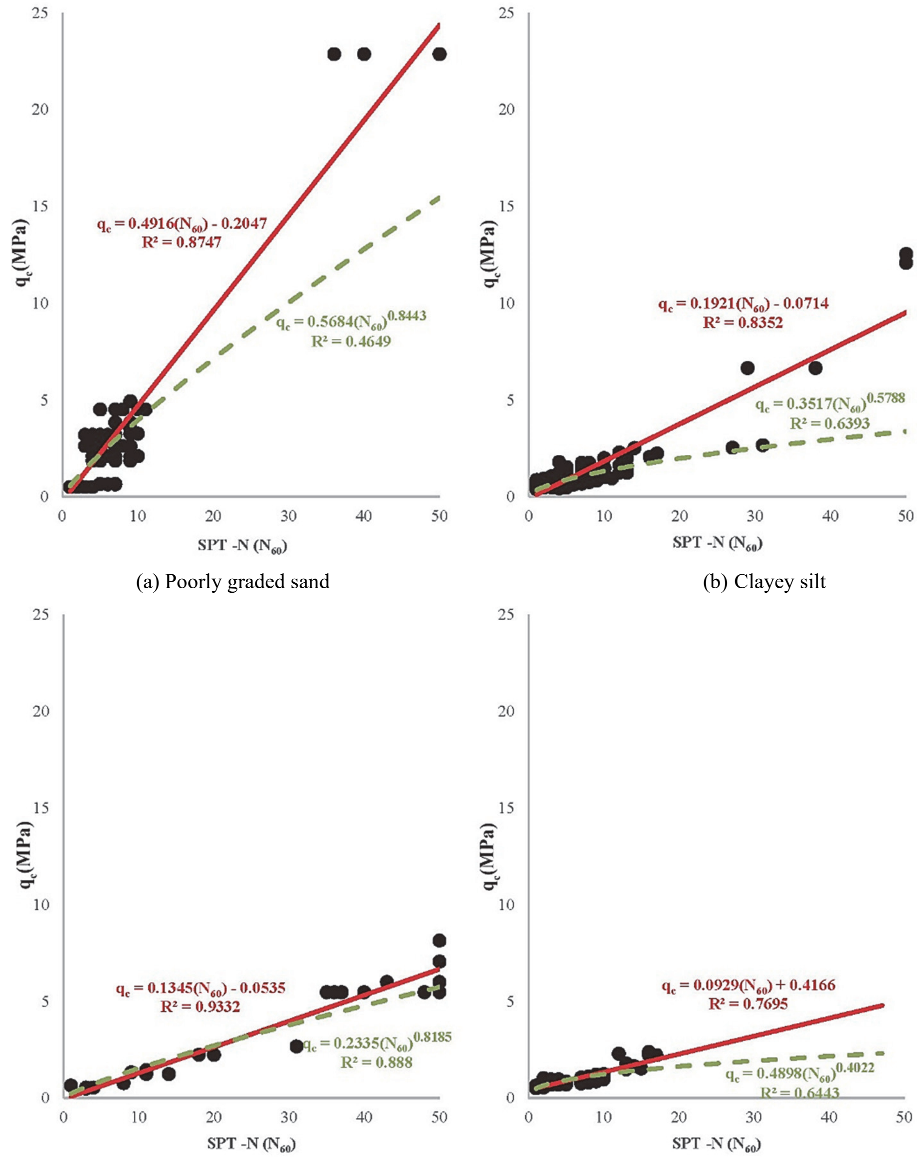
After data training, 70%-90% of all data are selected for each soil type. The correlations between q_c and N_{60} for trained data are shown in Fig. 7. The figure shows improved correlations between SPT-N_{60} and CPT-q_c in trained data for each soil type. Table 7 compares the results for each soil type for trained data using linear and non-linear correlation equations.

5.2 Correlation between CPT-f_s and SPT-N (N_{60})

Most research projects were focused on q_c and N relationships. The cone tip resistance (q_c) value is thought to be more reliable than sleeve friction (f_s). The CPT f_s significantly impacts the accuracy of identifying the soil behavior type, although generally recognized as less reliable than cone tip resistance.

According to Lunne and Andersen (2007), the inaccuracy of the sleeve friction measurement is related to several factors, including pore pressure effects on both ends of the sleeve, design tolerance between the cone and sleeve, sleeve surface roughness, and load cell design and calibration. This study developed correlations between CPT-f_s and SPT-N (N_{60}) for each soil type, as shown in Fig. 8. Correlations between f_s and N_{60} are developed using all data. Table 8 summarizes the correlation equations between f_s and N_{60} for each soil type.

Figure 8 shows that f_s and N_{60} show less correlation than q_c and N_{60} except for fine sand. For fine sand, a strong correlation is observed between f_s and N_{60}. For other soil types, a mild correlation is found between f_s and N_{60}. Jarushi *et al.* (2015) have developed correlations between SPT-CPT parameters for various soils in Florida.



(a) Poorly graded sand (b) Clayey silt

(c) Silty sand (d) Silty clay

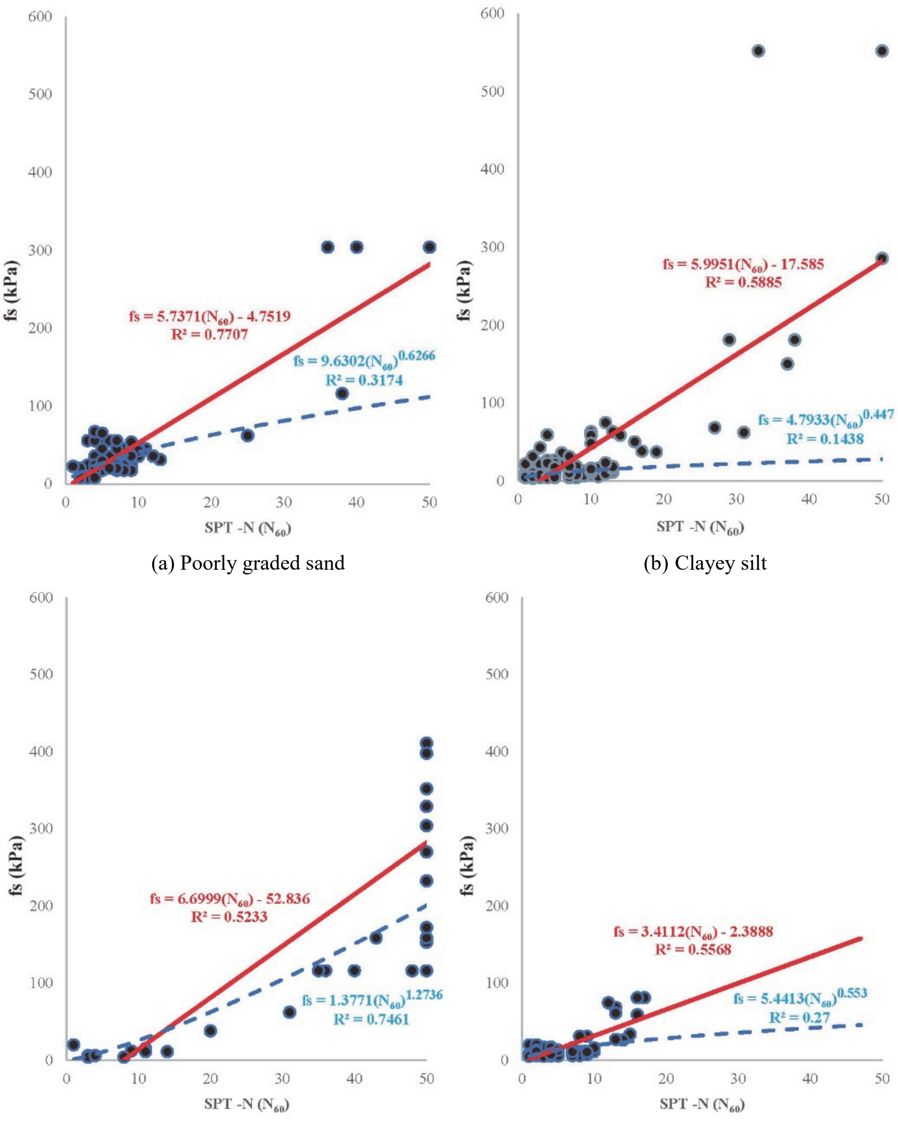
Fig. 7 Correlation between q_c and N_{60} based on training data

Table 6 Summary of q_c and N_{60} relationships for all types of soil

Soil description (USCS)	Correlation equations		Correlation coefficient, R^2	
	All data			
	Linear	Power	Linear	Power
Poorly graded sand (SP)	$q_c = 0.4138\ N_{60} + 0.0371$	$q_c = 0.6714\ (N_{60})^{0.7197}$	0.73	0.39
Clayey silt (ML)	$q_c = 0.2156\ N_{60} - 0.199$	$q_c = 0.3612\ (N_{60})^{0.552}$	0.75	0.53
Silty sand (SM)	$q_c = 0.2794\ N_{60} - 1.739$	$q_c = 0.1633\ (N_{60})^{1.0408}$	0.61	0.82
Silty clay (CL)	$q_c = 0.0967\ N_{60} + 0.439$	$q_c = 0.5014\ (N_{60})^{0.4097}$	0.70	0.60

Table 7 Summary of q_c and N_{60} relationships for all types of soil (trained data)

Soil description (USCS)	Correlation equations		Correlation coefficient, R^2	
	Trained data			
	Linear	Power	Linear	Power
Poorly graded sand (SP)	$q_c = 0.4916\ N_{60} - 0.2047$	$q_c = 0.5684\ (N_{60})^{0.8443}$	0.87	0.46
Clayey silt (ML)	$q_c = 0.1921\ N_{60} - 0.0714$	$q_c =0.3517\ (N_{60})^{0.5788}$	0.84	0.64
Silty sand (SM)	$q_c = 0.1345\ N_{60} - 0.0535$	$q_c = 0.2335\ (N_{60})^{0.8185}$	0.93	0.89
Silty clay (CL)	$q_c = 0.0929\ N_{60} + 0.4166$	$q_c = 0.4898\ (N_{60})^{0.4022}$	0.77	0.64



(a) Poorly graded sand (b) Clayey silt

(c) Silty sand (d) Silty clay

Fig. 8 Correlation between f_s and N_{60} for different soil types based on all data

Table 8 Summary of f_s and N_{60} relationships for all types of soil based on all data

Soil description (USCS)	Correlation equations	Correlation coefficient, R^2
Poorly graded sand (SP)	$f_s = 5.7317\ N_{60} - 4.7519$	0.77
Clayey silt (ML)	$f_s = 5.9951\ N_{60} - 17.585$	0.59
Silty sand (SM)	$f_s = 6.6999\ N_{60} - 52.836$	0.52
Silty clay (CL)	$f_s = 3.4112\ N_{60} - 2.3888$	0.56

According to this paper,

$$f_s = 2.4\ N + 33 \quad \text{(Poorly graded sand; } R^2 = 0.33) \tag{6}$$

$$f_s = 0.5\ N + 92 \quad \text{(Silty sand; } R^2 = 0.05) \tag{7}$$

It has been noticed that the correlation found in this study follows a similar trend as developed by Jarushi *et al.* (2015).

5.3 Correlation between q_c and N_{60} with mean grain size, D_{50}

Numerous investigations have been conducted to determine the relationship between SPT-N and CPT-q_c. There is now a large variety of q_c/N ratios, which causes a lot of misperception. The published q_c/N ratio changes can be partially explained by developing a correlation between q_c/N ratios and mean grain size, D_{50}. According to Robertson *et al.* (1983), the q_c/N ratio increases with grain size. A correlation between $(q_c/p_a)/N_{60}$ *vs* D_{50} has been proposed by Robertson, where p_a = atmospheric pressure (100 kPa). The mean grain size (D_{50}) for current research is found between 0.008 to 0.342 mm. The data used in this study matches the trend suggested by Robertson *et al.* (1983), as depicted in Fig. 9.

For granular soil, several correlations have been proposed to relate q_c and N_{60} against the mean grain size (D_{50} in mm). These correlations are in the form of $(q_c / P_a) / N_{60} = c\ (D_{50})^a$; where c and a values are variables. It is found that a correlation between q_c/N ratio and D_{50}, developed in this study, are practically similar to the developed correlation by Robertson *et al.* (1983). According to the current research,

$$\frac{(q_c / P_a)}{N_{60}} = 5.3084\ (D_{50})^{0.4977} \tag{8}$$

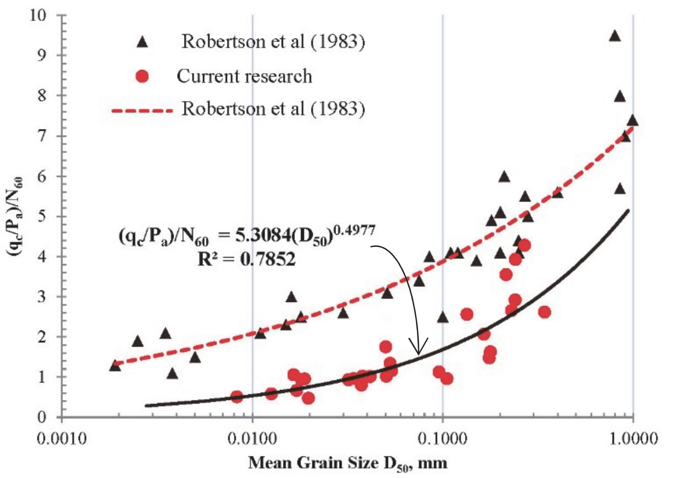


Fig. 9 Correlation between the mean grain size (D_{50}) and the ratio of the CPT tip resistance (q_c) and the SPT-N value

According to Robertson *et al.* (1983),

$$\frac{(q_c / P_a)}{N_{60}} = 5.75\,(D_{50})^{0.31} \tag{9}$$

Minor variation may occur due to the fact that a wide range of D_{50} from 0.0083 mm to 0.3417 mm was observed. c and a values determined in this study are compared with other previous studies as presented in Table 9 (Das and Sivakugan 2018). It's observed that the c and a values developed in this study are close to previous authors.

Table 9 Comparison of c and a

Reference	Values in literature			Current study	
		c	a	c	a
Burland *et al.* (1985)	Upper Limit	15.49	0.33	5.30 (R^2 = 0.78)	0.49 (R^2 = 0.78)
	Lower Limit	4.9	0.32		
Robertson *et al.* (1983)	Upper Limit	10	0.26		
	Lower Limit	5.75	0.31		
Kulhawy and Mayne (1990)		5.44	0.26		
Anagnostopoulos *et al.* (2003)		7.64	0.26		

5.4 Correlation between q_c and N_{60} with soil behavior type index, I_c

The correlation between $(q_c/P_a)/N_{60}$ and soil behavior type index, I_c, is displayed in Fig. 10. The figure shows that $(q_c/p_a)/N_{60}$ value decreases as I_c increases. It is also evident that the correlation between $(q_c/P_a)/N_{60}$ and I_c is almost identical to prior researchers' reported relationships. According to Arifuzzaman and Anisuzzaman (2022),

$$(q_c/P_a)/N_{60} = 7.9\,(1 - I_c/4.8); \qquad R^2 = 0.2091 \tag{10}$$

According to Lunne *et al.* (1997),

$$(q_c/P_a)/N_{60} = 8.5\,(1 - I_c/4.6) \tag{11}$$

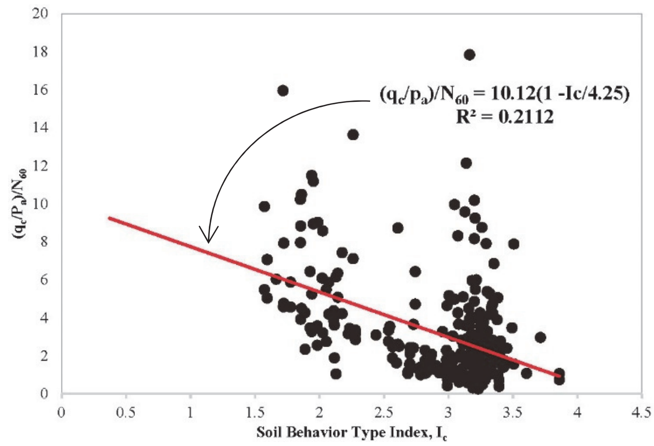


Fig. 10 Correlation between the soil behavior type index, I_c, and the ratio of the CPT tip resistance to the SPT-N value

According to Hore *et al.* (2018),

$$(q_c/P_a)/N_{60} = -3.095 \times I_c + 9.898; \qquad R^2 = 0.3042 \tag{12}$$

According to the current study,

$$(q_c/P_a)/N_{60} = 10.12\,(1 - I_c/4.25); \qquad R^2 = 0.2112 \tag{13}$$

The correlation coefficient (R^2) of $(q_c/p_a)/N_{60}$ with the soil behavior index (I_c) is found only 0.2112, indicating a less significant linear correlation between them as observed in the previous studies.

5.5 Correlation Between q_c and N_{60} with Fines Content, F_c(%)

The correlation between $(q_c/P_a)/N_{60}$ and fines content, F_c, is shown in Fig. 11. In this study, both coarse-grained and fine-grained soils are found. It's found that fines content value varies from 2% to 46% for coarse-grained soil, and for fine-grained soil, fines content value ranges from 55% to 99%. It's also observed from Fig. 11 that the correlation between $(q_c/P_a)/N_{60}$ and fines content, F_c, is almost similar to the previous researchers.

According to Kulhawy and Mayne (1990),

$$(q_c/p_a)/N = 4.25 - 0.024 F_c\,(\%) \tag{14}$$

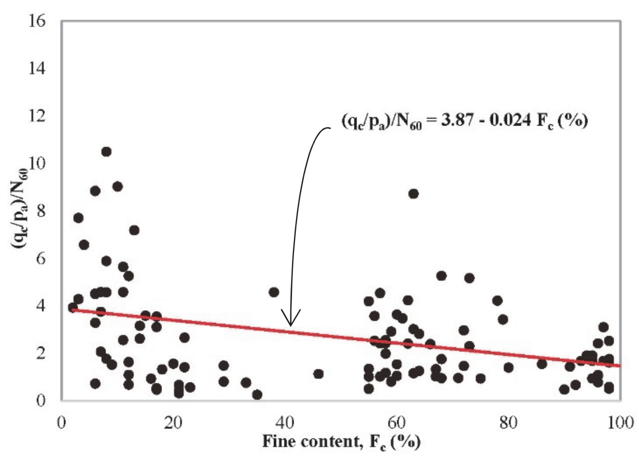


Fig. 11 Correlation between the fines content, F_c, and the ratio of the CPT tip resistance to the SPT-N value

whereas, the current study proposes the correlation as,

$$(q_c/p_a)/N_{60} = 3.87 - 0.024F_c\,(\%) \quad (15)$$

A minor variation is observed due to the variation in fines content. The correlation coefficient (R^2) for $(q_c/P_a)/N_{60}$ and F_c is found 0.11, which indicates a nearly insignificant correlation between the data through the downward trend is indentified.

5.6 Determination of q_c/N ratios for each type of soil and comparison with the literature

Several researchers have proposed k values ($k = q_c/N$). Some authors have used field SPT-N value for developing the q_c/N ratio, and some have used corrected SPT values. As a result, there are numerous varieties. In this study, k values are determined in two methods. k value ranges from 0.1 to 1.0.

5.6.1 Arithmetic Average Method

Table 10 shows the results of calculating the k-value using the average arithmetic approach. It can be seen from Table 10 that there is a minor difference in k-values for all and trained data. The maximum difference is observed in k-values for silty sand. Table 11 shows the comparison between k-values from this study and previous studies.

5.6.2 Statistical Method

Table 12 compares the k-value (statistical method) between current research and previous studies. In Tables 11 and 12, it is observed that k-values from arithmetic and statistical approaches are close to previous studies. For silty clay, the k-value from the statistical approach is much smaller than in previous studies, but the arithmetic approach is more comparable to previous studies. In this study, k-values found from the arithmetic approach are much closer to earlier studies than the statistical approach.

There is a minor difference between the correlations from existing and present research correlations, which could be caused by one or more of the following Jarushi *et al.* (2015):

1. Each of the suggested k-values (q_c/N) given in the literature was derived by conducting SPT-N, CPT q_c and f_s, utilizing specified in-field procedures. As an example, for field procedures, some studies employed the corrected N. In contrast, others used the uncorrected N. CPT data, which were achieved using various cone kinds and designs, which could have resulted in significantly different values than other cone types. The current research uses a donut hammer with 60% hammer efficiency.
2. The variety of cone types and designs significantly impacted the results in the literature. For example, electrical cones in sands provide less tip resistance than mechanical cones, while the opposite is true for clays and silts Kulhawy and Mayne (1990).
3. The variance of correlation values was thought to be influenced by regional subsurface features and characteristics.
4. The distance between SPT and CPT used to build the correlation could considerably impact the correlation's quality.

Table 10 Determination of q_c/N ratios using the average arithmetic method

Soil type (USCS)	No. of data pairs, N_f		Summation of k_1 ($k_1 = q_c/N$)		$k = k_1/(N_f)$		k-value	
	All	Trained	All	Trained	All	Trained	All	Trained
Poorly graded sand (SP)	126	105	57.28	50.90	57.28/126	50.90/105	0.45	0.48
Clayey silt (ML)	427	347	88.20	72.17	88.20/427	72.17/347	0.21	0.21
Silty sand (SM)	32	23	6.89	3.54	6.89/32	3.54/23	0.22	0.15
Silty clay (CL)	53	49	12.07	10.57	13.12/55	10.57/49	0.23	0.22

Table 11 Comparison of q_c/N ratios (average arithmetic approach) between current research and previous works

Soil type (USCS)	Current study		De Alencar Velloso (1959)	Schmertmann (1970)	Akca (2003)	Chin *et al.* (1988)	Danziger *et al.* (1998)	Chang (1988)
	All	Trained						
Poorly graded sand (SP)	0.45	0.48	0.6	0.3-0.6	0.77	0.5	0.57	–
Clayey silt (ML)	0.21	0.21	–	–	–	–	0.31	0.18
Silty sand (SM)	0.22	0.15	0.2	0.3-0.4	0.70	0.4-0.5	0.5-0.64	–
Silty clay (CL)	0.23	0.22	0.35	–	0.3	–	–	–

Table 12 Comparison of q_c/N ratios (statistical approach) between current research and previous works

Soil type (USCS)	Current study		De Alencar Velloso (1959)	Schmertmann (1970)	Akca (2003)	Chin *et al.* (1988)	Danziger *et al.* (1998)	Chang (1988)
	All	Trained						
Poorly graded sand (SP)	0.41	0.49	0.6	0.3-0.6	0.77	0.5	0.57	–
Clayey silt (ML)	0.22	0.19	–	–	–	–	0.31	0.18
Silty sand (SM)	0.28	0.13	0.2	0.3-0.4	0.70	0.4-0.5	0.5-0.64	–
Silty clay (CL)	0.10	0.10	0.35	–	0.3	–	–	–

6. CONCLUSIONS

This study investigates the relationship between SPT and CPT for reclaimed soil by river dredging of the Jolshiri residential area located at the extended Dhaka. Mainly, four types of soil have been identified in this study: fine sand (SP), silty sand (SM), silty clay (CL), and clayey silt (ML). A total of six out of fifteen residential plots are considered for both SPT and CPT investigation, whereas only SPT tests were conducted for the remaining nine plots for various numbers of boreholes. After filtration, a database of 523 pairs of SPT-CPT data points for different soil properties is created, and a good number of SPT-CPT correlation approaches have been developed. The key findings of this study are discussed below.

1. The dredged river sediment primarily consists of fine sand, clayey silt, or silty sand. The SPT N_{60} of the fine sands varies in a wide range of 1 to 50. The clayey silt and silty sand exhibit higher skin friction values, whereas silty clay exhibits the lowest values of both q_c and skin friction. The mean value of D_{50} is 0.103, with a standard deviation of 0.096. The basic soil properties of the river sediments present the typical characteristics of the alluvial deposits in the rivers of the South Asian deltaic region.
2. The relationship between both q_c and f_s with SPT-N_{60} is found linear. A strong correlation has been observed between q_c and N_{60} except for silty sand; R^2 values range from 0.61-0.75. A moderate correlation has been observed between f_s and N_{60} except for fine sand where R^2 values range from 0.52-0.77.
3. A weaker correlation has been observed in the case of a nonlinear relationship between q_c and N_{60}, except in silty sand, where R^2 values are found in a range of 0.39-0.82
4. The data training, data filtration, and the removal of out layers of the data improved the correlations that have been found between q_c and N_{60} for each soil type; R^2 values are found in a range from 0.77-0.93.
5. The relationship between the q_c/N ratio and mean grain size (D_{50}) is also found satisfactory, which follows a similar trend as proposed by Robertson. The general equation is also proposed between q_c/p_a and D_{50}, where the values of the variables c and a are found 5.31 and 0.50, respectively.
6. The relationship between the q_c/N ratio and soil behavior type index (I_c) is found less significant, which follows a similar trend proposed by previous researchers. Expectedly, a minor difference between test and training data has been observed in q_c/N ratios.
7. The k as q_c/N values, developed from the average arithmetic method, are found much closer to the k values developed by previous researchers for each soil type. However, lower q_c/N ratios have been found for silty sand and silty clay in the current research than the values available in the existing literature.

Though SPT-CPT correlations are available in the literature for different soil types, their global applicability is constrained by the intrinsic diversity of the test methodologies and the kind and state of the soils studied. The study on reclaimed soil particularly when the soil source from river sediments is very limited. Therefore, the SPT and CPT correlations developed from the actual test data manifest a trustworthy correlation in the reclaimed soils of the Jolshiri area of Dhaka city or similar other reclaimed soils. Geotechnical engineers may use the regression equations developed in this study to find CPT parameters from SPT data for similar reclaimed sites.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the test facilities and technical support provided by the Terzaghi Lab of the Department of Civil Engineering of Military Institute of Science and Technology (MIST).

FUNDING

Military Institute of Science and Technology (MIST) provided the funds for conducting SPT and CPT tests of this study.

DATA AVAILABILITY

The data used in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST STATEMENT

The authors declares that there is no conflict of interest.

REFERENCES

Akca, N. (2003). “Correlation of SPT-CPT data from the United Arab Emirates.” *Engineering Geology*, **67**(3-4), 219-231. https://doi.org/10.1016/S0013-7952(02)00181-3

Alam, M., Aaqib, M., Sadiq, S., Mandokhail, S.J., Adeel, M.B., Maqsood-Ur-Rehman, and Kakar, N.A. (2018). “Empirical SPT-CPT correlation for soils from Lahore, Pakistan.” *IOP Conference Series: Materials Science and Engineering*, **414**(1). https://doi.org/10.1088/1757-899X/414/1/012015

Andrus, R. and Youd, T.L. (1989). *Penetration Tests in Liquefiable Gravels*. Congrès International de Mécanique Des Sols et Des Travaux de Fondations. **12**, 679-682.

Arifuzzaman, and Anisuzzaman, M. (2022). “An initiative to correlate the SPT and CPT data for an alluvial deposit of Dhaka city.” *International Journal of Geo-Engineering*, **13**(5), 1-13. https://doi.org/10.1186/s40703-021-00170-3

Baez, J.I., Martin, G.R., and Youd, T.L. (2000). “Comparison of SPT-CPT liquefaction evaluations and CPT interpretations.” *Innovations and Applications in Geotechnical Site Characterization*, 17-32. https://doi.org/10.1061/40505(285)2

Burland, J.B., Burbidge, M.C., Wilson, E.J., and Terzaghi. (1985). “Settlement of foundations on sand and gravel.” *Proceedings of the Institution of Civil Engineers*, **78**(6), 1325-1381. https://doi.org/10.1680/iicep.1985.1058

Chang, M.F. (1988). “In-situ testing of residual soils in Singapore.” *International Conference on Geomechanics in Tropical Soils*. Singapore, **2**, 97-108.

Chin, C.-T., Duann, S.-W., and Kao, T.-C. (1988). “SPT-CPT correlations for granular soils.” *Proceedings of International Symposium on Penetration Testing, ISOPT-1*, Orlando, USA, Balkema, Rotterdam, **1**(2), 335-339. https://doi.org/10.1016/0148-9062(90)95081-B

Clayton, C.R.I. (1995). *The Standard Penetration Test (SPT):*

Methods and Use. Construction Industry Research and Information Association.

Danziger, B.R. and Velloso, D.A. (1995). "Correlations between the CPT and the SPT for some Brazilian soils." *Proceedings of the International Symposium on Cone Penetration Testing CPT*, Swedish Geotechnical Society, Linkoping, Sweden, **2**, 155-160.

Danziger, F.A.B., Politano, C.F., and Danziger, B.R. (1998). "CPT-SPT correlations for some Brazilian residual soils." *Proceedings of the First International Conference on Site Characterization - ISC'98*, *Geotechnical Site Characterization*. Volume 2, Atlanta, Georgia, USA, 907-912.

Das, B.M. and Sivakugan, N. (2018). *Principles of Foundation Engineering*. 9th Ed., Cengage Learning.

De Alencar Velloso, D. (1959). O ensaio de diepsondeering ea determinacao da capacidade de cargo do solo. Rodovia, 29.

Duan, W., Cai, G., Liu, S., Du, Y., Zhu, L., and Puppala, A.J. (2018). "SPT-CPTU correlations and liquefaction evaluation for the island and tunnel project of the Hong Kong-Zhuhai-Macao Bridge." *International Journal of Civil Engineering*, **16**(10), 1423-1434.
https://doi.org/10.1007/s40999-017-0281-9

Feda Aral, I. and Gunes, E. (2017). "Correlation of standard and cone penetration tests: Case study from Tekirdag (Turkey)." *IOP Conference Series: Materials Science and Engineering*, **245**(3). https://doi.org/10.1088/1757-899X/245/3/032028

Hayati, H. and Andrus, R.D. (2009). "Updated liquefaction resistance correction factors for aged sands." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **135**(11), 1683-1692.
https://doi.org/10.1061/(ASCE)GT.1943-5606.0000118

Hore, R., Al-Mamun, S., and Ansary, M.A. (2018). "SPT-CPT correlation for reclaimed areas of Dhaka." *Journal of Engineering Science*, **9**(1), 35-46.

Idriss, I.M. and Boulanger, R.W. (2006). "Semi-empirical procedures for evaluating liquefaction potential during earthquakes." *Soil Dynamics and Earthquake Engineering*, **26**(2–4), 115-130. https://doi.org/10.1016/j.soildyn.2004.11.023

Ismael, N.F. and Jeragh, A.M. (1986). "Static cone tests and settlement of calcareous desert sands." *Canadian Geotechnical Journal*, **23**(3), 297-303. https://doi.org/10.1139/t86-043

Jamiolkowski, M., Baldi, G., Belloti, R., Ghionna, V., and Pasqualini, E. (1985). "Penetration resistance and liquefaction of sands." *Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, **4**, 1891-1896.

Jarushi, F., S. Alkaabim, and Paul Cosentino. (2015). "A new correlation between SPT and CPT for various soils." *International Journal of Environmental*, *Ecological, Geological and Geophysical Engineering*, **9**(2), 101-107.

Jefferies, M.G. and Davies, M.P. (1993). "Use of CPTU to estimate equivalent SPT N60." *Geotechnical Testing Journal*, **16**(4), 458-468. https://doi.org/10.1520/GTJ10286J

Kulhawy, F.H. and Mayne, P.W. (1990). *Manual on Estimating Soil Properties for Foundation Design*. Electric Power Research Institute, Palo Alto, CA (USA); Cornell Univ., Ithaca, NY(USA) Geotechnical Engineering Group.

Lunne, T. and Andersen, K.H. (2007). "Soft clay shear strength parameters for deepwater geotechnical design." *Offshore Site Investigation and Geotechnics: Confronting New Challenges and Sharing Knowledge*, London, UK, 151-176.

Lunne, T., Robertson, P.K., and Powell, J.J.M. (1997). *Cone Penetration Testing in Geotechnical Practice*. Blackie Academic. Chapman. Hall Publishers, UK.
https://doi.org/10.1007/s11204-010-9072-x

Muromachi, T. and Kobayashi, S. (1982). "Comparative study of static and dynamic penetration tests currently in use in Japan." *Proceedings of the 2nd European Symposium. on Penetration Testing*, Amsterdam, **1**, 297-302.
https://doi.org/10.1201/9780203743959

Robertson, P.K. (1990). "Soil classification using the cone penetration test." *Canadian Geotechnical Journal*, **27**(1), 151-158.
https://doi.org/10.1139/t90-014

Robertson, P.K. (2010). "Soil behaviour type from the CPT: An update." *2nd International Symposium on Cone Penetration Testing*, **2**(56), 1-8.

Robertson, P.K. (2012). "Interpretation of in-situ tests—Some insights." *Mitchell Lecture-ISC*, **4**, 1-22.

Robertson, P.K., Campanella, R.G., and Wightman, A. (1983). "SPT-CPT correlations." *Journal of Geotechnical Engineering*, ASCE, **109**(11), 1449-1459.
https://doi.org/10.1061/(ASCE)0733-9410(1983)109:11(1449

Schmertmann, J.H. (1970). "Static cone to compute static settlement over sand." *Journal of the Soil Mechanics and Foundations Division*, ASCE, **96**(3), 1011-1043.
https://doi.org/10.1061/JSFEAQ.0001418

Seed, H.B. and De Alba, P. (1986). "Use of SPT and CPT tests for evaluating the liquefaction resistance of sands." *Proceedings of In Situ Test in Geotechnical Engineering*, ASCE, 281-302.

Shahien, M.M. and Albatal, A.H. (2014). "SPT-CPT correlations for Nile Delta silty sand deposits in Egypt." *3rd International Symposium on Cone Penetration Testin*g, Las Vegas, Nevada, USA, 699-708.

Souza, J.M.S., Danziger, B.R., and Danziger, F.A.B. (2012). "The influence of the relative density of sands in SPT and CPT correlations." *Soils and Rocks*, **35**(1), 99-113.
https://doi.org/10.28927/SR.351099

Stark, T.D. and Olson, S.M. (1995). "Liquefaction resistance using CPT and field case histories." *Journal of Geotechnical Engineering*, ASCE, **121**(12), 856-869.
https://doi.org/10.1061/(ASCE)0733-9410(1995)121:12(856)

Suzuki, Y., Sanematsu, T., and Tokimatsu, K. (1998). "Correlation between SPT and seismic CPT." *Geotechnical Site Characterization*, 1375-1380.

Tarawneh, B. (2014). "Correlation of standard and cone penetration tests for sandy and silty sand to sandy silt soil." *Electronic Journal of Geotechnical Engineering*, **19**, 6717-6727.
https://doi.org/10.13140/2.1.3552.5124

Yusof, N.Q.A.M. and Zabidi, H. (2018). "Reliability of using standard penetration test (SPT) in predicting properties of soil." *Journal of Physics: Conference Series*, **1082**(1), 1-6.
https://doi.org/10.1088/1742-6596/1082/1/012094