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EFFECT OF STANDARD PENETRATION TEST CORRECTIONS ON THE ESTIMATION OF UNDRAINED SHEAR STRENGTH

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Abstract. This paper evaluated the influence of Standard Penetration Test (SPT) correction factors, namely the hammer energy efficiency, borehole diameter, drill rod length, and sampling method, on the correlations between SPT resistance (SPT-N) and undrained shear strength (S_u). Comparisons were made between new equations (with and without SPT corrections), which were derived from soil data collected from Penang Island, Malaysia. The coefficient of determination, Absolute Average Relative Error, Standard Deviation, and Analysis of Variance (ANOVA) were employed as the basis for the assessments. Finally, a comprehensive analysis was carried out to evaluate the relationship between uncorrected ratio (S_u/N) or corrected ratio (S_u/N_{60}) and Plasticity Index (PI)/Liquidity Index (LI). Based on the results, all correction factors recorded a significant impact on the estimated S_u, as the ANOVA calculation suggested that the borehole diameter correction was the most statistically significant. Furthermore, the S_u/N and S_u/N_{60} exhibited increasing trends with increased PI and LI, which may be attributed to the soil's state and behaviour. Additionally, cubic regression is the best-fit equation to correlate the parameters. In summary, this study provided new insights into the influence of correction factors, which can be used to improve the accuracy of the empirical correlations and engineering designs.

Keywords: fine-grained soils, standard penetration test correction, standard penetration test correlation, standard penetration test resistance, undrained shear strength.

Introduction

The varying characteristics of soil types pose a challenge during the design and construction of infrastructures. For the design of embankment structures on cohesive soils, it is important to primarily determine the soil's undrained (S_u) since cohesive soil is loaded rapidly without sufficient time for the pore pressure to dissipate (Sivrikaya, 2009; Sivrikaya & Toğrol, 2006). Hence, in-situ soil testing is particularly crucial to acquiring sufficient data on soil engineering properties (Lv & Zhou, 2018). In-situ soil testing also provides readily reliable data and results that facilitate engineers to evaluate and decide the choice of foundation type based on the subsurface features of the soil.

One of the most common and popular in-situ tests is the Standard Penetration Test (SPT) (Singh et al., 2017; Yusof & Zabidi, 2018). This dynamic penetration test is designed to provide the SPT blow count (SPT-N) to estimate soil stiffness. Apart from that, the SPT-N value has been extensively used in empirical geotechnical correlations to estimate soil properties, such as unit weight, relative density, and friction angle (Sivrikaya & Toğrol, 2006). In fact, SPT-N can be used for the in-situ S_u estimation of fine-grained soils (Nassaji & Kalantari, 2011; Sivrikaya, 2009; Sivrikaya & Toğrol, 2006; Kayabaşı, 2020; Narepalem & Godavarti, 2019).

The SPT-N is influenced by several factors, such as the SPT hammer energy efficiency (E_r), borehole diameter, and sampler liner (Anbazhagan et al., 2022). In view of this, several corrections have been made to minimise the influence of variables on field-measured SPT-N value (El-Sherbiny & Salem, 2013; Sivrikaya & Toğrol, 2006; Skempton, 1986). The corrected SPT-N value (N_{60}) corrections for field procedures and apparatus) can be computed using Eqn (1):

$$N_{60} = C_B C_E C_R C_S N, \quad (1)$$

where C_B represents the borehole diameter correction factor, C_E denotes the SPT hammer E_r correction factor, C_R refers to the drill rod length correction factor, and C_S is

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the sampling method correction factor. Table 1 summarises several correction factors for SPT-N, as proposed by Skempton (1986). The SPT hammer E_r represents a certain amount of the total energy that is transferred from the drop hammer to the drill rod and sampler. The formula of C_E for normalising to a standard E_r or E_{rb} is shown in Table 1. Meanwhile, Table 2 summarises the rod E_r and correction factors (for normalising to 60% E_{rb}) for different types of SPT hammer and release in different countries, as provided by Skempton (1986). Past studies have stated that an E_{rb} of 60% is commonly used to correct the SPT-N value (El-Sherbiny & Salem, 2013; Kovacs & Salomone, 1982; Kovacs et al., 1984; Seed et al., 1985; Skempton, 1986; Thusyanthan & Nawaz, 2017).

In addition, the empirical relations between the SPT-N value and S_u in terms of S_u/N ratios have been developed in previous studies (Terzaghi & Peck, 1967; Sivrikaya & Toğrol, 2006; Stroud, 1974). For instance, Stroud (1974) collected SPT data from numerous sites in the United Kingdom (UK) to determine the S_u of insensitive stiff clay via the Unconsolidated-Undrained (UU) Triaxial Compression test. Based on the obtained results, the author derived Eqn (2), which describes a simple relationship between the SPT-N value and S_u (Stroud, 1974):

$$S_u = f_1 N, \quad (2)$$

where the ratio of S_u to SPT-N value ranges from 4 to 7. The author observed the relatively small influences of drilling methods on the types of ground and SPT standardisation in the UK, which yielded results with a good correlation. The findings also pointed out that the value of S_u was not constant and was influenced by the Plasticity Index (PI) through an inverse proportional relationship.

In contrast to Stroud (1974), Sowers (1979) reported that the value of S_u increased with increasing PI for homogeneous clay and proposed the S_u value of 3.75 N, 7.5 N, and 12.5 N for low plastic clay, medium plastic clay, and highly plastic clay, respectively. Regardless, both Sowers (1979) and Stroud (1974) provided neither statistical information for their results nor the SPT corrections used in their research works. Décourt (1989), Hara et al. (1974), and Sanglerat (1972) also proposed that the SPT-N value correlated with S_u, as per Table 3. Despite that a large number of S_u/N ratios have been proposed in geotechnical literature, the correlation results may be confusing and debatable since the inadequate information on the SPT data, correction, or type of laboratory test used in these studies. The significance of the correlations is also speculated due to the insufficient statistical information within most of the literature.

Currently, the construction industry estimates the S_u using the field SPT-N value without corrections. There are no studies on the assessment of correction factors and their correlations with the S_u in Malaysia. Hence, this paper evaluated the effects of SPT corrections on the correlations between SPT-N value and S_u specifically in the northern region of Malaysia. The influence of each correction factor (borehole diameter, drill rod length, sampling method, and SPT hammer E_r) on the estimation of S_u was also examined via statistical approaches. Furthermore, this study explored the impact of the Plasticity Index (PI) and Liquidity Index (LI) on both the S_u/N and S_u/N_{60} ratios.

Table 1. Summary table of correction factors for SPT-N (Skempton, 1986)

Correction factor	Variable	Term	Correction
Energy efficiency	E_r varies depending on types of SPT hammer and release (See more details in Table 2)	C_E	$\frac{E_r}{E_{rb}}$
Borehole diameter	65–115 mm 150 mm 200 mm	C_B	1.0 1.05 1.15
Drill rod length	>10 m 6–10 m 4–6 m 3–4 m	C_R	1 0.95 0.85 0.75
Sampling method	Standard sampler Sampler without liner	C_S	1 1.2

Table 2. Rod E_r and correction factors (for normalising to an E_{rb} of 60%) for different types of SPT hammer and release (Skempton, 1986)

Country	Hammer	Release	Energy ratio, E_r	Correction factor, C_E
Japan	Donut Donut	Tonbi 2 turns of rope	78 65	1.3 1.1
China	Pilcon Donut	Trip Manual	60 55	1.0 0.9
United States	Safety Donut	2 turns of rope 2 turns of rope	55 45	0.9 0.75
United Kingdom	Pilcon, Dando, old standard	Trip	60	1.0

Table 3. Existing correlations between SPT-N value and S_u

Reference	Explanation	Undrained shear strength, S_u (kPa)
Terzaghi and Peck (1967)	Fine-grained soil	6.25N
Sanglerat (1972)	Clay Silty clay	12.5N 10N
Hara et al. (1974)	Fine-grained soil	$29N_{60}^{0.72}$
Stroud (1974)	PI < 20 20 < PI < 30 PI > 30	6-7N 4-5N 4.2N
Sowers (1979)	Low plastic clay Medium plastic clay Highly plastic clay	3.75N 7.5N 12.5N
Nixon (1982)	Clay	12N
Décourt (1989)	Over consolidated & insensitive clay	12.5N $15\ N_{60}$
Sivrikaya and Toğrol (2002)	Highly plastic clay Low plastic clay Fine-grained soil	4.85N $6.82\ N_{60}$ 3.35N $4.93N_{60}$ 4.32N $6.18\ N_{60}$
Sivrikaya and Toğrol (2006)	Highly plastic clay Low plastic clay Clay Fine-grained soil	5.50N $7.80\ N_{60}$ 3.70N $5.35N_{60}$ 4.75N $6.9\ N_{60}$ 4.45N $6.35\ N_{60}$
Hettiarachchi and Brown (2009)	Clay	$4.1N_{60}$
Sivrikaya (2009)	UU test UU test UC test UC test	$3.33N - 0.75w_n + 0.20LL + 1.67PI$ $4.43N_{60} - 1.29w_n + 1.06LL + 1.02PI$ $2.41N - 0.82w_n + 0.14LL + 1.44PI$ $3.24N_{60} - 0.53w_n - 0.43LL + 2.14PI$
Nassaji and Kalantari (2011)	PI ≤ 20	$1.6N + 15.4$ $2.1N_{60} + 17.6$ $1.5N - 0.1w_n - 0.9LL + 2.4PI + 21.1$ $2N_{60} - 0.4w_n - 1.1LL + 2.4PI + 33.3$
Singh et al. (2017)	Fine-grained soil PI < 20 20 < PI < 30 PI > 30	4.94N 5.4N 5N 4.7N

The regression analysis was employed to determine the relationship between PI/LI and both S_u/N and S_u/N_{60} ratios. Based on the R^2 value, the best-fit regression was also established to assign a specific equation that defines these relationships.

1. Methodology

1.1. Data collection

The Soil Investigation (S.I.) reports, dated between December 2013 and August 2019, were collected from the City Council of Penang Island. The S.I. reports provided essential soil data, including the subsoil stratigraphy, soil type and condition, borehole location and depth, SPT-N value, groundwater level, which are crucial to studying the influence of the SPT corrections.

For the S.I. works, exploratory borings (borehole diameter of 75–125 mm) were carried out using a rotary drilling rig or wash boring machine. Rotary drilling is a boring system that consists of a rapidly rotating drill bit attached to the bottom of the drill rod to grind and loosen the soil. Typically, a drilling mud (mixture of bentonite and water) was used as a flushing medium to sink the exploratory borehole. During the drilling process, a steel casing was rimmed and installed into the borehole to stabilise the borehole walls. In the wash boring system, the exploratory borehole was advanced by the chopping and jetting action of a chopping bit fitted at the lower end of the casing. Similar to the rotary drilling system, the casing was installed to prevent the borehole collapse. Soils within the casing were loosened and flushed out using high-velocity circulating water and discharged into a tub for the settling process. The recovered soil samples (highly disturbed) were then inspected for preliminary results.

Based on the Geological Map of Pulau Pinang and Butterworth Area as published by the Director-General of the Department of Mineral and Geoscience (JMG) Malaysia, all boreholes were previously drilled (into the flat ground) on alluvium from the Quaternary Period, which was composed of unconsolidated marine clay, sand, and gravel deposits. The SPT and soil sampling (collected for laboratory testing) were then performed at the exploratory boreholes. The S.I. works, including the drilling process, SPT, soil sampling, and laboratory tests, were carried out in line with the British Standard (BS) 1377, which was developed by the British Standards Institution (BSI) in the UK, and the codes of practice have been used worldwide, especially in Commonwealth countries. The typical SPT consists of the SPT drop hammer, anvil (drive head), and drill rod. For the SPT, a 63.5 kg hammer with a drop height of 750–760 mm was used to drive a standard sampler (outer diameter of 50 mm) into the ground at a depth of 450 mm. Subsequently, the SPT-N was determined by combining the number of blows needed to drive the last two 150 mm intervals. Usually, the number of blows for the first 150 mm of soil penetration is omitted due to the borehole contamination and fall-in in the borehole. With advancements in SPT testing, valuable information relating to groundwater and soil samples was also collected with the SPT-N.

In this study, the laboratory tests included Atterberg limits, particle size distribution, and Unconsolidated-undrained (UU) triaxial test. In the Atterberg limits test, the Liquid Limit (LL), Plastic Limit (PL), and PI of the soils were determined to identify the nature, composition, and classification of fine-grained soils. The LL, which refers to the water content at which the soil starts to behave like a liquid, was determined using the Casagrande Method. On the contrary, the PL is the water content at which a soil starts to behave like a plastic and crumble when rolled into 3-mm diameter threads. The difference between LL and PL is referred to as the PI. Meanwhile, the particle size distribution analysis identifies the size and range of soil mass fraction. The sieve analysis (soil shaking through a stack of sieves with openings of known sizes) was employed for the soil grains larger than 0.075 mm in diameter, while the hydrometer test was used in place of the sieve analysis when the soil grains are finer than 0.075 mm in diameter. Furthermore, the UU test was conducted to determine the S_u of saturated cohesive soil. During the test, a cell pressure was applied to the soil sample without allowing pore pressure drainage, followed by increments of the vertical stress (until the failure of the soil sample).

According to the S.I. reports, the S_u values were obtained from the results of the UU test, and the corresponding SPT-N values were determined from the exploratory borehole logs. A total of 234 pairs of SPT-N and S_u were collected from previous S.I. works. Predominantly granular soil samples (SAND and GRAVEL) were omitted from this study to avoid interfering with the accuracy of the estimated S_u of fine-grained soils. Both capitalised name of the soil type (SAND and GRAVEL) was used to indicate the predominant or principal soil type (British Standards Institution, 2010). Furthermore, it was observed that some of the collected samples for the laboratory analysis were located above the groundwater tables. Additionally, the present study recorded a series of UU tests from several projects that provided an internal friction angle greater than zero (inconsistent S_u), indicating that the samples were possibly under non-saturated conditions. Thus, these soil samples were excluded from the data analyses.

After the data screening process, a total of 98 pairs of SPT-N and S_u from 84 boreholes located in Balik Pulau, Bayan Lepas, and Georgetown were employed for the subsequent data analyses. In this study, the soil data generally consisted of very soft to very stiff sandy/silty CLAY and very soft to very stiff sandy/clayey SILT. The soil samples were encountered at depths between 2 m below ground level (b.g.l) and 30 m b.g.l. The obtained SPT-N values do not exceed 24, and the laboratory S_u values varied from 8 kPa to 89 kPa. In addition, the LL of the soil data was between 35.67% and 138%, while the PL was in the range of 20% to 48%. The PI for the soil data was about 9.33% to 90%. Table 4 and Table A1 (see Appendix) summarise the main geotechnical properties of the studied soil data in Penang Island.

1.2. Data analysis

Two predictive equations were developed using a linear regression analysis method; one with a field SPT-N value and the other with a corrected SPT-N value obtained by multiplying the correction factors by the field SPT-N value. The linear regression analysis describes the linear association between a dependent variable and an inde-

Table 4. Main geotechnical properties of studied fine-grained soils of Penang Island, Malaysia

Properties	Minimum value	Maximum value	Average value	Standard deviation
SPT-N	0	24	4.35	5.97
Undrained shear strength, S_u (kPa)	8.1	89	26.9	17.58
Moisture content, MC (%)	15.5	108	55.62	25.09
Plastic limit, PL (%)	20	48	32.51	5.99
Liquid limit, LL (%)	35.67	138	75.68	26.23
Plasticity index, PI (%)	9.33	90	43.25	21.17

pendent variable (Bartholomew et al., 2008; Chatterjee & Hadi, 2012; dos Santos & Bicalho, 2017). The corrected SPT-N (N_{60}) was considered the independent variable in this study, while the S_u was considered the dependent variable. Furthermore, the coefficient of determination (R^2) was used to express the degree of approximation between the linear regression line to the actual data points (Chatterjee & Hadi, 2012). An R^2 value of 1 indicates that all data points fit the regression line, signifying a perfect correlation.

The correction factors that account for the influence of SPT hammer E_r, the presence or absence of a sampler liner, the length of the drill rod, and the borehole diameter were analysed in this study. As stated in the S.I. reports, a 63.5 kg automatic release trip hammer (free-fall/tonbi) was used during the SPT. Therefore, based on Table 2, the adopted E_r is 78%. For this study, an E_{rb} of 60% was adopted, which served as a basis in most SPT correlations studies (Hettiarachchi & Brown, 2009; Isik & Cabalar, 2018), while the C_E was set at 1.3 based on the SPT hammer E_r.

In line with previous S.I. works, the disturbed and undisturbed soil samples were extracted from the boreholes using a split spoon sampler and thin-walled sampling tube, respectively. The C_S was fixed at 1.2 since liners were practically excluded in both sampling methods used during the S.I. works. Due to varying borehole diameters from 65 mm to 115 mm, the C_B was set at 1.0, while the C_R was adjusted from 0.75 to 1.00 depending on the length of SPT drill rods (soil sampling depth) used during the S.I. works. The corrected SPT-N value (N_{60}) was computed using the Eqn (1).

The effect of SPT corrections was examined by comparing the newly developed correlations with and without SPT corrections on a scatter diagram. These were also compared to the previously published correlations and the actual soil data obtained in this study. The previously published correlations for S_u were Terzaghi and Peck (1967) equation, which is one of the oldest and most commonly used expressions relating the S_u to the SPT-N value, as well as the formulations by Stroud (1974), which are also frequently used in the construction industry to estimate S_u. Statistical evaluation of the correlations was performed based on the Absolute Average Relative Error (AARE) and Standard Deviation (SD) of the relative error, as follows:

$$AARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{X_l - X_p}{X_l}\right|; \quad (3)$$

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{X_l - X_p}{X_l}\right| - AARE\right)^2}, \quad (4)$$

where X_l is the laboratory S_u and X_p is the predicted S_u.

The performance of the two newly developed equations was then validated using the soil data outside Penang Island. A total of 34 pairs of SPT-N and S_u were acquired from previous S.I. works at various parts of Seberang Perai, Malaysia. The Geological Map of Pulau Pinang and Butterworth Area published by the JMG Malaysia indicates that the soil data were from within the alluvium deposits from the Quaternary Period. Based on the soil data review, the soil samples generally consisted of very soft to soft CLAY and very soft SILT and were located around 3 m to 18 m b.g.l. Table 5 presents the geotechnical properties of the soil data of Seberang Perai used for the validation process. Subsequently, the corrected SPT-N value was computed using Eqn (1). Based on previous S.I. works, the correction factor values were similar to the last case. The proposed equations were also compared and validated with fine-grained soil data as reported by Nassaji and Kalantari (2011).

In addition, the influences of each correction factor (C_B, C_S, C_R and C_E) on the estimation of S_u were also studied. The effect of one correction factor on the AARE and SD of previously published correlations was investigated while maintaining other correction factors. The one-way Analysis of Variance (ANOVA) was also adopted to evaluate the significance between the calculated S_u and all the correction factors. For this analysis, the p-value was used as the indicator to select the most significant factor that affects the calculation of shear strength. Moreover, the soil properties, such as the PI and LI, were investigated on both S_u/N and S_u/N_{60} ratios. This analysis adopted regression correlation analysis, similar to the previous investigation. The regression analysis was used to assist in formulating a specific equation to define the relationships. Prior to the analysis, this study applied the polynomial and linear regressions, while the R^2 was used as an indicator for each regression equation to select the best-fit equation for these relationships.

Table 5. Main geotechnical properties of fine-grained soils of Seberang Perai, Malaysia

Properties	Minimum value	Maximum value	Average value	Standard deviation
SPT-N	0	4	1	1.46
Undrained shear strength, S_u (kPa)	7	37.93	20.13	7.89
Moisture content, MC (%)	21.12	99.45	65.8	24.57
Plastic limit, PL (%)	28	46	34	4.21
Liquid limit, LL (%)	42	141	89.18	18.54
Plasticity index, PI (%)	13	95	55.18	15.1

2. Results and discussion

2.1. Influence of SPT corrections on the S_u estimation

Figure 1 presents the comparison of the regression equations with and without SPT corrections. As seen from this figure, there is a noticeable difference between the gradients or slopes of the regression lines. Besides, the y-intercept of the regression lines is almost the same. The overall trend of the soil data indicates that S_u increases with the increasing SPT-N regardless of the SPT corrections. However, the gradient and scattering of the soil data were different in these two cases (with and without SPT corrections).

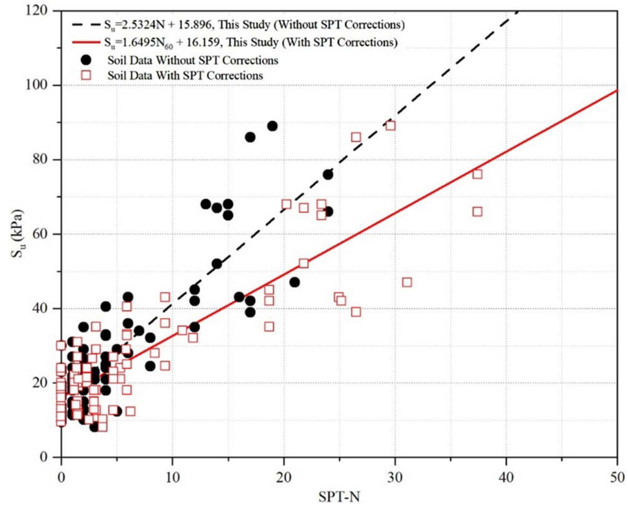

Figure 1. Comparison of correlations developed for fine-grained soils with and without SPT corrections

Using the linear regression analysis, the correlation between the SPT-N and S_u can be expressed as:

$$S_u = 2.5324N + 15.896\ (R^2{:}0.74), \tag{5}$$

whereas the correlation between the corrected SPT-N value (N_{60}) and S_u is:

$$S_u = 1.6495N_{60} + 16.159\ (R^2{:}0.755). \tag{6}$$

Both generated equations have an acceptable R^2 value, suggesting that both inputs were strongly correlated (Mahmoud, 2013; Yusof & Zabidi, 2018). Comparatively, Eqn (6) provided a higher correlation than Eqn (5) due to the influence of the correction factors. Thus, this observation proved that the correction factors are significant inputs for the calculation of S_u.

As shown in Figure 2, the predicted S_u from both newly developed equations were compared with those predicted in previous studies. Interestingly, the newly developed equations match closely with the soil data and demonstrated significant S_u differences between the soil data and the results of previous studies (Stroud, 1974; Terzaghi & Peck, 1967). Based on Figure 2, the newly developed equations fit better with the soil data compared to other correlations.

In terms of SPT without corrections, the predicted values from the correlations differed from the soil data by up to 85 kPa. The newly developed equation recorded an AARE and SD of 0.29 and 0.31, which were lower than those of Terzaghi and Peck (1967) and Stroud (1974) (AARE values are about 0.6 and SD values range from 0.32 to 0.41). In contrast, the predicted values from the correlations differed from the soil data in the case of SPT with corrections by up to 168 kPa. The study also observed minimal AARE and SD differences between the

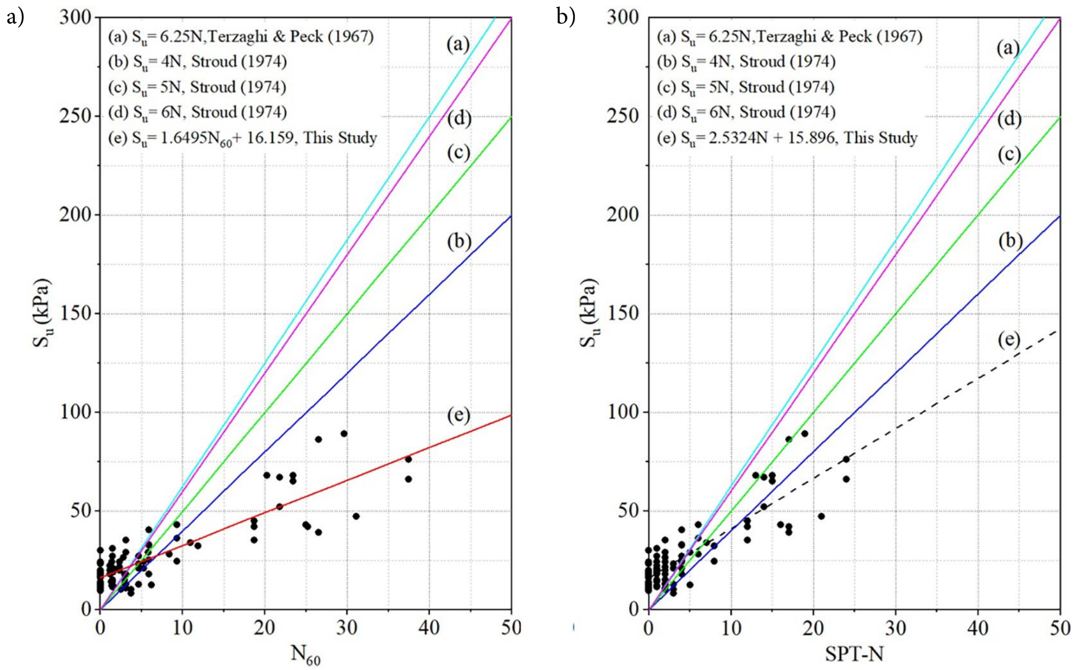

Figure 2. Scatter plot for fine-grained soils of Penang Island: (a) S_u versus N_{60} and (b) S_u versus SPT-N

newly developed equations. When the SPT corrections were applied to the previously published correlations, a considerable increase in AARE (11.67% to 46.15%) and SD (25% to 70.7%) was observed with some of the data points in Figure 2a tend to be more on the right side of the graph than the data points in Figure 2b. A summary of the AARE and SD of the correlations over both cases (SPT with and without corrections) is presented in Table 6.

In other words, predicting S_u from N_{60} may result in more deviations from the actual shear strength values. Thus, existing empirical correlations should be used with caution. Stroud (1974) did not consider SPT correction, while Terzaghi and Peck (1967) did not provide any information on the SPT data, test procedures, and corrections used. Therefore, their proposed equations had major issues, especially in the performance and precision. Overall, the variations in the R^2, gradient, AARE and SD indicate the substantial impact of SPT corrections on the estimation of S_u.

Moreover, the research findings highlighted the importance of SPT corrections to be considered in the empirical correlations. Different SPT equipment, procedures, and laboratory tests might influence the S_u/N ratios, which in turn would significantly underestimate or overestimate the shear strength parameters. For example, the overestimation of shear strength values could cause catastrophic failures of engineered structures, ground settlement or subsidence and embankment failures. Consequently, there is the possibility that the cost and safety of the design may be affected, which would substantially impact the construction industry and a delay in project completion. The chain of circumstances would eventually contribute to societal risks. Therefore, engineers should be aware of these crucial factors and acquire sufficient engineering input to initiate any engineering design before relying on correlations, which should be evaluated based on relevant and reliable test results and information. Sampling and laboratory testing are also vital to supplement conventional SPT results. Given that the S.I. works were conducted via the standard procedure, several factors, such as the drilling unevenness, can be neglected as their effects have been handled properly. Referring to the literature survey at Google Scholar and Elsevier databases with keywords "effect of drilling unevenness" and "SPT test", no outcome appeared to indicate that this factor was already ignored.

Figure 3 compares the predicted values (from the newly developed equations) and the soil data used for the validation process. Based on the results, the newly developed equations (with and without SPT corrections) matched closely with the soil data located in Seberang Perai, Malaysia and Tehran, Iran. The predicted values from the newly developed equations differed from the soil data by up to 45 kPa. Furthermore, the newly developed equations recorded an AARE of 0.35–0.42 and SD of 0.26–0.35, indicating good reliability.

2.2. Variation in borehole diameter correction factor

An attempt was made to further investigate the influence of C_B on the estimation of S_u of fine-grained soils. The scatter plot of both AARE and SD versus the C_B is given in Figure 4.

Table 6. AARE and SD of predicted S_u by each correlation for cases of SPT with and without corrections

Case	Equation	Absolute Average Relative Error, AARE	Standard Deviation, SD
SPT without corrections	S_u = 6.25N (Terzaghi & Peck, 1967)	0.65	0.41
	S_u = 4N (Stroud, 1974)	0.6	0.32
	S_u = 5N (Stroud, 1974)	0.6	0.35
	S_u = 6N (Stroud, 1974)	0.64	0.39
	S_u = 2.5324N + 15.896 (This Study)	0.29	0.31
SPT with corrections	S_u = 6.25N (Terzaghi & Peck, 1967)	0.90	0.66
	S_u = 4N (Stroud, 1974)	0.66	0.38
	S_u = 5N (Stroud, 1974)	0.75	0.48
	S_u = 6N (Stroud, 1974)	0.87	0.62
	S_u = 1.6495N_{60} + 16.159 (This Study)	0.29	0.29

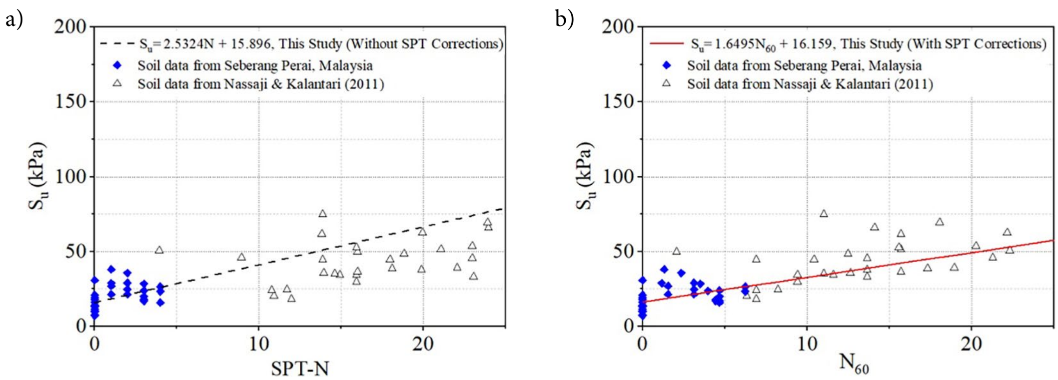

Figure 3. Comparison of predicted S_u values of the newly developed equations with soil data used for validation process

Similar to Figure 2, the increased AARE and SD values were observed with increasing S_u/N ratios. Moreover, both AARE and SD increased gradually with the increasing correction factors. For instance, the C_B range of 1 to 1.15 corresponds to the increased AARE by 7.49% to 13.98% and SD by 15.3% to 21.8%, which signifies a large variation between the predicted and laboratory values across higher correction factors. Overall, Terzaghi and Peck (1967) produced the highest AARE and SD at C_B of 1.15 with the AARE and SD of approximately 1 and 0.8, respectively.

The present research findings suggest the importance of extracting the accurate borehole diameter given its significant effect on the corrected SPT blow counts and S_u/N ratios. In fact, different borehole sizes have been adopted in the construction industry. Skempton (1986) explained that the SPT was originally performed from the bottom of 66-mm or 100-mm diameter wash borings and is still adopted in current practice. In comparison, Yoshimi and Tokimatsu (1983) stated that most of the SPT tests in Japan have been carried out using 66 mm- or 86 mm-boreholes, while Seed et al. (1985) noted the usual borehole size in the United States is 101–152 mm in diameter. On the contrary, Nixon (1982) described the extensive use of 150 mm-boreholes in many countries with even 200 mm-boreholes allowed in certain regions.

2.3. Variation in drill rod length correction factor

Figure 5 presents the influence of C_R as measured by the variation in AARE and SD. Similar to the previous case, an increasing trend in the AARE and SD values was observed (9.55% to 26.12% and 16.32% to 43.76%, respectively) with the increase in C_R. Previously, Terzaghi and Peck (1967) reported the highest AARE and SD of 0.95 and 0.72, respectively, at a C_R value of 1.0.

Several authors have also noted the relationship between the hammer energy transfer and the drill rod length. The drill rod would receive a lot of reflected energy if the drill rod was less than 3 m long, reducing the total energy delivered to the sampler. However, the results would not be significantly affected if the drill rod was longer than 10 m (Skempton, 1986). As the length of the drill rod increases, the hammer-rod contact time also increases, resulting in a greater hammer energy transfer to the drill rod. Interestingly, the energy transferred to the drill rods was also inversely proportional to the penetration resistance. Therefore, the present study highlighted the significant effect of drilling rod length as the misuse of its corresponding correction factor affected the SPT-N and the S_u estimation.

2.4. Variation in sampling method correction factor

Figure 6 presents the variations in AARE and SD with C_S. The curves show a trend of gradual increase of AARE and SD values (6.45% to 16.88% and 8.57% to 39.6%, respectively) with increasing C_S, which resembles the behaviour of Figure 4. The percentage increase in AARE and SD indicated the significant effects of C_S to the S_u estimation. Likewise, the present research findings revealed that the highest AARE and SD were reported by Terzaghi and Peck (1967) at C_S of 1.2 (AARE = 0.9 and SD = 0.67).

The present study highlighted the significant effect of the sampling method correction factor on SPT-N, which in turn affects the estimation of S_u. Schmertmann (1979) found that the removal of the liner increased the sample recovery and removal (due to less side friction) but it also significantly reduced the SPT-N value. Seed et al. (1985) suggested that the use of a liner in an ASTM sampler would improve the measured SPT-N value by 10% to 30%. They explained that the presence of a liner within the split-spoon samplers exerted side friction, and therefore increased the driving resistance.

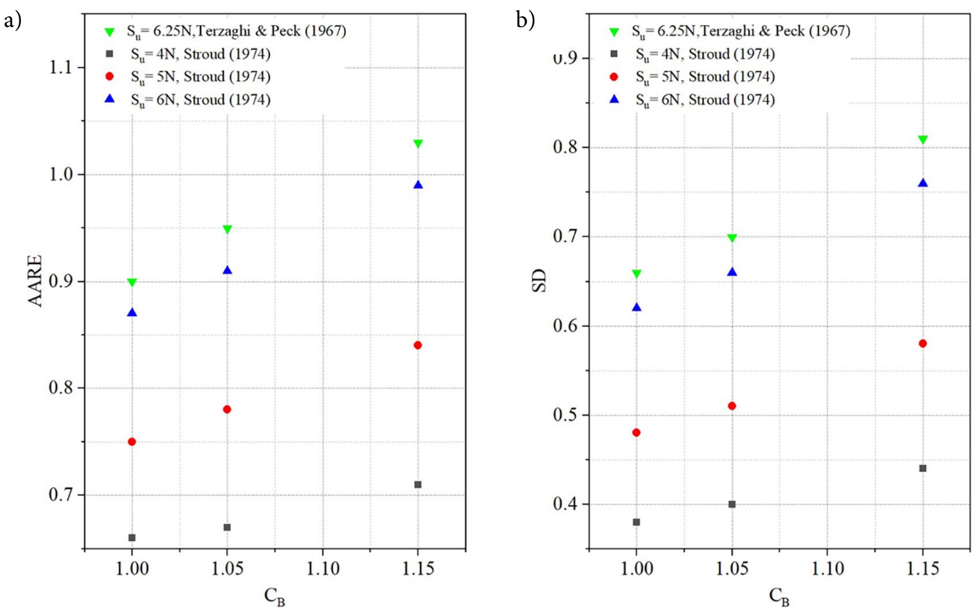

Figure 4. Effects of C_B on the AARE and SD values

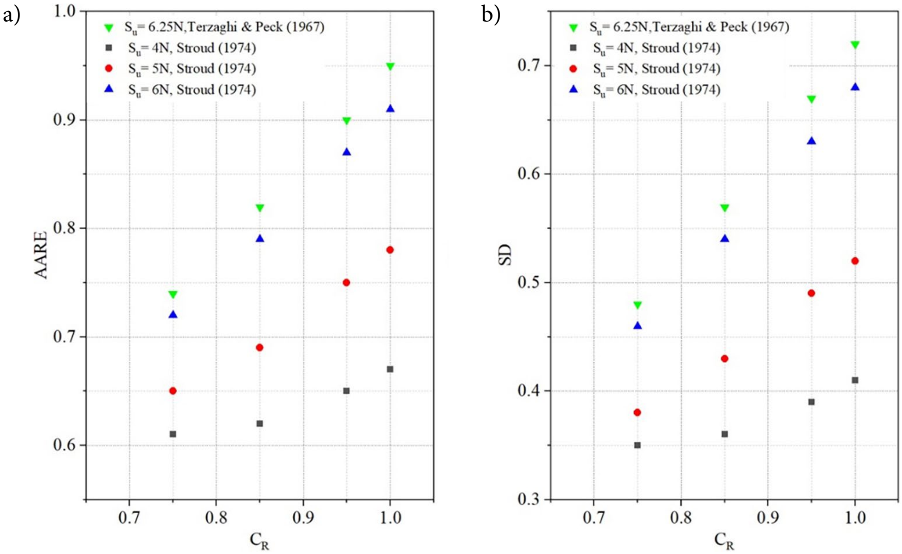

Figure 5. Effects of C_R on the AARE and SD values

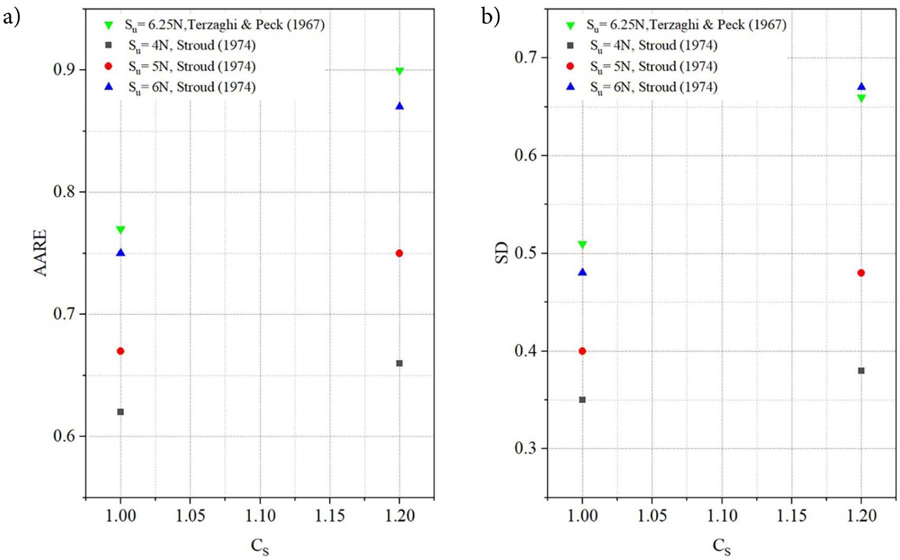

Figure 6. Effects of C_S on the AARE and SD values

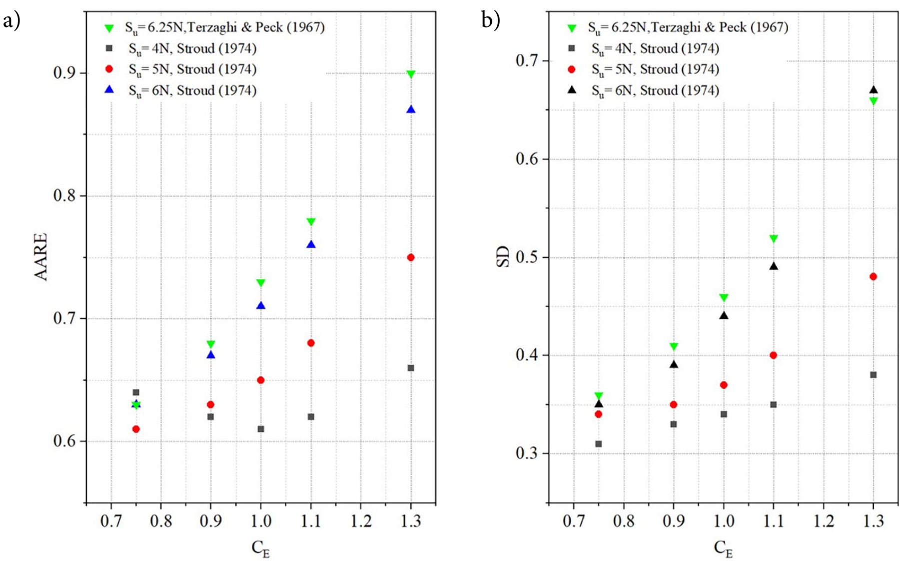

Figure 7. Effects of C_E on the AARE and SD values

2.5. Variation in SPT hammer energy efficiency correction factor

Figure 7 illustrates the impact of C_E as measured by the change in AARE and SD. Although it was found that the increased AARE and SD with increasing C_E for each correlation was similar to the previous analysis, the increasing trend was remarkably steeper compared to the last three cases. For the Terzaghi and Peck (1967) and Stroud (1974) equations, the AARE increased by 21.36% to 37.52%, while the SD increased by 36.8% to 72.3%.

The steepest curves were observed when the C_E values ranged from 1.1 to 1.3. Referring to Table 2, a C_E value of 1.1 and 1.3 is linked to a donut hammer with tonbi and 2 turns of rope release methods, respectively. The values of the shear strength parameter could be either underestimated or overestimated if an engineer misunderstood the release method adopted during S.I. works, which may have a major impact on the engineering designs.

Conversely, Stroud (1974) ($S_u = 4N$) recorded minimal changes in AARE. The AARE showed a small decrease at C_E of 0.75 to 1.0 and gradually increased at C_E of 1.0 to 1.3. Overall, the net AARE and SD increased approximately 3.35% and 21%, respectively. Based on these outcomes, the C_E was considered the most significant factor influenced the correlation between SPT-N and S_u. These trends agreed with similar findings reported by previous studies (El-Sherbiny & Salem, 2013; Kovacs & Salomone, 1982; Schmertmann, 1975).

2.6. Significance of ANOVA findings

The one-way ANOVA method via the Microsoft Excel Data Solver package was applied to identify the most significant factor that influences the shear strength based on the previous analysis. The ANOVA is frequently used to evaluate the significant relationship between the final data and inputs (Dolev et al., 2019; Weina et al., 2018). In this case, the *p*-value was used as an evaluation parameter, where a smaller p-value indicates a statistically stronger correlation between the input and output, and vice versa (McShane et al., 2019). In order to minimise the error, the confidence interval for this analysis was set at 99% (Das, 2019). Table 7 lists the calculated p-value for all parameters.

According to the ANOVA results, all the correction factors are statistically significant since all the calculated p-values were less than 0.01. As such, the lowest p-value recorded by the borehole diameter correction factor indicates that it is more influential than the three other correction factors. Karkush et al. (2020) explained that the increasing diameter of the borehole suggestively reduced the confining pressure, thus affecting the SPT-N value. In short, this study highlighted the vital role of C_B to calculate the sample's shear strength since different sizes of the borehole may affect the shear stress value of soil. In contrast, the previous analysis indicated that the SPT hammer E_r correction factor appeared to be the most influential factor for shear strength calculation.

Table 7. The p-value for the ANOVA calculation

Correction factor	Symbol	p-value
Borehole diameter	C_B	1.8E–10
SPT hammer energy efficiency	C_E	6.75E–10
Drill rod length	C_R	2.0E–10
Sampling method	C_S	4.35E–10

2.7. Influence of soil properties on the S_u/N and S_u/N_{60} ratios

Following the linear regression analysis, an in-depth analysis was performed to explore the relationship between S_u/N or S_u/N_{60} and PI/LI. Before this analysis, only soil data with SPT-N/N_{60} greater than zero was included in the analysis. The correlation equation between S_u/N and PI can be expressed as follows:

$$S_u/N = 0.1233PI + 4.2918 \ (R^2 \text{ of } 0.1375), \quad (7)$$

whereas the correlation between S_u/N_{60} and PI is:

$$S_u/N_{60} = 0.0795PI + 3.3386 \ (R^2 \text{ of } 0.1053). \quad (8)$$

Both equations have relatively low R^2 (0.1375 and 0.1053), suggesting a weak correlation between the inputs. The correlation with R^2 for fine-grained soils, which relate LI to S_u/N, is presented as follows:

$$S_u/N = 3.3702LI + 7.7925 \ (R^2 \text{ of } 0.0981), \quad (9)$$

whereas the correlation with R^2, which relate LI to S_u/N_{60}, is provided as follows:

$$S_u/N_{60} = 2.8356LI + 5.411 \ (R^2 \text{ of } 0.1277). \quad (10)$$

While Eqn (10) recorded a better correlation than Eqn (9), both equations displayed weak positive correlations (R^2 of 0.0981 and 0.1277, respectively). Figure 8 shows the influences of PI and LI on the S_u/N and S_u/N_{60} ratios. Specifically, Figure 8a shows that the scattered data plots in the S_u/N and S_u/N_{60} relationships indicated the increase in both S_u/N and S_u/N_{60} ratios with elevated PI. Hence, this supports the findings of Sivrikaya and Toğrol (2006) and Sowers (1979). Based on the data review, almost all data points (with high S_u and SPT-N or N_{60}) tend to be located on the left side of the graph. However, most of these data points exhibit a low SPT-N or N_{60} of 1 to 2 when the PI is greater than 30%, resulting in higher S_u/N and S_u/N_{60} ratios. The SPT-N and N_{60} showed that the soils tend to be softer and behave more in a plastic state with an increase in PI, as depicted in Figure 8a. Soils with higher PI values have high plasticity characteristics and experience high plastic volume changes.

At present, there is no published report on the influence of LI on the S_u/N and S_u/N_{60} ratios. According to Figure 8b, the scattered data plots in the S_u/N and S_u/N_{60} relationships demonstrate an increasing trend of both S_u/N and S_u/N_{60} ratios as the LI increases, much like the behaviour in Figure 8a. Similarly, almost all data points have high S_u and SPT-N or N_{60} on the left side of the graph.

However, most of the data points with low SPT-N or N_{60} of 1 to 2 were observed when LI is greater than 0.

It is imperative to note that the negative values of LI from Figure 8b indicate the drier soil conditions (stiff, hard, or brittle behaviour) compared to the positive values of LI. Generally, the soils were in brittle solid to semi-solid states, and the negative values of LI increased due to the lesser natural water content compared to that of the PL. For these states, the soil strength and resistance to flow are high. The moisture content increases for LI between 0 and 1, and the soils are in a plastic solid-state. Nevertheless, the soil strength and resistance to flow decreased due to the soil plasticity behaviour. As the value of LI is greater than 1, the soils behave more like a liquid or viscous fluid and offer no resistance to flow. As the amount of data beyond LI of 1 was deemed insufficient, the impact of LI on both S_u/N and S_u/N_{60} ratios was not investigated in this study.

The relationship between S_u/N and S_u/N_{60} with PI and LI was further studied to generate the best-fit equation with improved R^2 via the graph builder in Microsoft Excel 2019. Previously, Nassaji and Kalantari (2011) suggested the exclusion of data with PI > 20% as this data caused a significant error that affects the final equation. Therefore, the present study only considers the data with PI ≤ 20%. Table 8 lists all the best-fit equations together with the R^2 value. For S_u/N_{60} vs PI, the R^2 for linear regression was improved compared to the previous estimation. However, after further examination, the cubic regression was found to be the most suitable regression to define the relation-

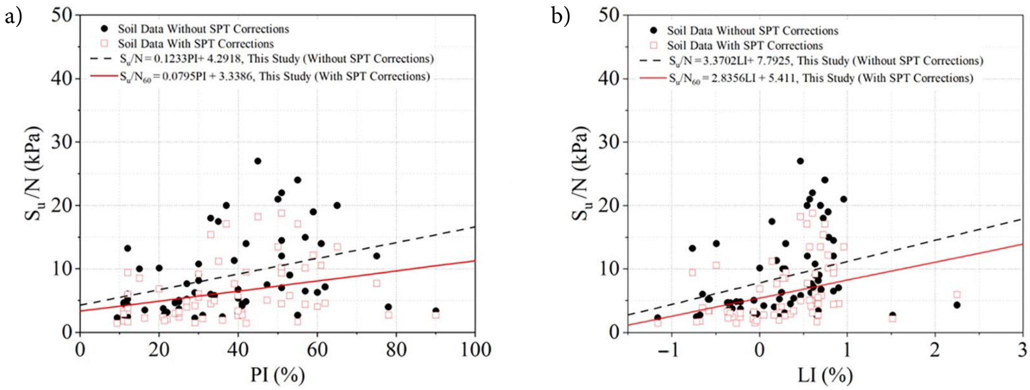

Figure 8. The influence of soil properties on S_u/N and S_u/N_{60} ratios

Table 8. Best-fit equations for S_u/N and S_u/N_{60} versus PI/LI

S_u/N_{60} vs PI		
Type of regression	R^2	Equation
Linear	0.4125	$S_u/N_{60} = 0.9057PI - 7.0014$
Quadratic	0.4197	$S_u/N_{60} = 16.103 - 0.4745PI + 0.0458PI^2$
Cubic	0.4647	$S_u/N_{60} = 23.825PI - 1.6512PI^2 + 0.0384PI^3 - 108.94$
S_u/N vs PI		
Type of regression	R^2	Equation
Linear	0.4161	$S_u/N = 1.3001PI - 10.093$
Quadratic	0.4413	$S_u/N = 16.103 - 2.3865PI + 0.1223PI^2$
Cubic	0.5081	$S_u/N = 39.768PI - 2.8338PI^2 + 0.0669PI^3 - 178.55$
S_u/N_{60} vs LI		
Type of regression	R^2	Equation
Linear	0.1092	$S_u/N_{60} = 5.9687 + 3.1928LI$
Quadratic	0.1389	$S_u/N_{60} = 4.9639 + 2.8885LI + 3.3851LI^2$
Cubic	0.14488	$S_u/N_{60} = 4.9867 + 1.5856LI + 3.5603LI^2 + 2.3539LI^3$
S_u/N vs LI		
Type of regression	R^2	Equation
Linear	0.108	$S_u/N = 8.35 + 4.31LI$
Quadratic	0.144	$S_u/N = 6.92 + 3.78LI + 5.04LI^2$
Cubic	0.154	$S_u/N = 6.93 + 1.47LI + 5.41LI^2 + 4.23LI^3$

ship between these data as the R^2 was higher than the R^2 of the quadratic and linear regressions. A similar observation was also recorded for S_u/N vs PI as the R^2 for cubic regression was higher than in other regressions. Thus, it was assumed that the S_u/N and S_u/N_{60} vs PI relationship can be defined with the cubic equation.

For S_u/N and S_u/N_{60} vs LI, the analysis was limited to samples with LI < 1 as most data were scattered in the region below 1. Based on the investigation, the cubic regression appeared to offer the best-fit equation to correlate the relationship between S_u/N_{60} and LI with higher R^2 compared to the R^2 of the linear and quadratic equations. Similar observations were noted for the S_u/N vs LI. Therefore, it was deduced that the cubic regression is the best model to describe the relationship between S_u/N and S_u/N_{60} with PI or LI. Since the data is randomly scattered, the linear regression is not the equation to elaborate their correlation. This analysis facilitates the understanding of the relationship between shear strength and PI/LI, which could not be observed using the R^2 of linear regression (Yusof & Zabidi, 2018). The R^2 is expected to increase as the increasing order of polynomials would generate better fit equations. Nevertheless, these equations would be more complex as the number of parameters increases. Therefore, linear equations are preferable in these cases due to their simplicity and fast calculations (Karkush et al., 2020).

Conclusions

This study investigated the influence of the correction factors, particularly the SPT hammer E_r, borehole diameter, drill rod length and sampling method, on the SPT-N value for the estimation of the S_u. An in-depth analysis was also performed to examine the effects of PI and LI on both S_u/N and S_u/N_{60} relationships. The main conclusions of this study are as follows:

(1) Based on the R^2, gradient, AARE, and SD of the newly developed regression lines (with and without SPT corrections), the SPT-N with correction factors showed a higher correlation compared to the uncorrected one in S_u estimations.

(2) The incorporation of corrections led to a considerable increase in the values of AARE and SD (more deviations from the actual soil data) for the previously published correlation equations. The AARE and SD increased as the S_u/N ratios increased. Thus, this study recommended that the correlations should be evaluated critically, which is of vital importance when designing engineering works.

(3) The AARE and SD increased with the increasing correction factors for all cases. Although the SPT hammer E_r correction recorded the most significant influence on the estimation of S_u from the SPT-N value, the ANOVA calculation suggested that the borehole diameter correction was more statistically significant compared to the other factors.

(4) The S_u/N and S_u/N_{60} ratios exhibited increasing trends with increased PI and LI values, which may be attributed to the state and behaviour of the soils due to the change of PI and LI, consequently affecting the S_u/N and S_u/N_{60} ratios.

(5) The cubic regression best describes the relationship between the PI/LI and both S_u/N and S_u/N_{60} ratios as the calculated R^2 was higher than the R^2 of linear and quadratic regressions.

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Disclosure statement

The authors declare that they have no known competing financial, professional, or personal interests that could have appeared to influence the work reported in this paper.

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APPENDIX

Table A1. Main geotechnical properties of studied fine-grained soils of Penang Island

Soil Data No.	Term	SPT-N	S_u (kPa)	Moisture Content (%)	PL (%)	LL (%)	PI (%)
1	Sandy CLAY	12	45	17.45	24	45	21
2	Silty CLAY	0	23.5	60.9	34	80	46
3	Silty CLAY	0	23	80.66	34	94	60
4	Sandy CLAY	14	52	19.58	25	50	25
5	Silty CLAY	0	24	72.94	36	85	49
6	Silty CLAY	0	30	35.75	28	64	36
7	Silty CLAY	1	22	64.78	34	85	51
8	Silty CLAY	1	21	60.5	32	82	50
9	Sandy CLAY	19	89	20	28	52	24
10	Silty CLAY	2	18	67	31	84	53
11	Silty CLAY	0	14	84	28	77	49
12	Silty CLAY	1	24	72	31	86	55
13	Silty CLAY	1	19	80	34	93	59
14	Silty CLAY	16	43	69	33	88	55
15	Silty CLAY	1	27	52	31	76	45
16	Silty CLAY	6	43	70	32	94	62
17	Silty CLAY	4	18	54.7	30	71	41
18	Silty CLAY	8	24.5	41.55	30	70	40
19	Silty CLAY	1	18	96	42	128	86
20	Silty CLAY	0	24	90	43	124	81
21	Silty CLAY	0	20	91	42	110	68
22	Silty CLAY	1	12	73	39	103	64
23	Silty CLAY	0	20	72	39	104	65
24	Silty CLAY	0	14	85	38	112	74
25	Silty CLAY	1	20	83	38	103	65
26	Silty CLAY	0	12	98	43	131	88
27	Silty CLAY	1	20	48	28	65	37
28	Silty CLAY	1	12	84	43	118	75
29	Silty CLAY	1	18	52	28	61	33
30	Silty CLAY	0	10	85	38	110	72
31	Silty CLAY	0	10	86	37	106	69
32	Silty CLAY	0	24	70	32	77	45
33	Silty CLAY	4	27	60	32	72	40
34	Silty CLAY	4	24	48	26	59	33
35	Silty CLAY	0	16	63	31	76	45
36	Silty CLAY	3	23	39	23	50	27
37	Silty CLAY	2	18	42	23	53	30
38	Silty CLAY	4	25	41	24	53	29
39	Silty CLAY	0	18	83	34	94	60
40	Silty CLAY	0	17	75	33	88	55
41	Silty CLAY	0	19	69	31	81	50
42	Silty CLAY	0	16	87	37	99	62
43	Silty CLAY	7	34	55	30	72	42
44	Silty CLAY	5	29	43	27	61	34
45	Silty CLAY	0	8	83	45	131	86
46	Silty CLAY	2	35	38	31	66	35
47	Sandy CLAY	14	67	19.6	25	50	25
48	Sandy CLAY	17	86	22.39	24	49	25

End of Table A1

Soil Data No.	Term	SPT-N	S_u (kPa)	Moisture Content (%)	PL (%)	LL (%)	PI (%)
49	Sandy CLAY	21	47	26.58	28	57	29
50	Sandy CLAY	2	20	41	22	52	30
51	Silty CLAY	1	10	40.48	33	72	39
52	Silty CLAY	3	10	40.94	39	71	41
53	Silty CLAY	1	5	42.55	30	72	42
54	Silty CLAY	2	10	48.63	33	73	40
55	Silty CLAY	3	10	108	48	138	90
56	Silty CLAY	2	22	55	40	100	60
57	Silty CLAY	1	15	83	38	95	57
58	Silty CLAY	1	14	9	39	100	61
59	Silty CLAY	0	13	87	38	98	60
60	Silty CLAY	0	17	80	39	100	61
61	Silty CLAY	2	29	70	27	78	51
62	Silty CLAY	1	21	79	31	81	50
63	Silty CLAY	0	17	85	38	91	53
64	Silty CLAY	0	19	84	36	89	53
65	Silty CLAY	3	21	76	30	81	51
66	Silty CLAY	0	16	84	38	91	53
67	Silty CLAY	2	24	76	33	84	51
68	Sandy CLAY	0	11	39	20	48	28
69	Silty CLAY	4	28	43	23	53	30
70	Sandy CLAY	12	42	16.5	22.33	38.67	16.33
71	Sandy CLAY	12	35	24	24.67	46	21.33
72	Silty CLAY	0	19	82	40	109	69
73	Silty CLAY	2	13	86	38	95	57
74	Sandy CLAY	2	16	55	32	83	51
75	Sandy CLAY	2	11	58	35	89	54
76	Sandy SILT	6	28	23.08	27	38	11
77	Sandy SILT	13	68	21.16	28	40	12
78	Sandy SILT	2	20	36.35	32	47	15
79	Sandy SILT	6	28	23	27	38	11
80	Sandy SILT	13	68	21	28	40	12
81	Sandy SILT	2	20	36	32	47	15
82	Clayey SILT	1	31	22.41	34	54	20
83	Clayey SILT	4	33	21.15	31	50	19
84	Sandy SILT	24	66	19.57	27	38	11
85	Sandy SILT	6	36	22.22	30	42	12
86	Sandy SILT	24	76	30.47	32	54	22
87	Sandy SILT	15	68	30.89	27	38	11
88	Clayey SILT	4	21	41.1	35	62	27
89	Sandy SILT	2	26.5	16.84	26	38	12
90	Clayey SILT	0	12	86.67	37	81	44
91	Sandy SILT	15	65	19	28	40	12
92	Clayey SILT	4	32	32	32	52	20
93	Sandy SILT	17	42	21.4	30	42	12
94	Clayey SILT	5	12	41	33	69	36
95	Sandy SILT	3	6	79	32	63	31
96	Clayey SILT	8	32	61	48	126	78
97	Clayey SILT	2	15	61.5	34.67	82	47.33
98	Sandy SILT	17	39	15.5	26.33	35.67	9.33