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ESTIMATION OF UNDRAINED STRENGTH FROM SOIL STRENGTH PROBE

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ABSTRACT: Undrained strength (Su) of fine-grained soils plays an important role in the geotechnical stability of infrastructure. In the absence of direct measurement of Su, correlation with in-situ cone penetration test can be useful. This study attempts to estimate undrained vane strength in select Indonesian soils from soil strength probe (SSP) cone resistance. The study is located in Riau Province, Indonesia. Fieldwork, consisting of a vane test, SSP test, and hand boring test, was performed close to each other (in a 1.5m radius) and at a depth of up to three meters at 90 locations. The physical properties of the soils were determined in the laboratory. Soils can be classified as high and low plasticity silt and clay with insensitive to moderate sensitivity. Field tests show SSP can assess soils from very soft to medium consistency. Based on the well-known Terzaghi equation, a very strong correlation, i.e. coefficient of correlation greater equal than 0.96, between uncorrected and corrected (by index plasticity) undrained shear strength from the vane shear test and SSP cone penetration test was found. The range of cone factor (N_k) values from *SSP* were between 27.9-42 for uncorrected Su and 37.5-69.8 for corrected Su. SSP cone factor does not correlate with plasticity index or sensitivity. The empirical correlation could be useful practically in soft to medium silty soils when direct Su measurements are unavailable.

Keywords: Soil strength probe, Cone resistance, Undrained field vane strength, soft-medium soils

1. INTRODUCTION

Indonesia has large areas of soft soils, which encompass approximately 20 million hectares, accounting for about 10% of its total land area [1]. The presence of soft clay/silt poses substantial challenges in infrastructure construction, such as roads, due to its problematic characteristics, e.g., its large settlement and low bearing capacity [2–6]. Soft soils also result in large lateral soil pressure on retaining structures [4,6].

Undrained strength (Su) is an essential geotechnical parameter in soft soils, as it directly relates to the geotechnical stability of infrastructure, particularly during building construction and right after the loading [7,8]. Furthermore, Su is also important in selecting ground improvement methods for soft soils [9]. Ideally, Su is determined from laboratory tests such as undrained triaxial tests. However, obtaining a high-quality, undisturbed sample of soft soil is very challenging due to the soil's sensitivity and variability. So, in practice, it is not uncommon to determine Su indirectly using empirical correlation with in-situ tests. For example, Sitthiphat and Sirichai found that the measurement from the fruit sclerometer is twice the undrained strength (from unconfined compression test) of Bangkok clay [10]. Soralump et al. developed a correlation between undrained strength from field vane test and screw driving sounding on Bangkok clay [11]. Nevertheless, the most widely used undrained strength empirical correlation is based on the Cone Penetration Test (CPT) [8,12]. The most common equation used in practice is based on Terzaghi's bearing capacity equation and can be rewritten as follows [13]

$$Su = \frac{q_c - p_0}{N_k} \tag{1}$$

where

q_c= cone tip resistance

N_k is the theoretical cone factor,

p_0 is the total vertical stress

Generally, N_k ranges at 10-20, but it is not uncommon to get a value outside this range [14–27]. This correlation is well-supported by both empirical data and theoretical models [28,29]. The empirical correlations not only apply to normally consolidated and over-consolidated soils but also apply to under-consolidated clays [30].

Soil strength probe (SSP) is one type of cone penetration test that consists of a thin rod with a cone at the end that is statically pressed into the soil by hand [31,32]. SSP has two cones: a small standard cone to measure penetration resistance and a vane cone blade to measure torque resistance (Fig. 1). This study only focuses on small cone measurements. Table 1 shows some differences between SSP and other penetration tests such as the hand cone

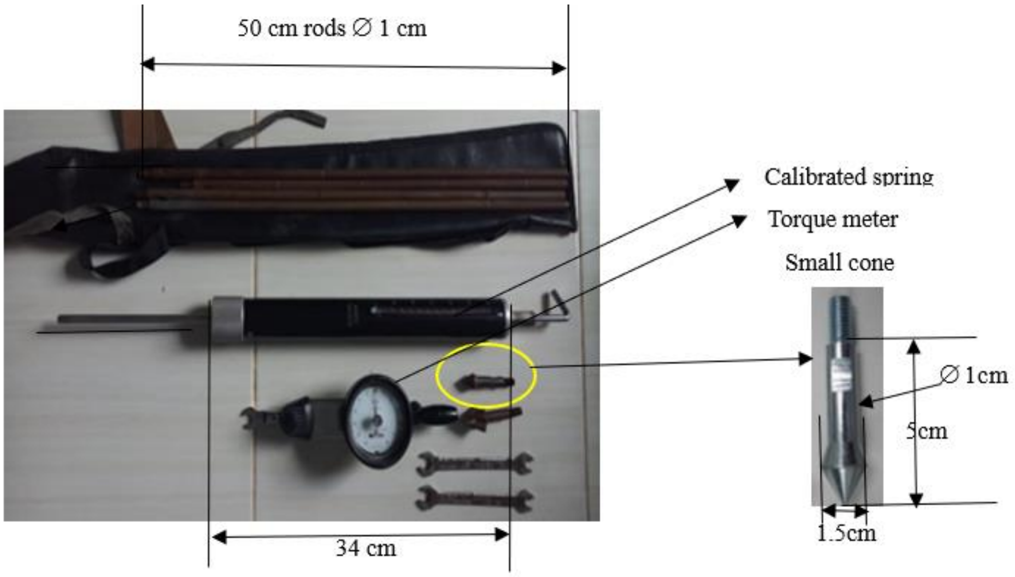

Fig. 1 Soil Strength Probe

penetration test (HCP), dynamic cone penetration test (DCP), cone penetration test (CPT) and Macintosh probe (MCP) in terms of dimension of the cone and rod diameter. SSP was relatively newly introduced in Indonesia (circa 2017). SSP has a significant advantage in soft soil conditions because it is much lighter, i.e., only 5.5kg, compared to CPT, which weighs about 500kg. Thus, SSP is preferable to CPT due to its portability in very soft soil.

The next section describes the importance of this research, location and equipment used in this study. This then followed by presentation of the results (fieldwork and laboratory test) and discussions.

Table 1. Cone and rod size of penetration

Test	Cone angle (degree)	Cone dia. (mm)	Rod dia. (mm)
HCP	30	28.6	16
DCP	60	20	15.9
CPT	60	35.7	36
MCP	30	27.9	12.7
SSP	60	**15**	**10**

2. RESEARCH SIGNIFICANCE

The number of cases and previous studies of SSP outside Japan is still very limited. For example, Yusa et al. conducted SSP tests to study the geotechnical properties of Bengkalis peat [33,34]. On the other side, although there have been many empirical correlations between CPT and undrained strength, to the author's knowledge, there has not been any empirical equation of *small cone size* such as SSP with undrained strength, particularly in Indonesian soft clay/silt. This research aims to examine a range of vane strengths where SSP can be applied and to find a range of cone factors attributed to the SSP small cone. Thus, this study expands and adds the database of the range cone factor attributed to different cone penetrometer types and the use of other methods to measure undrained strength, as reported by Mayne and Puechen [22].

3. METHODOLOGY

3.1 Location

The locations are in the eastern coastal area of Riau Province, Sumatra Island. The longitude and latitude of the area from a handheld Global Positioning Satellite (GPS) range from 100°35'10.00 "E, 2° 4'59.00" N to 102° 3'7.00" E, 0°46'56.00 "N. Figure 2 (top) shows the study's locations regionally, which are relatively close to Malaysia, while Fig. 2 (bottom) presents the zoomed area.

The sites can be grouped into three main areas, i.e. Rokan Hilir Regency, City of Dumai and Siak Regency. In each test area, there are thirty (30) points of soil investigations were conducted; thus, there were ninety (90) soundings in total.

Regarding geological condition, the eastern coastal region of Riau Province can be classified as alluvial with Holocene Pleistocene age. Based on the geological map with scale of 1: 250.000, i.e. sheet of Dumai and Bagansiapiapi, the lithology at Dumai and Rokan Hilir regency area is defined as Qh, a young superficial deposit consisting of clays, silts and clean gravel, vegetation raft and peat swamps. While Siak regency, based on one geological sheet of Bengkalis and Siak Sri Indrapura (scale 1:250.000), the lithology of the area is classified as alluvial composed of clay, silt, clean gravel, vegetation raft, peat swamps and granite sand [35,36].

3.2 Experimental Work

3.2.1 Field work

Fieldwork consisted of SSP, hand boring, and portable field vane shear (Fig. 3). The diameter area of the field tests was set to be as close as it could (i.e., in this case, is about 1.5m) to minimize the effect of spatial heterogeneity. Hand boring is conducted in the middle of SSP and field vane shear. The depth of interest was selected up to 3 meters to minimize surface friction's effect on the rods' periphery. In addition, the thin diameter of the rods, i.e. only 10 mm, also results in less disturbance compared to the larger rods in other in-situ tests.

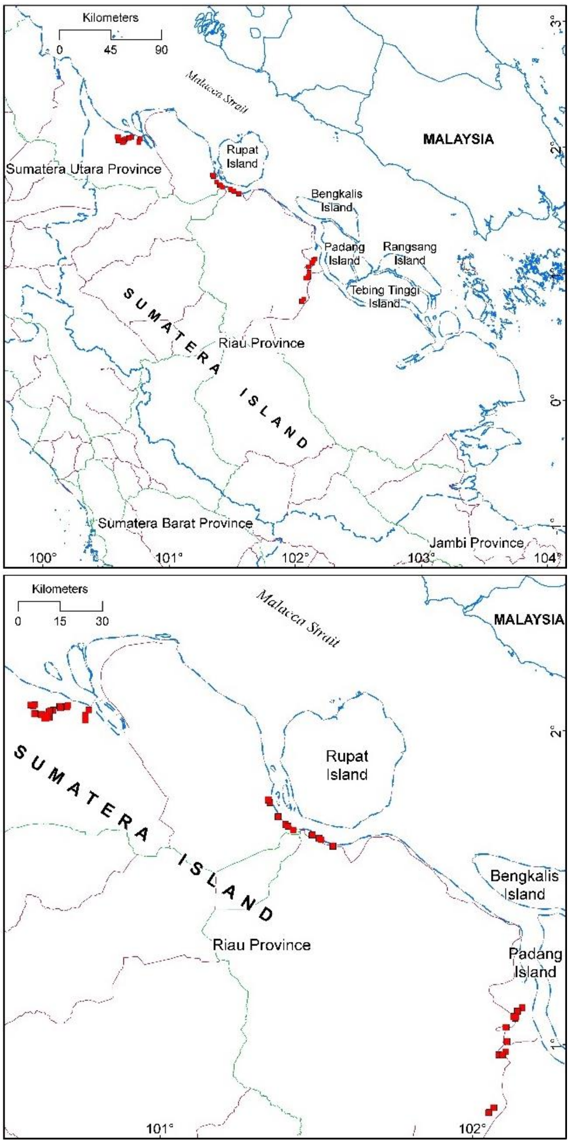

Fig. 2 Study location and investigation points

In this study, SSP cone resistance, q_{dk} is defined as

$$q_{dk} = \frac{Q_{dk}/_{1000}}{A} \tag{2}$$

$$Q_{dk} = W + (m^0 + nm^1)g \tag{3}$$

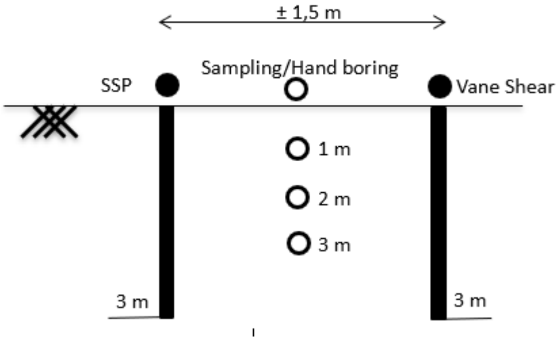

Fig. 3 Fieldwork arrangement

Where:
q_{dk}= SSP penetration resistance (kPa)
Q_{dk}= Total vertical force (N)
A= *cone area* (1,76 x 10^4 m^2)
W= Vertical force reading (N)
m^0= weight of cone and 450 mm rod (kg)
n= number of 500 mm rod
m^1= weight of 500 mm rod (kg)
g= gravity acceleration 9,81 m/s^2

The portable field vane shear used in this study is shown in Fig. 4. The vane was pushed by hand into, i.e. one-meter intervals and then rotated at the rate of 0.1 degree/s. The procedure followed ASTM D 2573-1. Undrained strength from the vane shear test was determined by multiplying the dial reading with a calibration factor that depends on the blade size (Table 2). In addition, some researchers believed that the undrained strength from the vane shear is too high and should be corrected by the plasticity index [37,38]. In practice, the widely used correction factor is the one proposed by Bjerrum [39].

$$Su_{design} = \beta\, Su_{field} \tag{4}$$

Decisision whether to use plasticity correction or not is on engineer hands, neverthless both uncorrected and corrected studies were used for this study.

3.2.2 Laboratory work

Soil samples were taken at an interval of 1-meter depth from hand boring. Samples were taken by gently pushing the tube by hand to the selected depth. The sample tube was then sealed to prevent water content changes. The samples were then transported to the soil mechanic laboratory of Universitas Riau. The laboratory tests were conducted according to ASTM to obtain soil physical properties such as sand, silty, and clay fraction, water content, unit weight, liquid limit, and plastic limit.

3.2.3 Statistical analysis

Correlation analysis was conducted on cone resistances and undrained strengths. Equation 1 assumes q_c-p_o at the surface equals zero; thus, the correlation passes through the origin. However, the correlation does not necessarily pass through the origin thus, Eq. 5 was also used [40];

Table 2. Blade size calibration factor

Blade size (mm)	Calibration factor
16 × 32	2
20 × 40	1
25,4 × 50,8	0,5

Fig. 4 Field vane apparatus

$$Su = k + \frac{q_c - p_o}{N_k} \tag{5}$$

where k is an intercept that depends on the soil type and the data scatter degree. A possible correlation between the cone resistance (less than 1500 kPa) and undrained strength less equal than 50 kPa (uncorrected and corrected by the index of plasticity) at the same depth was investigated using Eq. 1 and Eq. 5. The strength of the relationship (coefficient of correlation) among variables was determined based on Table 3.

Table 3 Pearson's Correlation Coefficient

Scale of correlation coefficient	Classification
$0 < r \leq 0.19$	Very Low
$0.2 \leq r \leq 0.39$	Low
$0.4 \leq r \leq 0.59$	Moderate
$0.6 \leq r \leq 0.79$	Strong
$0.8 \leq r \leq 1.0$	Very Strong

4. RESULTS

4.1 SSP

SSP cone resistance was measured at a 20 cm interval, similar to a typical mechanical CPT measurement interval. Profile of SSP cone resistance with depth for all locations is presented in Fig. 5. The graph visually reveals the heterogeneity of the soil with cone resistance ranging from 168 to 1600 kPa, which is consistent with soft soil criteria. The majority fall below 1000 kPa. The coefficient of variation (COV) for SSP cone resistance is 41%. This value is slightly higher than the range values of CPT cone resistance q_c for clay reported by Phoon et al., i.e. 16-40% [41]. Further analysis of Fig. 6 shows that the distribution of cone resistance is positively skewed, with most of the values concentrated in the lower resistance range (400–800 kPa) and fewer occurrences at higher resistance values. This positively skewed distribution type is a common distribution found in geotechnical properties besides normal distribution [42].

4.2 Field Vane Test

The results from portable field vane shear measurements at one-meter depth intervals are shown in Fig. 7. Generally, the graph shows undrained vane strength ranging from 5 kPa to 50 kPa. These values indicate soft to firm consistency. This study's coefficient of variation (COV) for Su values is 39%. This value is slightly higher than the range values of Su from the vane test for clay reported by Phoon et al., i.e. 13-36% [41]. Figure 8 shows a positively skewed distribution. Most undrained shear strength values are concentrated in a narrow range around 10-30 kPa, with a few larger values extending into the higher range (40–50 kPa). The figure also shows that most values fall within the 20 kPa range, which can be classified as soft soil. Regarding sensitivity, the soils can be classified as insensitive to medium sensitive.

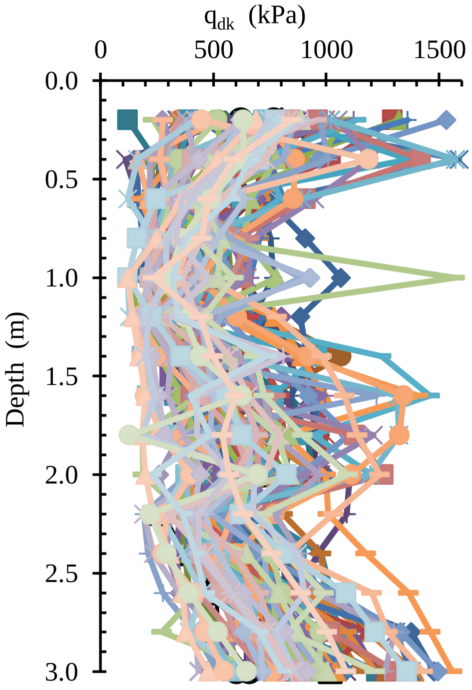

Fig. 5 Cone resistances profile

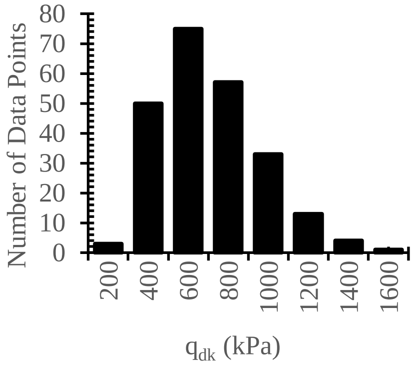

Fig. 6 Cone resistance distribution

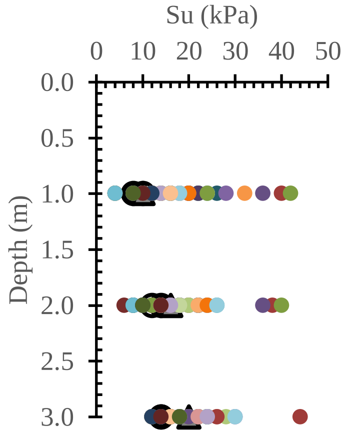

Fig. 7 Undrained field vane shear strength

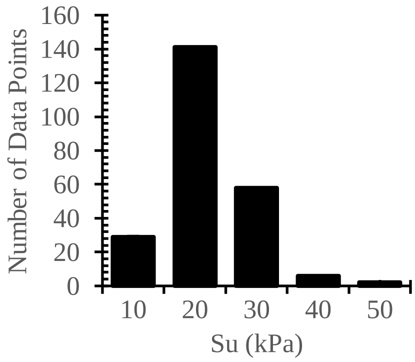

Fig. 8 Undrained strength distribution

4.3 Laboratory Test

Table 3 shows a recapitulation of physical properties. In general, parameters such as unit weight and water content indicate soft consistency. In addition, the coefficient of variation is generally within the values reported by Phoon et al. [41]. The distribution of water content, liquid limit, and plastic limit is shown in Figs. 9 to 11.

Plotting plasticity index and liquid limit in Atterberg chart (Fig. 12) shows that the majority, i.e. 70 % of the soft soils in this study, can be classified as silt with high and low plasticity (MH, ML), 30 % of soils classified as clay with high and low plasticity (CH, CL, CL-ML) with low and high plasticity.

Table 3. Physical Properties

Parameter	Mean	COV (%)
γ (kN/m^3)	14.3	9
w (%)	107	45
LL (%)	56	18
PL (%)	39	21
PI (%)	17	45

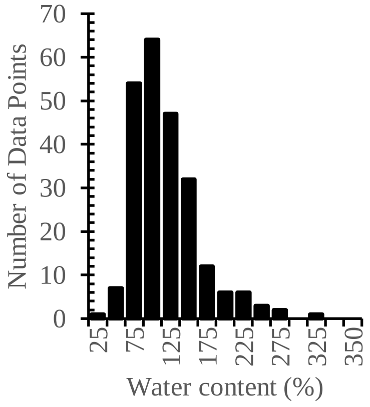

Fig. 9 Water content distribution

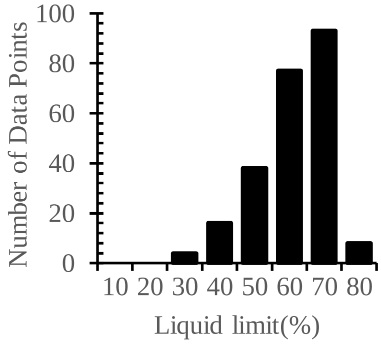

Fig. 10 Liquid limit distribution

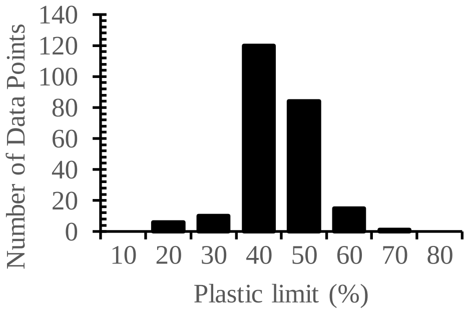

Fig. 11 Plastic limit distribution

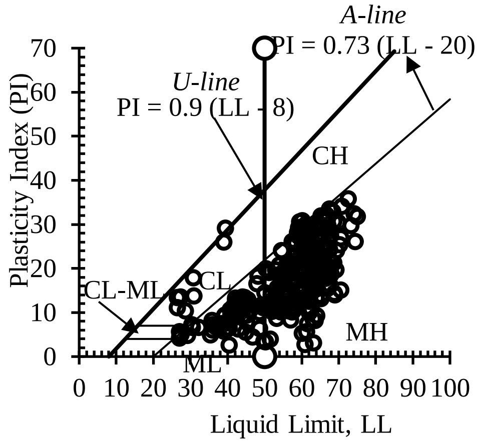

Fig. 12 Atterberg chart

5. DISCCUSSIONS

5.1 Cone Penetration Vs Su Vane for All Data

Figures 10 and 11 illustrate the visual relationship between net SSP cone resistance (q_{dk}-p_o) with uncorrected with undrained vane strength and its residual plot, respectively. Linear correlation was selected in this preliminary study because of its simplicity and practicality. The figures show that Eq. 1 gives a stronger correlation than Eq. 5. Gebreselassie observed a similar trend for Germany's soft soils [21]. Figures 10 reveal a very strong positive correlation between the net cone resistance and the undrained strength with coefficient correlation r = 0.96 (for positive correlation, r is the square root of R^2). The probability of value (p) is less than 0.05; hence, the correlation can be considered statistically significant. The scatter could be attributed to the natural variability of the soil. In addition, SSP and field vane shear tests have different shearing mechanisms. FVT shearing occurs between soil and soil, while SSP shearing occurs between the cone and the soil. The direction of shearing force in vane shear is radial, while in SSP, it is vertical and horizontal [11].

For practical purposes, the empirical equation that can be used in practice are

$$Su = \frac{q_{dk} - p_0}{35} \tag{6}$$

with lower and upper limits (95% confidence interval)

$$\text{Lower } Su = \frac{q_{dk} - p_0}{36.5} \tag{7}$$

$$\text{Upper } Su = \frac{q_{dk} - p_0}{33.8} \tag{8}$$

Figure 15 and Fig. 16 present a correlation for corrected undrained strength and corresponding residual plots. The correlation coefficient is slightly higher (r=0.97) than the one for uncorrected undrained strength. The cone factor, N_k, for both uncorrected and corrected vane values are 35 and 39, respectively. Thus, the cone factor values for all soil in this study are slightly higher than the typical value (10-20) but still within the range of values found in previous studies. Regarding Indonesian soft soils, the values for these Sumatran soft soils are also higher than those reported for Bandung and Kalimantan soft soils, which are 13 and 5-26, respectively [15, 26]. For both locations, CPTu and laboratory undrained tests were used for comparison. In addition to natural variability, the differences may be attributed to the different cone sizes and undrained strength measurements [22]. Potvin et al. reported that the influence zone of the cone (i.e., the zone around the cone that influences cone resistance value) is a function of both cone diameter and undrained shear strength [43]. It should be noted that the correlation may be affected by environmental and site conditions (e.g., temperature, pore pressure), but they are beyond the scope of this study.

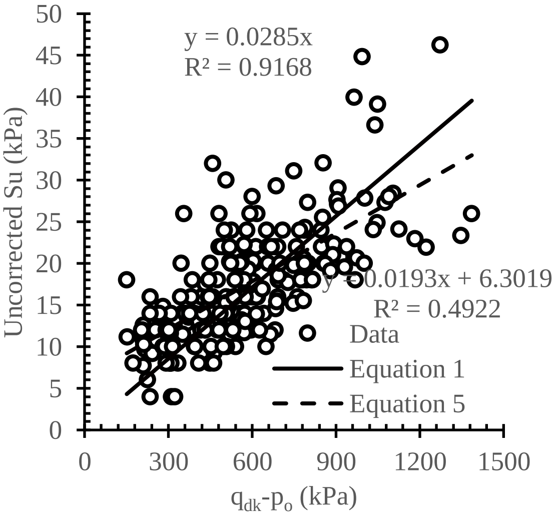

Fig. 13 Net cone resistance and uncorrected Su (all)

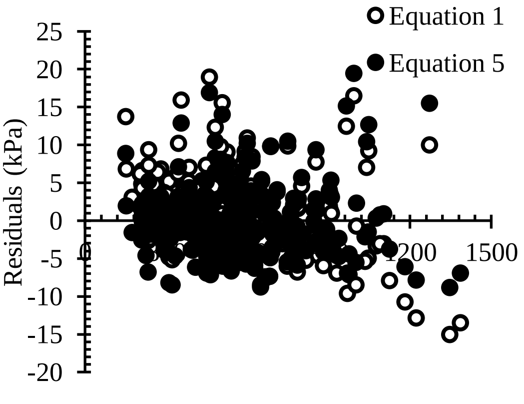

Fig. 14 Residual plot of uncorrected Su (all)

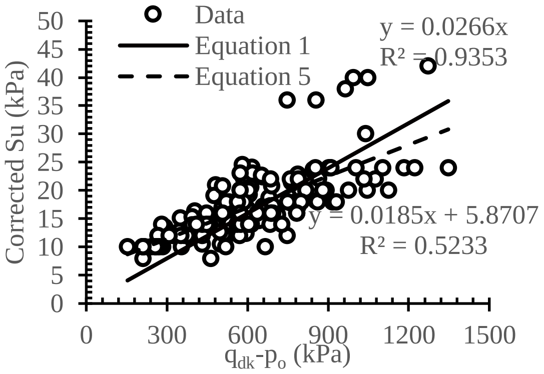

Fig. 15 Net cone resistance and corrected Su (all)

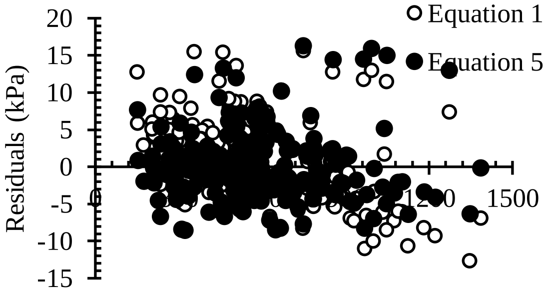

Fig. 16 Residual plot of corrected Su (all)

An investigation is also attempted to see whether the cone factor correlates to plasticity index and sensitivity, as indicated by previous researchers [44–47]. Figure 17 shows that although there is a tendency to decrease the cone factor as a function of the plasticity index, statistically, there is no correlation between the cone factor and the plasticity index. A similar observation was reported by previous researchers [48–50]. Likewise, this study also revealed that no correlation exists between cone factor and sensitivity (Fig. 18). Paniagua et al. suggested that N_k could be affected by more than one factor in combination, e.g. PI and OCR [46].

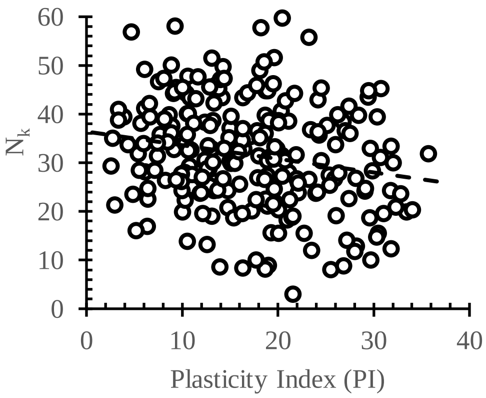

Fig. 17 N_k (uncorrected Su) PI for all

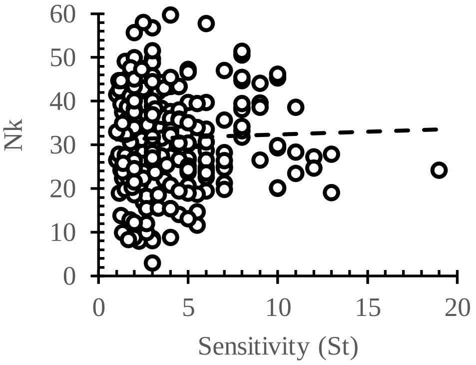

Fig. 18 N_k (uncorrected Su) and St for all

5.2 Cone Penetration Vs Su for Each Soil Type

Abu-Farsakh and Mojumder reported that the accuracy of correlations between cone resistance and undrained strength can vary significantly depending on soil conditions and the specific empirical models employed [51]. Tian and Sheng made a similar finding [52]. Thus, further analysis is conducted to investigate the relationship between SSP cone resistance and undrained strength for each soil type in this study, i.e. high and low plasticity silt (MH and ML), high and low plasticity clay (CH, CL, CL-ML). Due to fewer amounts of data compared to those for silty soils, high and low-plasticity clays were combined.

The analysis results are represented in Fig. 19 to Fig. 23. Equations 1 correlations were found for each soil type with a coefficient r greater than 0.94 for each soil type. A weaker correlation using Eq. 5 was found with a correlation coefficient ranging from 0.57 to 0.78, which can still be classified as moderate to strong. Probability values (p) were less than 0.05, thus statistically significant. It should be noted that the data for clay and organic soils is significantly less than that for silty soils, so one must use the correlation with caution. For further research, it is recommended similar study on more various soil types (particularly clay) and environments other than alluvial areas, such as lacustrine, marine, etc. The corresponding N_k value associated with equation 1 for each soil type is shown in Table 4. The cone factor value of MH, ML, and clay soil in this study is comparable with the range of values reported by Zein [27].

Table 4. Cone factor based on soil type

Soil	Eq. 1		Eq. 5	
	1	2	1	2
All	35.1	37.6	51.8	54.1
MH	33.4	34.5	59.2	58.8
ML	39.2	42.4	59.5	69.9
Clay	27.9	27.8	37.5	41.3

1= Uncorrected Su; 2= Corrected Su

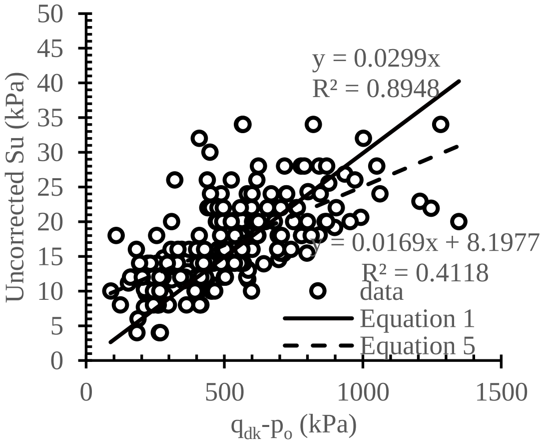

Fig. 19 Net cone resistance and uncorrected Su for MH

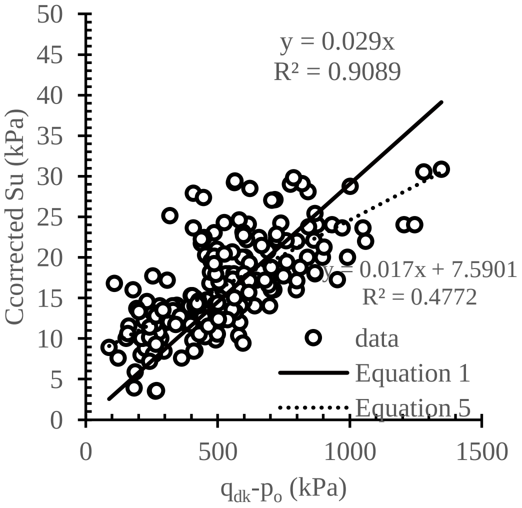

Fig. 20 Net cone resistance and corrected Su for MH

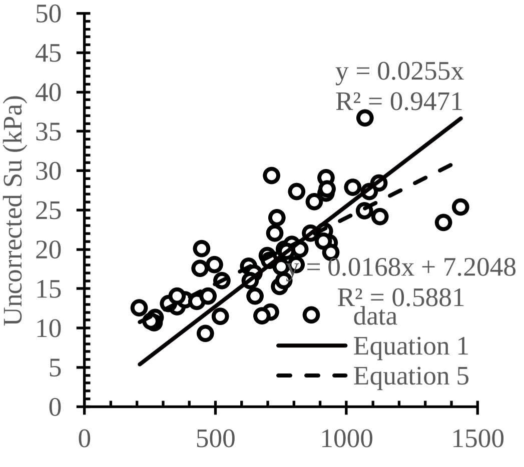

Fig. 21 Net cone resistance and uncorrected Su for ML

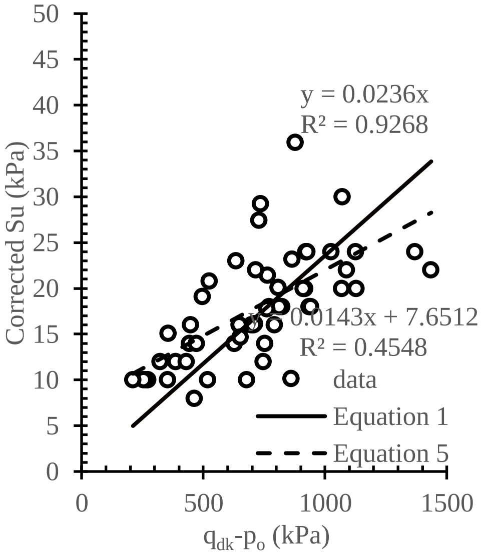

Fig. 22 Net cone resistance and corrected Su for ML

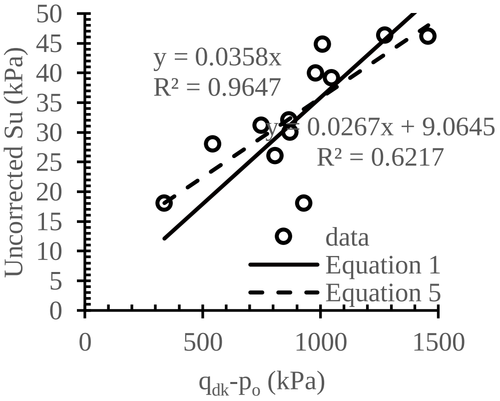

Fig. 23 Net cone resistance and uncorrected Su for Clay

6. CONCLUSIONS

An attempt to find a correlation between SSP cone resistance, a relatively new portable soil investigation tool introduced in Indonesia, to undrained strength from field vane shear for select Indonesian soft-medium, insensitive-moderately sensitive soils consisting of clay and silt with high and low plasticity has been conducted. Based on the well-known Terzaghi bearing capacity equation, a very strong relationship with a coefficient of correlation of more than 0.96 was found for all soils and each soil type. Moreover, there is no correlation between cone factor value and index of plasticity or sensitivity for the soils in this study. The range of cone factor values using SSP for soft-medium soils at the site location in this study is 27.9-42.4 for uncorrected Su. The empirical correlation could be useful in alluvial areas of soft to medium silty soils when direct Su measurements are unavailable.

7. ACKNOWLEDGMENTS

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