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SOIL STRENGTH ESTIMATION USING SCREW DRIVING SOUNDING TECHNIQUE FOR BANGKOK CLAY LAYERS

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ABSTRACT: The Screw Driving Sounding (SDS) test is an improvised and modified version of the Swedish Weight sounding (SWS) test. It is an emerging technique for in-situ field characterization used to estimate strength parameters from field tests directly, rather than by obtaining samples from the field and performing laboratory tests. For this research, several boreholes with standard penetration tests (SPTs) were conducted in the central region of Bangkok. SDS tests and field vane shear tests were performed in the vicinity of these boreholes. The undrained shear strengths from these tests were correlated separately to the SDS torque for marine and intertidal clay deposits. These equations differed slightly due to the difference in the shearing during failure of soil. These empirical equations are supported by an analytical equation that is derived based on the shearing mechanism of soil when the SDS screw head is penetrated into the soil. The correlation to estimate the SPT N was developed for stiff and hard alluvium clay, and compared with the equation from past research. Plots of SDS penetration energy with the consistency index showed that the clays could be clustered as two distinct groups based on their state and consistency. The SDS penetration resistance parameters were extremely affected by differences in the state of clay, which depended on the soil's depositional history and depositional environment. The past researches were mainly empirical and dealt with sand or Japanese clay, formed in different depositional environment. Those equations do not give reliable results when applied directly to Bangkok clay. Hence, from this research, the undrained shear strength of soft clay and SPT N of stiff clay of the Bangkok deposit can be estimated directly from the equations.

Keywords: Bangkok Clay, Formation History, Correlation, Geotechnical Testing, Screw Driving Sounding Test

1. INTRODUCTION

There are numerous methods for site investigation, including the SWS, and SDS test, which are simple and convenient [1-3]. A continuous soil profile can be obtained from SWS. Obtaining a continuous soil profile is crucial so that even the thinnest layer of weak or soft soil can be identified. SWS was first introduced in Sweden in 1917, and officially recommended as an investigation tool by the Ministry of Land, Infrastructure, and Transport, Government of Japan in 2001 [4]. However, there are various limitations of SWS that have been discussed in the literature [1, 3, 5]. Thus, the SDS machine was developed as a method for site characterization, which is a modified and improvised form of SWS [1, 3].

The principle of operation of SDS is the same as that of SWS [2, 4]. However, the working procedure is slightly different. There exist several empirical equations which can estimate soil parameters from SWS [4]. SDS possesses several advantages over the SWS technique. It requires less space for operation making it an ideal field characterization technique in congested areas. It is quick, easy to operate, and fully automated, unlike SWS which is labor-intensive. SDS can be used together with other conventional tests to obtain a greater number of soil exploration points, when area is large. A larger number of site investigation points gives a better understanding of the soil profile and soil properties.

Initially, SDS was used mainly for light structures such as residential house projects in Japan and Thailand. Now, its application is broadened to various Engineering projects related to reclaimed lands, dams, canals, roads, housing projects, landslide-prone areas, and many more in Thailand and other parts of the world [3, 6-9]. Researchers from New Zealand, Malaysia, Thailand, and Japan have used this technique for their study [6, 8-15]. The future scope and applications of this research are broad, and can be used in numerous geotechnical projects. In addition, the standard SDS machine is customized for this research to achieve higher penetration ability. It can hence be used not only for light structures like residential houses but also for heavy structures, especially for pile foundation. The S_u and SPT N are the two most important parameters for pile design in clay, which can be estimated by the equations of the research without having the need to perform borehole tests. For pile design, a continuous soil profile is a vital requirement which is the biggest advantage of SDS.

Numerous researchers [2, 6, 11]have provided various correlation equations however, those do not include the S_u and SPT N of clay. Correlations from [11] are developed from insufficient number of samples. Although empirical formulae have been developed to estimate S_u and SPT N for Japanese alluvial clay as in [3] and [14], the sample size is less and data from both sand and clay are used. Moreover, this cannot be used in soft Bangkok clay because these two clays have different mineralogy and microstructure which results in differences in their geotechnical properties [16, 17]. In addition, these two clays were formed in different depositional environments and have different depositional histories. It has been recognized that the mechanical properties of soil are strongly influenced by the composition of clay minerals and existing environmental conditions both during and after sedimentation [17]. Literature such as [18] explains why most of the widely used empirical equations developed from a particular soil deposit cannot be used in other soil deposits. Due to these reasons, there is a need to develop a separate correlation that predominantly deals with Bangkok clay, which has been accomplished in this research. Furthermore, all past research in SDS or SWS [2-4, 8, 10, 11, 13] have either developed empirical equations or used finite element modeling [10], but there exists no analytical equation to support the empirical equation. This research has attempted to introduce an analytical equation based on the shape of soil that is sheared by the SDS screw head. It also explains the shearing mechanism of soil when the SDS screw head penetrates into the soil and compares this with the shearing mechanism of different tests such as FVT, CPT, and UC. Furthermore, the past research deals with the standard form of SDS machine, however, in this research, the SDS equipment is customized such that the penetration ability is highly increased. This supports the use of SDS in deeper soil layers.

2. RESEARCH SIGNIFICANCE

The main purpose of this research is to develop empirical correlations to use in pile driving. The common construction practice in Bangkok clay requires a pile foundation, the depth of which depends upon the type of superstructure. For residential houses, the pile can rest over stiff-to-very-stiff clay as shown in Fig. 1. FVT and conventional SDS can only explore soil profiles up to soft to medium-stiff clay. The target depth of exploration of the customized SDS is up to the first sand layer, where the piles of the slightly heavier structures rest. The undrained shear strength and SPT number of blows (N) are the two most important parameters of interest, which can be estimated directly from correlations developed in the current research.

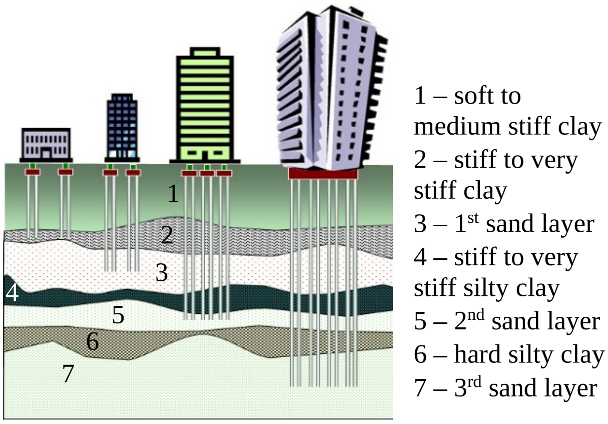

Fig. 1 Required depth of pile foundations during construction in Bangkok according to the type of super-structures [19]

3. SCREW DRIVING SOUNDING

3.1. SDS Equipment

The standard form of SDS machine can penetrate only through an approximate SPT number of blows (N) —15 blows/ft [2]. This was not sufficient for the current research because the aim was to explore stiff and hard clay layers. Hence, the SDS machine was customized to increase its ability to penetrate those layers. Many studies have explained the working procedure of the machine in detail [2, 8, 9, 11, 15]. Fig. 2 illustrates the customized SDS equipment used during the current research.

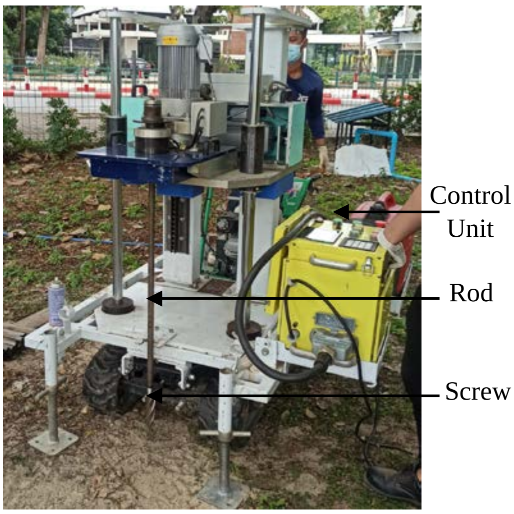

Fig. 2 Customized SDS equipment in action

3.2. SDS Penetration Resistance Parameters

Two penetration resistance parameters are mainly prevalent: average torque (T_{av}) and the total penetration energy ($E_{0.25}$). T_{av} at each 0.25 m can be defined as the average value of corrected torques to penetrate every 0.25 m. Similarly, $E_{0.25}$ can be defined as the total energy required to penetrate the screw point every 0.25 m, as described in [3].

3.3. Shearing Mechanism in SDS Compared with Conventional In-situ Tests and Anisotropy of Soil

The undrained shear strength (S_u) of clay is not a unique parameter and depends on the type of test used, the rate of strain, and the orientation of the failure planes [20]. Since this research aimed to correlate S_u and SPT N with the torque, it is necessary to understand the shearing mechanism and orientation of the failure surface in the various tests.

During SPT, the clay samples cut the soil vertically downwards using dynamic loading. Hence, the soil is sheared in the vertical direction. In the case of field vane shear test (FVT), the shearing force is applied in the form of torque [21]. Therefore, the soil shears in the radial direction, making a cylindrical shear surface [22, 23]. In FVT, the shearing of soil takes place between soil and soil, unlike for SPT, the cone penetration test (CPT), and SDS, where shearing occurs between soil and the surface of the sampler, the CPT cone, and the screw, respectively. For CPT, as the cone advances downward, the soil touches the cone and continuously shears in a direction parallel to the slant length of the cone. Since the cone tip usually has an apex angle of 60°, the direction of the shear plane of soil will be at 60° to the horizontal. However, in the case of SDS, the soil is sheared by the screw head by the vertical load and torque. Hence, the soil is sheared vertically as well as radially.

A natural soil deposit is anisotropic due to its mode of deposition which is rather one-dimensional. Several studies have been conducted on the effect of the anisotropy of soft Bangkok clays on their engineering properties [24, 25]. Bangkok clay is anisotropic and is stiffer in the horizontal direction [25]. Hence, the difference in shearing direction gives different values of engineering properties. During SPT, since the sampler shears the soil vertically, the soil properties in the vertical direction are dominant. A similar case occurs in the case of CPT on the soil around the sleeve portion, whereas for soil in the cone portion, soil properties in both vertical and horizontal directions are equally prominent. In FVT, since the soil is sheared radially, the soil properties in the horizontal direction are dominant. In SDS, soil properties in both the vertical and horizontal directions are equally important. The differences between these tests are tabulated in Table 1

4. METHODOLOGY

4.1. Study Area

4.1.1. Bangkok clay

Bangkok was covered by a shallow marine sea, resulting in soft marine clay being deposited 3,000–5,000 years ago, which gradually subsided and formed a 0–20 m thick clay layer referred to as Bangkok clay [26, 27]. The history of the formation of soft Bangkok clay deposits has been described in the literature [28].

An investigation by [16] of the pore water chemistry and mineralogy of Bangkok clay concluded that Bangkok clay can be separated into three zones: (a) an upper zone, consists of 0–2 m of weathered clay; (b) a middle zone, consisting of soft clay or marine clay; and (c) a bottom zone of medium-soft clay or intertidal clay. Below the intertidal clay, there exists a stiff-to-hard clay layer called alluvium clay. The Atterberg limits of stiff-to-very-stiff clay and the hard layer (alluvium clay) are practically almost the same but are substantially different from that of soft-to-medium-stiff clays (marine and intertidal clay) [26].

Table 1 Comparison between SPT, FVT CPT, and SDS

	Standard Penetration Test (SPT)	Field Vane Shear Test (FVT)	Cone Penetration Test (CPT)	Screw Driving Sounding Test (SDS)
Load	Dynamic	Torque	Static or dynamic	Static
Shearing device	samplers	Vane	Cone	Screw
Shearing between two surfaces	Soil and wall of sampler	Soil and soil	Soil and CPT surface	Soil and screw
The direction of shearing force	Vertical	Radial	Vertical and horizontal	Both vertical and radial
The direction of shear of soil due to anisotropy	Vertical	Horizontal	Vertical and horizontal	Vertical and horizontal

This is because alluvium clay was formed near the end of the Pleistocene epoch in a freshwater environment, while marine and intertidal clays were formed during the Holocene epoch in a marine environment [27, 29].

4.1.2. Test site

Boreholes with SPT; FVT, and SDS tests were performed in the vicinity of each other, in various parts of Bangkok province. Since the Bangkok soil deposit is itself uniform, homogeneous, and consistent, it is particularly easy to control the tests.

4.2. Soil Properties

Table 2 summarizes the various soil parameters obtained and used in this research, along with the total number of tests performed.

Table 2 Soil properties and number of tests performed

Soil property	Number of tests
Undrained shear strength from unconfined compression (UC) test	64
Undrained shear strength from unconsolidated undrained (UU) test	60
Undisturbed undrained shear strength from FVT	68
SPT number of blows	52
Natural moisture content	105
Unit weight	104
Consistency index (CI)	105

The CPT test was performed on the test site to obtain better information on the soil profile. Fig. 3a and 3b show the tip resistance and sleeve friction profiles of the test site, respectively. The profile of undrained shear strength (S_u) of the study area is shown in Fig. 3c. The undrained shear strength in the plot has been obtained from the UC test in the laboratory for soft clays and from SPT for stiffer clays. Fig. 3d shows the natural moisture content (W_n) along with the PL and LL values of the clay samples from the laboratory tests. The LL and PL values of the marine and intertidal clays are grouped as one and alluvial clay is grouped as another class. The marine and intertidal clays have softer consistency, with low undrained shear strength and high moisture content. The alluvium clay layer underlying this layer has stiffer consistency, which is characterized by higher undrained shear strength and lower moisture content. Large variation in their W_n and S_u values results in distinct differences between their properties.

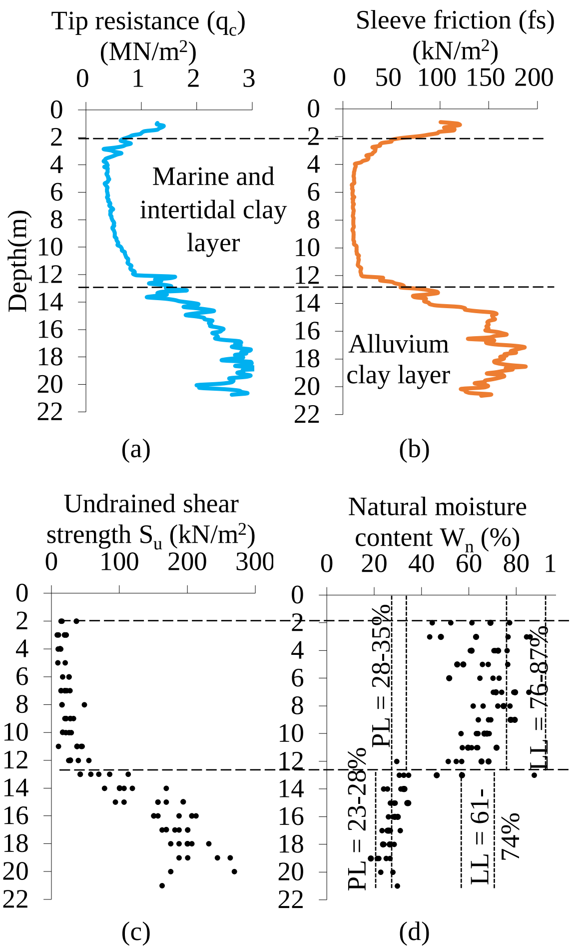

Fig. 3 a) Profile of CPT tip resistance (q_c) on test site, b) Profile of CPT sleeve friction (f_s) on test site, c) Profile of undrained shear strength (S_u) with depth, d) Profile of natural moisture content on test site indicating liquid limit (LL) and plastic limit (PL) ranges of each type of soil layer

RESULTS AND DISCUSSION

4.3. Deterministic Equation for Determination of Undrained Shear Strength of Clay from SDS Torque

The SDS screw is a tapered screw with 4 helices. However, when rotated on its vertical axis, it creates a shear surface by stiffer clays sticking on the helical depression and filling the voids on the screw. In simpler form, this shear surface can be assumed to be assembled shapes of a frustum on the top, then a cylinder and a frustum in the middle and cone on the bottom, as shown in Fig. 4. However, this is an approximation, and the real shear surface may indeed be along the helix.

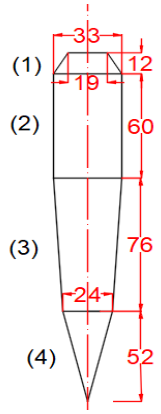

Fig. 4 SDS screw point depicted in simplified form, with dimensions in millimeters.

The torque (T) required to penetrate through the soil is equal to the sum of resisting moments from each shape (M_1–M_4), and a 5 cm rod portion (M_5). All SDS parameters, such as torque, are measured by the SDS machine as an average over the 0.25 m length; however, the length of the screw point is just 0.2 m. Hence, it is necessary to include the resisting moment from the rod with a length of 0.05 m.

The uppermost part of the screw is a frustum. The resisting moment due to shape 1 (M_1) is the force multiplied by the perpendicular distance for the shape (1) of Fig. 4. Let, r_u be the upper radius of the frustum, r_l be the lower radius of the frustum, h be the height of frustum, and r_p be the average perpendicular distance. Hence, M_1 can be written as:

M_1 = Force × Perpendicular distance

= (S_u× Surface area of frustum) × Average perpendicular distance

$$= S_u \times \{\pi \times (r_u + r_l) \times \sqrt{(r_u - r_l)^2 + h^2}\} \times r_p$$

$$= S_u \times \{\pi \times (0.0095 + 0.0165) \times \sqrt{(0.0095 - 0.0165)^2 + 0.012^2}\} \times 0.013$$

$$= S_u \times 1.5 \times 10^{-5}$$

Similarly,

$$M_2 = S_u \times 1.026 \times 10^{-4}$$

$$M_3 = S_u \times 6.66 \times 10^{-5}$$

$$M_4 = S_u \times 1.04 \times 10^{-5}$$

$$M_5 = S_u \times 3.8013 \times 10^{-5}$$

The total torque (T) is: $T = M_1 + M_2 + M_3 + M_4 + M_5$

i.e., $T = S_u 2.4 \times 10^{-4}$ (1)

i.e., $S_u = 4166 \times T$ (2)

where, T = average torque obtained by SDS machine in Nm and S_u = undrained shear strength in N/m^2.

4.4. Empirical Correlation between Undrained Shear Strength (S_u) and Average Torque (T_{av})

From the borehole tests, clay samples were obtained. The S_u values of those samples were obtained from the UC test and the UU tri-axial test. From the FVT, the undisturbed undrained shear strength was obtained. These were correlated separately to T_{av} obtained from the SDS test at the same depth. The correlation between S_u from the UC test and T_{av}, as well as the upper and lower prediction intervals are shown in Fig. 5.

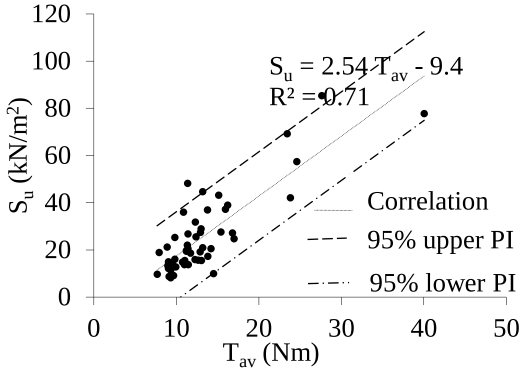

Fig. 5 Relationship between the undrained shear strength (S_u) from UC test and torque (T_{av})

The correlation equation between S_u from the UC test and T_{av} is written as:

$$S_{u,UC} = 2.5 \times T_{av} - 8 \quad (3)$$

The upper and lower prediction interval bands are written in Eq. 4 and 5 respectively:

$$S_{u,UC,95\%\ upper} = 2.5 \times T_{av} + 8.9 \quad (4)$$

$$S_{u,UC,95\%\ lower} = 2.5 \times T_{av} - 26.73 \quad (5)$$

The S_u of the clay samples determined in the laboratory based on the UU triaxial test were correlated with the corresponding value of T_{av}, as in Fig. 6.

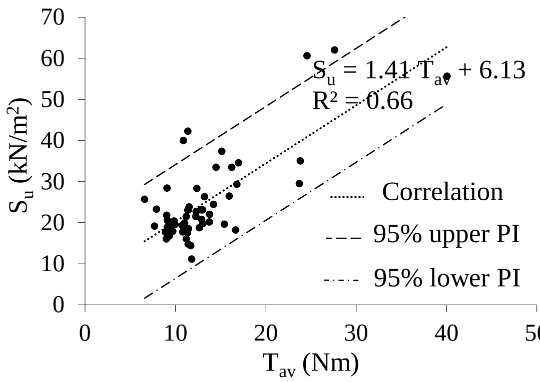

Fig. 6 Relationship between undrained shear strength (S_u) from UU test and torque (T_{av})

The correlation equation between the S_u of clay samples with T_{av} is presented in Eq. 6:

$$S_{u,UU} = 1.41 \times T_{av} - 6.13 \quad (6)$$

The upper and lower prediction intervals of the equation are presented in Eq. 7 and 8, respectively:

$$S_{u,UU,95\%\ upper} = 1.41 \times T_{av} - 20.55 \quad (7)$$

$$S_{u,UU,95\%\ lower} = 1.41 \times T_{av} - 8.28 \quad (8)$$

The undisturbed S_u of clay was determined from the field FVT and correlated with T_{av}, with the result shown in Fig. 7. This value of undisturbed S_u used in the plot was not adjusted by any correction factor so that the designers have the freedom to use the correction factor of their choice.

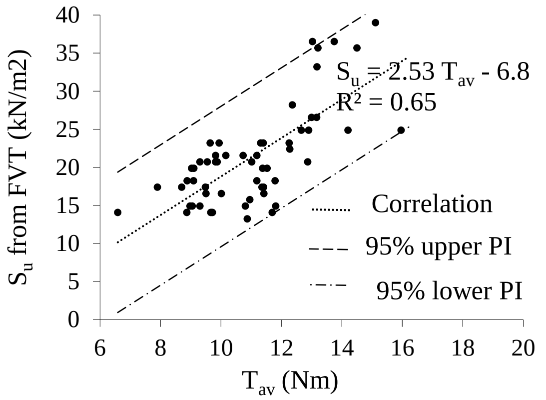

Fig. 7 Relationship between undisturbed undrained shear strength (S_u) from FVT test and torque (T_{av})

The correlation equation between S_u of clay samples with T_{av} is presented in Eq. 9:

$$S_{u,FVT} = 2.53 \times T_{av} - 6.5 \quad (9)$$

The upper and lower prediction intervals of the Eq. 9 are presented in Eq. 10 and 11, respectively:

$$S_{u,FVT,95\%\ upper} = 2.53 \times T_{av} - 2.72 \quad (10)$$

$$S_{u,FVT,95\%\ lower} = 2.53 \times T_{av} - 15.7 \quad (11)$$

As the S_u value of the clay increases, its resistance to externally applied force increases. This requires greater torque for penetration, which is the same in all three cases. To better understand the differences among these three correlation equations, they are plotted together, as shown in Fig. 8.

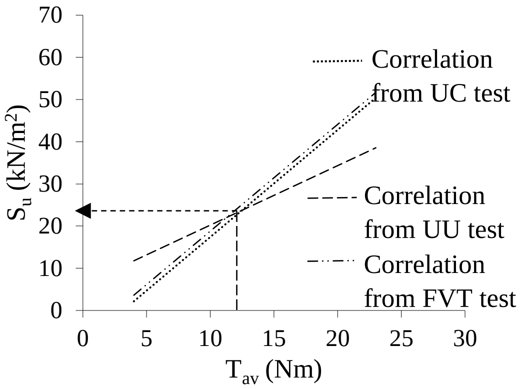

Fig. 8 Correlation between torque (T_{av}) and undrained shear strength (S_u) obtained from UC, UU, and FVT tests

The S_u parameter of clay is not unique and depends substantially on the type of test used, the rate of strain, and the orientation of the failure planes [25]. Hence, the correlations between average values of SDS torque and Su obtained from the UC test, UU test, and FVT tests are different.

The correlations between the torque and S_u obtained by UC and UU test were substantially different. The correlation from the UU test indicated a higher S_u value for clay (S_u lower than 25 kN/m^2) compared to that from the UC test. Clays having S_u below 25 kN/m^2 are soft clays. In the UU test, the sample is subjected to a confining pressure, due to which, S_u is greater than from the UC test, which has no confining pressure. However, in stiffer clays, the effect due to the confining pressure does not make the sample prominently stiffer than it is, since it already is stiff. Unlike in the UC test, the sample in the UU test is first saturated, which increases W_n in the sample. Clearly there is a smaller S_u for soil with a higher W_n. Stiffer soils have a lower W_n and a small increase in W_n largely decreases the soil strength as it becomes softer. The same situation will not be true for soft clays. Soft clays already have a higher W_n and a further increase in W_n will not have an equally important effect on their strength. In addition, W_n for soft clays having S_u less than 25 kN/m^2 are near their liquid limit. W_n of medium stiff and stiff clays is substantially less than the liquid limit and lies midway between the plastic and liquid limits. So, due to saturation of the sample in the UU test, when W_n of stiffer clays is increased, it approaches near the liquid limit or might even exceed it, thus decreasing the strength of the clay sample and hence decreasing the required torque. In contrast, since W_n in soft clays is already near the liquid limit, an increase in the water content will not substantially decrease its strength.

According to [25], Bangkok soil is anisotropic and is stiffer in the horizontal direction, indicating that S_u in the horizontal direction can be expected to be higher than in the vertical direction. The shear surface during the FVT test is radial and the S_u of soil is from the horizontal direction. In contrast, in the UC test, the failure surface is at an angle of 45° to the horizontal, indicating that the S_u, in that case is contributed from the horizontal and vertical directions. Hence, S_u from the FVT test is higher than from the UC test. In addition, the sample in the UC test is disturbed during transportation and handling and loses W_n, while it is undisturbed and W_n is preserved during the FVT test. Consequently, it would be expected for the laboratory-determined S_u to have a lower value than that obtained in the field using the in-situ tests. While using correlation equations to estimate the S_u of clay, it is best to use the one obtained from the FVT test as it excludes the soil disturbance as well as any loss in W_n in the sample.

These empirical equations developed above are for marine or intertidal clays, with soft to a stiff consistency, formed during Holocene Epoch. However, the correlation between the undrained shear strength and SDS torque in [14] consisted of Japanese alluvium clay, alluvium silt, and peat, indicating that there were variations in the clay sample. The past research equation also contains a lesser number of samples compared to this research. In addition to this, since there are differences in mineralogy, micro-structure, depositional environment, and history of the formation of Bangkok clay layers, previous equations cannot give an accurate result. For the application of the SDS technique on sites with Bangkok clay, the equations developed in this research give better and more relevant results.

4.5. Empirical Correlation between SPT Number of Blows (N) and Average Torque (T_{av})

SPT is one of the most popular in-situ tests globally. Many equations have been developed between various engineering soil properties and SPT N. The ability to estimate N directly from the SDS parameter will increase the usefulness of the SDS test results to relate to numerous engineering properties of soil. This research attempted to estimate the number of blows required for stiff-to-hard clay directly from the SDS penetration resistance. Fig. 9 indicates the relation between the N value and average SDS torque and is presented in Eq. 12:

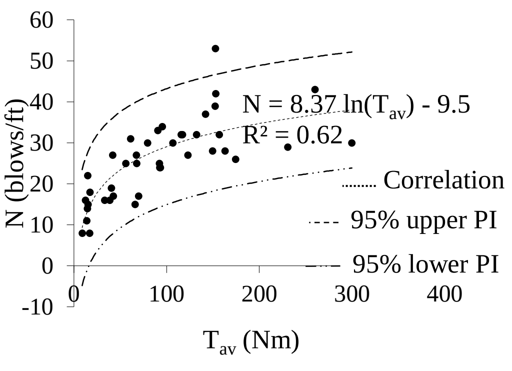

Fig. 9 Relationship between SPT blow count (N) and penetration energy ($E_{0.25}$)

$$N = 8.15 \times ln(T_{av}) - 8.48 \quad (12)$$

The equations for the 95% upper and lower prediction intervals are presented in Eq. 13 and 14, respectively:

$$N_{95\%\ upper} = 8.15 \times ln(T_{av}) + 5.7 \quad (13)$$

$$N_{95\%\ lower} = 8.15 \times ln(T_{av}) - 22.6 \quad (14)$$

A higher number of blows in clay indicates that it is stiffer, denser, and harder, which make it difficult for the screw point to penetrate and thus requiring a greater amount of torque. The scatter in the plot in Fig. 9 is due to the difference in the shear surface between these tests, as well as the difference in the penetration mechanism between the SPT and SDS tests (SPT applies dynamic loading whereas penetration in SDS is by static loading).

The derived equation is applicable only to clays with stiff-to-hard consistency, namely alluvium clay formed during the Pleistocene epoch, and is not applicable to any marine and intertidal clays. In addition, the average torque is used in this equation, unlike in past research where penetration energy ($E_{0.25}$) was used. The equation developed to estimate the SPT N from SDS $E_{0.25}$ from [2] only deals with sand. Tanaka et al. [3] developed a correlation between SPT N and $E_{0.25}$ which was a linear equation. The data from clay, silt, sand, organic silt, and loam of Japanese alluvium clay was used. The data from sand have a significant effect on this equation. Also, the clay samples used are only soft clays. However, the equation developed in this research, as shown in Eqn. 12 is a logarithmic equation, which comprises only clays with stiff to hard consistency i.e., alluvium clay, formed during Pleistocene Epoch and avoids any soft to medium stiff clays and does not contain sand or organic soil. In addition, the mineralogy, microstructure, and depositional environment of Bangkok clay are different from alluvium clay. Eq. 12 exclusively deals with the Bangkok clay deposit. The equation developed in this research gives more reliable results when tests are performed for the Bangkok clay deposit.

4.6. Consistency Index (CI)

CI plotted with $E_{0.25}$ is shown in Fig. 10.

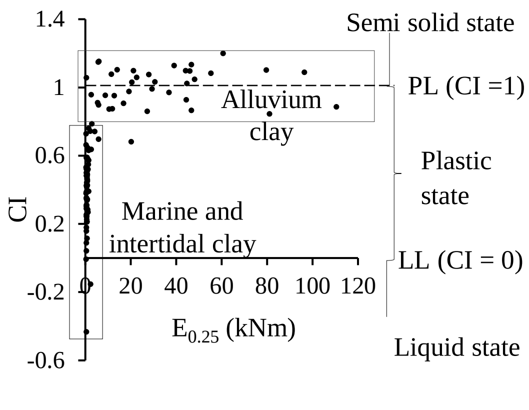

Fig. 10 Variation of penetration energy ($E_{0.25}$) with consistency Index (CI)

CI indicates the degree of firmness, which depends on W_n of clay. $E_{0.25}$ increases greatly with a decrease in W_n and an increase in the CI of the clay. Clay samples in the plot can be divided into two distinct groups. The clay with a CI below 0.8 is soft-to-medium in stiffness and is a marine or intertidal clay formed in the Holocene epoch in a saline environment. Such clays have a CI value less than 1 and some are even below 0, indicating they are in the liquid or plastic states. A small amount of penetration energy is sufficient to penetrate the clay. A further increase in W_n in these clay layers would not have a profound change in the state and a similar penetration energy is required to penetrate through these clays.

However, clay soils having a CI value higher than 0.8 are stiff-to-hard. They are alluvium clay and were deposited in the Pleistocene epoch in a freshwater environment, and were formed earlier than the overlying layer of the Bangkok plain. It has CI values of more than 1 or almost approaching 1, indicating they are either in the semi-solid state or have just entered a plastic state. They are dry and stiff and require more penetration energy to disintegrate the lump when SDS screw penetrates through it. Penetration energy is very sensitive to the natural moisture content of this layer, since the addition of the slightest amount of moisture can change or have a major effect on its state, resulting in substantially less energy for successful penetration.

The marine and intertidal clays are in a liquid state or even if they are plastic state, their natural moisture content is high enough to remain near to the liquid state. On the other hand, the alluvium clays are either in the semi-solid state or even if they are in the plastic state, their moisture content is so low that it is near to their plastic state.

5. CONCLUSION

The empirical equations are developed to estimate the values of S_u and SPT N of various deposit of Bangkok Clay. These are supported by the analytical equation which is derived based on the shape in which the soil shears when SDS screw head is penetrated into the soil. The conclusions are summarized as follows:

1. The correlation equations between SDS torque and S_u obtained from UU and UC tests have been developed for the soft marine and intertidal clay deposited during the Holocene epoch.
2. Different correlation equations to estimate the S_u from SDS torque from various tests such as UU, UC, and FVT are different from each other. This is because of the difference in the shearing mechanism of soil during failure.
3. The correlation between SPT N and torque specifically deals with alluvium clay deposited on the Pleistocene deposit.
4. The state and consistency of clay vary depending on the depositional history in the case of Bangkok clay layers. The marine clays and intertidal clays have W_n values near their liquid limits, whereas alluvium clay has W_n values close to the plastic limits or even less than the plastic limits. Hence, the penetration energy is either highly sensitive or insensitive to the W_n based on the depositional history, respectively.
5. An analytical equation is derived to estimate the S_u value of clay from the torque. This is derived based on the shearing mechanism of soil when the SDS screw is penetrated into the soil.

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