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Article

Soil Strength Estimation Using Screw Driving Sounding (SDS) Technique for Bangkok Clay Layers Considering Depositional History

Suttisak Soralump [1,*], Avidha Shah [2], Thapthai Chaithong [1], Go Sakai[3] and Tirawat Boonyatee[4]

[1*] Geotechnical Engineering Research and Development Centre, Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand; soralump_s@yahoo.com ; thapthai.c@gmail.com
[2] Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand; avidha.s@ku.th
[3] Japan Home Shield Corporation, Geoengineering laboratory, 17F, Ryogoku City Core,2-10-14, Ryogoku, Sumida-ku, Tokyo 130-0026 Japan; go.sakai@j-shield.co.jp
[4] Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand; tirawat.b@chula.ac.th
* Correspondence: soralump_s@yahoo.com

Abstract: Screw Driving Sounding (SDS) test is a new technique, which could be adopted as an alternative technique for in-situ field characterization. This research has attempted to determine the undrained shear strength of clay directly from SDS torque. It also aims to develop correlation equations between SDS torque, with undrained shear strength from various tests and Standard Penetration Test (SPT) number of blows, in Bangkok clay separately. Number of borehole tests with SPT were conducted in central region of Bangkok. SDS tests and Field vane shear test (FVT) tests were performed in vicinity of these boreholes. All field tests were performed in a highly controlled environment. The confining stress and saturation of sample during unconsolidated undrained test and anisotropy of Bangkok clay affects correlation equations. Plots of SDS penetration energy with natural moisture content and consistency index show that clays can be clustered in two distinct groups based on its state and consistency. The SDS penetration resistance parameters are extremely affected by difference in state of clay, which is dependent on the soil depositional history and depositional environment, in case of Bangkok clay layers. This demands development of the separate correlation equations solely applicable for Bangkok clay, which is accomplished in this research.

Keywords: geotechnical testing, Screw Driving Sounding (SDS), Bangkok clay, soil strength, formation history, correlation

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1. Introduction

There numerous methods for site investigation, some of the general tests are Standard Penetration tests (SPT), Field Vane Shear Test (FVT) and Swedish Weight Sounding (SWS) test. All tests have their own limitations. Although SPT is still popular worldwide, it suffers from many disadvantages such as poor repeatability and no continuous soil profile [1]. Various empirical equations are required in order to find the undrained shear strength of soil from SPT blows [2-5] and there exists uncertainties in those equations as well as confusion in which one to prefer. In addition, it is relatively expensive compared to FVT and SWS. FVT can be used to determine the undrained shear strength [6]. However, its application is limited to soft and silty soils. There is no direct formula which can convert field torque to undrained shear strength and rather a correction factor is required like Bjerrum et al. [7] and Chandler et al. [8]. In addition, continuous soil profile cannot be obtained by FVT. It is important to obtain continuous soil profile so that even thinnest layer of weak or soft soil can be identified. In such case, development of options for in-situ tests can give significant contribution in site investigation. SWS test is one of the options when continuous soil profile is desired [9]. SWS was officially recommended as an investigation tool by the Ministry of Land, Infrastructure and Transport, Government of Japan [1,9]. In 2020, the name of SWS in Japan was changed from Swedish weight sounding to Screw weight sounding due to revision of Japanese Industrial Standards (JIS). There exist various limitations of SWS, which have been discussed in various literatures [10-12]. It is highly labour intensive and particularly becomes more difficult as we go deeper due to increase in repellent force. It classifies silt and organic soil as cohesive soils [12]. In addition to that, the result of SWS is highly influenced by the rod friction, but there is no provision to measure it; making the results unreliable. The value of rod friction is significantly high especially when earth fill consists of gravel resulting in overvaluation of estimate [12]. Also, since the SWS test does not use the soil sampling, the result highly depends upon the knowledge of examiner and the local site conditions. Hence due to these several limitations of SWS, there was a need to develop a field test technique and a field test machine which possessed the major advantages of the SWS yet, was rid of its serious disadvantages. Thus, Screw Driving Sounding (SDS) machine is developed as a new method for site characterization which is a modified form of SWS [11,12].

The SDS test is one of the alternatives for site characterization by in-situ geotechnical tests. The test is quick and relatively cheap and gives continuous soil profile like SWS [1,11,12]. It occupies smaller space for operation, making it ideal field characterization technique in congested areas similar to CPT. Larger number of site investigation points gives better understanding of soil profile and soil properties. SDS can be used together with other tests to obtain greater number of soil exploration points. It is economical option when area of soil exploration is large, since the number of exploration points can be increased by using SDS test. For the soil exploration, there is a need of development of equations which can determine the undrained shear strength or SPT blows of the Bangkok clay directly from SDS parameter.

The central region of Thailand is the soft marine deposit formed due to interaction of Chao Phraya river and sea level change during Holocene period [13]. It is the immediate subsoil layer in Chao Phraya River basin and typically has very low undrained shear strength and high moisture content. It is mostly either in liquid or plastic state. The underlaying layer is stiff clay whose engineering properties is completely different that of soft marine clay. It has low moisture and clay is either in semi-solid state or plastic state, with moisture content very near to plastic limit. This layer was formed in Late Pleistocene period in fresh water environment [13,14]. The topmost 2m layer was exposed to the atmospheric environment for a long period of time which resulted this layer to weather and have relatively higher undrained shear strength and lower moisture content than underlying soft marine clay [15]. Numerous researches have been performed in properties of Bangkok clay deposit.

However, there is lack of equations to determine the undrained shear strength of clay directly from SDS parameters in Bangkok clay. Though there are empirical formulae developed in Japanese alluvial clay as in Tanaka et al.[12] and Yoshida et al. [16], this cannot be used in soft Bangkok clay. This is because the Japanese alluvial clay and soft Bangkok clay have different mineralogy and microstructure which results in difference in their geotechnical properties [17,18]. In addition, these two clays were formed in different depositional environment and have different depositional history. 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 [18]. Some literatures such as Tanaka et. al. [19] explain reason why most of the widely used empirical equations developed from a soil deposit cannot be used in other soil deposit.

Due to these reasons, there is an urge to develop separate correlation which particularly deals with Bangkok clay.

2. Materials and Method

2.1. Screw Driving Sounding (SDS)

The screw driving sounding technique of in-situ field characterization is the improvised form of the Swedish Weight Sounding technique. A typical SDS machine consists of a screw point attached to a rod, which is attached to a rod rotation motor, responsible for penetration into the soil layers. The principal of operation of SDS is same as that of SWS, which is; the screw point attached to the rod is penetrated into the into the ground by the help of fixed weights and torque [1,9]. However, the working procedure is slightly different. In case of SWS, the vertical load and torque are applied separately and referred to as static penetration and rotational penetration respectively [9]. While, in case of SDS, both vertical load and torque are applied simultaneously for penetration. There exist several empirical equations such as Inada et al. [20], Miki et al. [21] and Ueda et al. [22], which correlates the penetration resistance of SWS with soil properties such as SPT-N and uniaxial compressive strength.

The standard form of SDS machine can penetrate only through approximate SPT N value of 15 [1]. This is not sufficient for this research as we attempt to explore stiff and hard clay layers, underlaying the soft clay layer, whose number of SPT blows are way more. Due to this reason, the SDS machine was customized such that higher values of vertical load and torque can be applied. This increases its ability to penetrate on deeper and stiffer soil layers. Figure 1 shows schematic diagram of the screw point of SDS machine where all dimensions are in millimetres.

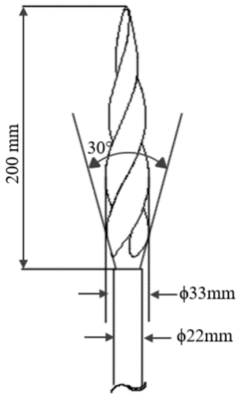


Figure 1. Schematic diagram of screw point of SDS machine

2.1.1 The Procedure of SDS test

While the standard form of SDS machine uses 7 steps of loading [1,10,11,23], the customized machine uses 20 steps of loading with maximum 2.3 kN load. The screw is penetrated with starting load of 0.05 kN. Load is increased by adding 0.05 kN after each complete rotation of rod, for each of the next loading step, until the vertical load of 0.25 kN is achieved. Then increased by 0.125 kN until the total vertical load reaches 2.3 kN or penetration depth of 0.25 m, whichever is encountered first. Various SDS parameters are recorded at the end of each complete rotation, which are; minimum torque (T_{min}), average torque (T_{avg}), maximum torque (T_{max}), penetration velocity (V), number of rotations of rod (N) and penetration length (L) [1,10,11,23]. Plenty of other SDS parameters can be calculated out using these parameters. When a penetration depth of 0.25 m is achieved, the screw point goes up by 0.02 m and makes one full rotation to measure the rod friction, and comes back to the original position and another cycle of penetration starts. The penetration is continued till the required depth of exploration. In case 0.25 m of penetration depth is not achieved even at 2.3 kN load, the penetration is continued at 2.3 kN load until 0.25 m and the load required to penetrate 0.25 m is calculated by extrapolating the trend line.

2.2. Background of research on correlations between soil Engineering properties and SDS parameters

Correlation equation between uniaxial compressive strength and SDS torque has been developed in Japanese alluvium clay [16]. The uniaxial compressive strength was determined by unconfined compression test. The correlation between undrained shear strength and SDS torque is then obtained by dividing the equation by 2. The correlation equation between the uniaxial compressive strength and Torque as below:

$$q_u = 3.6801 \times T_0 + 14.346 \quad (1)$$

Which gives,

$$S_u = \frac{q_u}{2} = 1.8 \times T_0 + 7.15 \quad (2)$$

Where

S_u = Undrained shear strength of alluvial clay deposit

q_u = Uniaxial compressive strength

T_0 = Torque

The depositional history of Japanese alluvium clay and Bangkok clay is different. The mineralogy, microstructure and properties of these two clays has huge variation [17,18]. Due to this reason, these equations 1 and 2 may not give accurate results when applied for Bangkok clay. Development of a correlation designed specifically for Bangkok clay would be helpful for determination of undrained shear strength for this area.

Tanaka et al. [12] developed equation between the penetration energy ($E_{0.25}$) and SPT number of blows (N) as follows;

$$E_{0.25} = 0.268\, N \quad (3)$$

Where,

$E_{0.25}$ = average penetration energy

N = SPT number of blows

The data used to obtain equation 3 are clay, silt, sand, organic clay, loam, which indicates that the equation is developed from various types of soil data. Thus, this may not give trustworthy result when applied for Bangkok clay, which demands the need of development of an empirical equation especially made of the Bangkok clay.

2.3. SDS Penetration Resistance Parameters:

Various SDS parameters are obtained during the SDS test. Among many of those parameters, the ones which are used in this research are the average torque and penetration energy, both of which are penetration resistance and are thoroughly explained as follows:

2.3.1. Average Torque (T_{av}):

The average torque is denoted by T_{av} and can be defined as the average value of corrected torques of various number of loading steps to penetrate 0.25 m. It can be expressed mathematically as:

$$T_{av} = \frac{1}{n} \times \sum_{i=1}^{n} T_i \quad (4)$$

Where;

n = number of loading steps required to penetrate 0.25 m

T_i = Corrected torque at i^{th} loading step

T_{av} = parameter is influenced by both applied torque as well as vertical load.

2.3.2. Total Penetration Energy ($E_{0.25}$):

Total energy to penetrate the screw point by 0.25 m is designated by $E_{0.25}$. Tanaka et al. [12] described penetration energy at the end of each loading step can be defined as;

$$\delta E' = 2\pi r T \frac{\delta n_{st}}{2} + W\delta s_t \quad (5)$$

Where, T is corrected torque, δn_{st} is incremental half turns, W is corrected load and δs_t is incremental settlement due to load.

The total penetration energy can be written as

$\sum E = \sum \delta E_i'$

Where i is number of loading steps required to penetrate 0.25 m.

$\sum E$ is the sum of penetration energy of every incremental load step, which is the penetration energy required for 0.25 m penetration, i.e., $E_{0.25}$.

2.4. Shearing Mechanism in SDS Compared with Other Conventional In-situ Tests and anisotropy of soil

This research aims to correlate the undrained shear strength and SPT blow counts with the SDS parameters. It thus becomes necessary to understand the shearing mechanism in various tests, because the value of undrained shear strength is also affected by orientation of failure plane. Various prevalent in-situ tests are conducted to obtain the undrained shear strength of soils. Evaluation of undrained shear strength in clays can also be performed by cone penetration test (CPT) [24,25]. The undrained shear strength of clay is not a unique parameter and depends significantly on the type of test used, the rate of strain, and the orientation of the failure planes [24]. So, it is necessary to consider the orientation of failure surface on each test.

In case of SPT, the clay samples are obtained by use of certain sampler. The sampler penetrates the soil and cuts it vertically using dynamic loading. Since the direction of applied force is vertically downwards, the soil is sheared in vertical direction as indicated by the direction of penetration of sampler as in figure 2a [3]. In case of field vane shear test, the vane is inserted into certain depth and the shearing force is applied in the form of torque [26]. The soil hence shears in radial direction as indicated in figure 2b, making a cylindrical shear surface [27,28]. The shearing plane in this case is not similar to that of SPT, but is totally different and rather cylindrical in shape. In case of FVT, the shearing of soil takes place between soil and soil unlike SPT, CPT and SDS where shearing occurs between soil and the surface of sampler, CPT cone and screw respectively. For CPT, as the cone advances below, the soil touches the cone and continuously shears in direction parallel to the slant length of cone as indicated in figure 2c. Since the cone tip usually has apex angle of 60°, the direction of shear plane of soil will be at 60° with horizontal. However, in case of SDS, the soil is sheared by application of vertical load as well as torque. The screw head is responsible to shear the soil, which contains 4 helices. Hence, the soil is sheared in vertical as well as radial direction as depicted in figure 2d. This shear direction in case of SDS test is unique due to the presence of helices in screw point and combination of vertical and rotational loads. Figure 2 shows the direction of shear in various popular in-situ tests. The direction of arrow in each figure shows the direction of shear of soil.

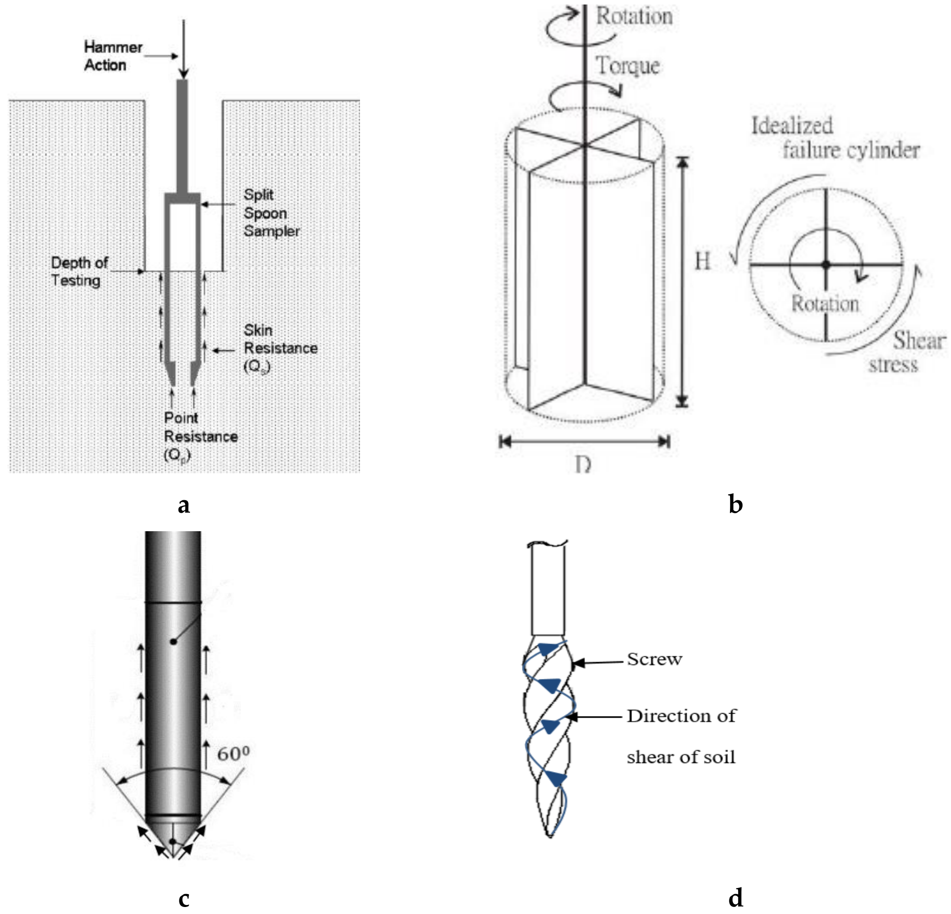


Figure 2. Direction of shear of soil in **a** Standard penetration test [3], **b** Field vane shear test [26], **c** Cone penetration test, **d** SDS test

Natural soil deposit is anisotropic in nature due to its mode of deposition which is rather one dimensional. Several studies have been conducted on the effect of anisotropy of soft Bangkok clays on its Engineering properties [29,30]. Bangkok clay is anisotropic and is stiffer in horizontal direction [30]. The Engineering properties of Bangkok clay in vertical direction is different than that in the horizontal direction. Hence, the difference in shearing direction gives different values of those properties. During SPT, since the sampler shears the soil vertically, the soil properties in vertical direction is dominant. In contrast, during FVT, since the direction of shear is radial, the soil properties in horizontal direction is dominant. Similar case as in SPT occurs in case of CPT, on the soil around sleeve portion. Whereas for soil in cone portion, soil properties in both vertical and horizontal directions are equally prominent. In case of SDS, the screw rotates as well as penetrates vertically downwards, so, the soil properties in both vertical as well as horizontal direction are equally significant. This case is the combination of shearing mechanism of FVT and SPT and it is completely different than that for the cone of CPT. This is because in case of CPT, no torque is applied and hence no radial shear of soil is present. In order to study the difference of anisotropy between Bangkok clay and Japanese clay, Tanaka et al. [18] defined the strength anisotropy by undrained shear strength ratio of the extension and compression strengths from the recompression triaxial test (S_{ue}/S_{uc}). For Japanese marine clays, this ratio increased with an increase in plasticity index, whereas, for the Bangkok clays, it is relatively high despite the moderate value of plasticity index [18]. The differences between SPT, FVT, CPT and SDS tests are tabulated in table 1.

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 (SDS) Test
Load	dynamic	torque	Static or dynamic	static
Shearing device	Various types of samplers	Vane	Cone	Screw
Shearing between two surfaces	Soil and wall of sampler	Soil and soil	Soil and CPT surface	Soil and screw
Direction of shearing force	Vertical	Radial	Vertical and 60° to horizontal	Both vertical and radial
Direction of shear of soil due to anisotropy	Vertical direction	Horizontal direction	Vertical and horizontal direction	Vertical and horizontal direction

2.5. Soft Bangkok Clay

Bangkok clay is a typical marine deposit with non- pyroclastic origin distributed in the Chao Phraya plain of central Thailand [17]. The history of formation of soft Bangkok clay deposit has been described by past research [31]. Bangkok was covered by shallow marine sea. The soft marine clay was deposited 5000-3000 years ago which gradually subsided and formed 0-20m thick clay layer referred to as Bangkok clay [14,32]. The uppermost 2m of soft clay was exposed to the surface and weathered for over 2700 years [33]. Due to this, the chemical and mineralogical characteristics of the sediments were altered.

Ohtsubo et al. [17] invested the pore water chemistry and mineralogy of Bangkok clay and concluded that Bangkok clay can be separated into three zones: (a) upper zone which consists of 0-2m of weathered clay, (b) middle zone consisting of soft clay or marine clay and (c) bottom zone of medium soft clay or intertidal clay. Below the intertidal clay, there exist very stiff to hard clay layer called alluvium clay. The surface and deeper zones were deposited on less marine environment than the middle layer. Atterberg's limit (liquid limit and plastic limit) of stiff to very stiff and hard layer is almost practically similar. But this highly differs from the Atterberg's limit of soft to medium stiff clays [32]. This is because, stiff to very stiff and hard layers (alluvium clay) were formed near the end of Pleistocene Epoch in fresh water environment, while soft to medium stiff clay (marine and intertidal clay) was formed during Holocene Epoch in marine environment [13,14]. Figure 2 shows the profile of these deposits along with their deposition period.

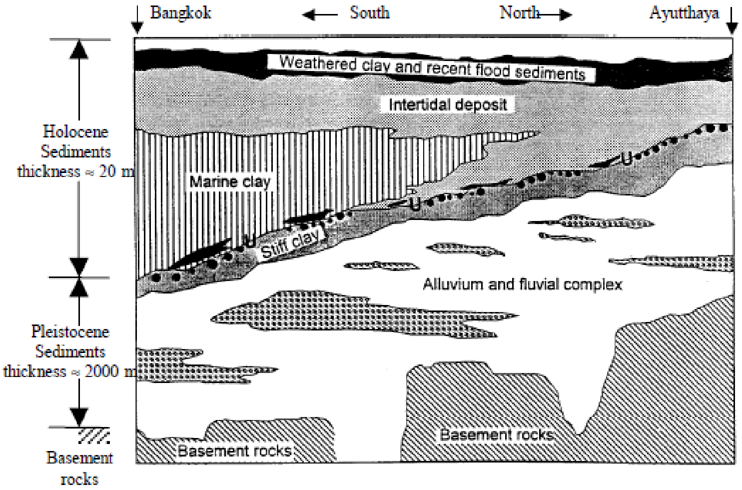


Figure 3. Composite stratigraphic succession of unconsolidated sediment in Lower Central Plain [13]

There have been numerous studies on Engineering properties of soft Bangkok clay in [34-36]. Oonchittikul [37] gave the values of range of properties of soft Bangkok clay, which are arranged in tabular form in table 2.

Table 2. Range of values of Engineering properties of Bangkok clay [37]

Clay layer	**Natural moisture content (%)**	**Undrained shear strength (kN/m2)**	**Total unit weight (kN/m3)**
Weathered clay	30-100	20	16-19
Soft clay	40-110	6-27	15-18
First stiff clay	15-40	30-270	18-22

Luckily, Bangkok clay layers by their nature itself, are quite homogeneous and have consistent soil properties. Figure 4a and 4b shows the profile of undrained shear strength and natural moisture content of soft Bangkok clay respectively. The undrained shear strength has been obtained by unconfined compression test. It can be observed in these figures that there are two unique characteristics of clays. The first layer lying immediately below the ground level refers to clays with softer consistency, with low undrained shear strength and high moisture content. They are either in liquid state or even if they are plastic state, their natural moisture content is high enough to remain near to the liquid state. They are marine and intertidal clays formed in Holocene epoch. These clays have uniform and consistent characteristics. The soil layer underlying this layer is stiffer clay which is characterized by higher undrained shear strength and lower moisture content. They are either in semi solid state or even if they are in plastic state, their moisture content is so low that it is near to their plastic state. Hence, they are of stiff to hard consistency. They are intertidal clays formed in Pleistocene epoch, and have consistent and uniform soil properties in themselves. The environment of deposition; marine and fluvial has direct effect on the property of soil even when the sediments are from the same parent material [13].

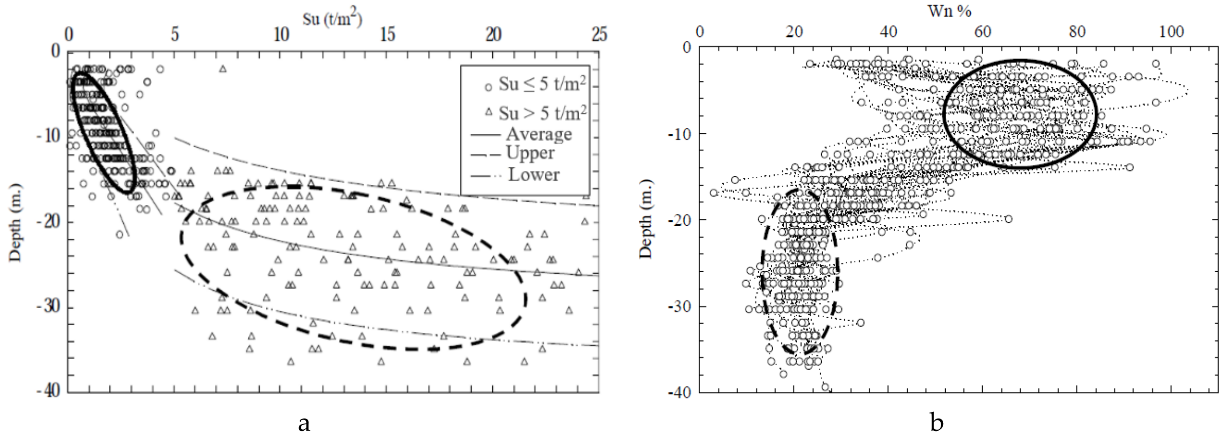


Figure 4. Profile of **a** Undrained shear strength, **b** natural moisture content [13]

The depth of soft Bangkok clay is not uniform throughout. It is thicker near the gulf of Thailand and gets thinner as we go farther away. The thickness of typical soft Bangkok clay on various locations near gulf of Thailand is shown in figure 5.

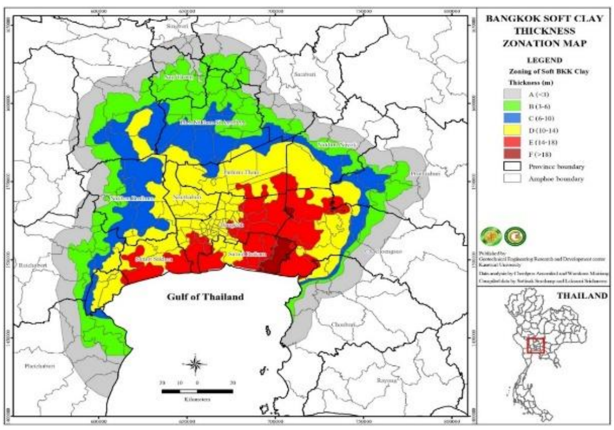


Figure 5. Thickness of soft Bangkok clay [38]

The main purpose of developing correlation equations in this research is to use it for pile driving. The common construction practice in soft Bangkok clay requires pile foundation, the depth of which depends upon the type of superstructure as shown in figure 6. For residential houses, the pile can rest over stiff to very stiff clay, whereas for larger buildings, the pile must rest on the underlaying 1st sand layer as shown in figure 6. So, it is required for SDS machine to penetrate up to that layer, since the 1st sand layer ends at that depth. This was also one of the reasons that SDS machine was customized for this research to penetrate into stiffer clay layers.

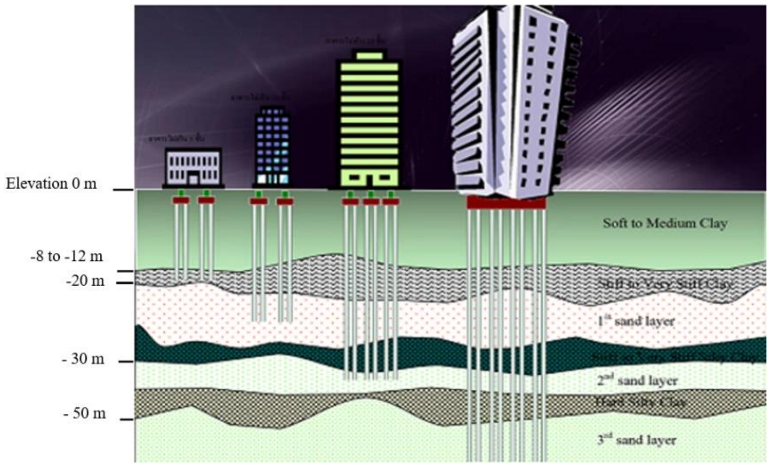


Figure 6. Required depth of pile foundations during construction in Bangkok according to type of superstructures [39]

2.6. Study Area

The test site is located in Kasetsart University in Bangkok province having soft Bangkok clay deposit. This research is based intensively on the in-situ field tests and laboratory tests where all SDS tests were performed by customized SDS machine. All field and laboratory tests are performed in highly controlled environment, so that errors in result could be minimised from every possible way. Since, Bangkok soil deposit is itself unform, homogeneous and consistent, it is particularly easy to control the tests. 6 SDS tests are performed on rugby field of Kasetsart University at a distance of 12 m with each other such that all of the test points lie on a straight line. For this, a plot of 72×10 square meter is divided into 6 equal plots of size 12×10 square meter as shown in figure 7a. Six borehole tests with SPT and six field vane shear tests were performed on the vicinity of the SDS tests such that each of their distance between SDS tests are 3m as shown in figure 7b.

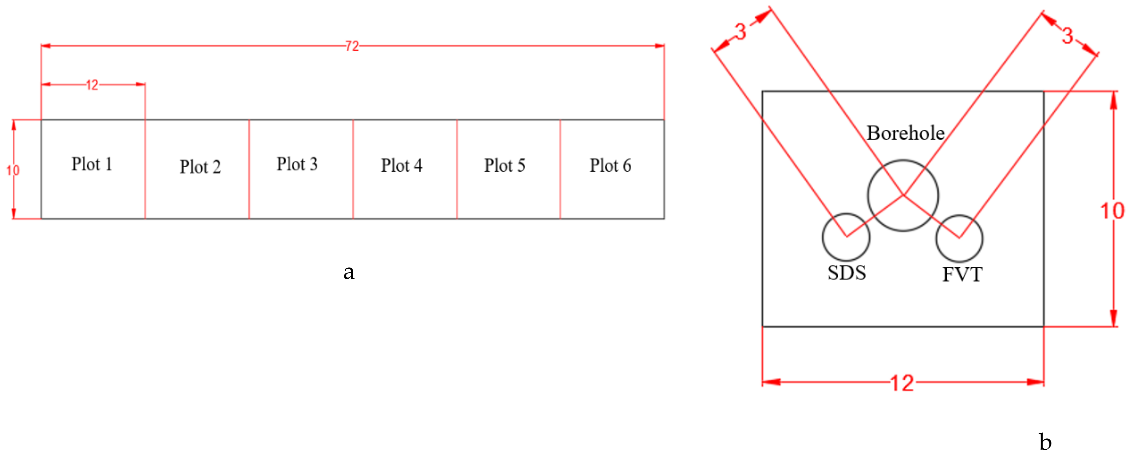


Figure 7. a Test details of plot, **b** Test details of each plot (all dimensions are in meters)

Figure 8a and 8b show SDS test being carried out in field on the vicinity of borehole test and customized SDS equipment during operation.

a b

Figure 8. a SDS test performed simultaneously with borehole, **b** SDS equipment in action

2.7. Soil Properties

Sampling from borehole test and SPT is done at each 1m depth. The samples were extracted, transported, handled and tested in extremely controlled environment to minimize every possible source of error in the result, as far as possible. Undrained shear strength, number of SPT blows, moisture content and Atterberg's limit are determined. Undisturbed undrained shear strength from field vane shear test (FVT) was also determined by FVT. Various soil properties obtained and used in this research, along with total number of tests performed is summarized in table 3.

Table 3. Soil properties and number of tests

Soil property	Number of tests
Undrained shear strength from Unconfined Compression (UC) test	54
Undrained shear strength from Unconsolidated Undrained (UU) test	60
Undisturbed undrained shear strength from FVT test	58
SPT number of blows	44
Natural moisture content	105
Vertical effective stress	104
Consistency Index (CI)	105

The undrained shear strength for soft to medium stiff clay is obtained by unconfined compression test and stiff to hard clay is obtained by correlation between SPT N and undrained shear strength as per Terzaghi, Peck and Mesri [5]. This profile can be seen in figure 9a. The marine clay and intertidal clay deposits have undrained shear strength of 8.28 kN/m^2 to 54.48 kN/m^2. These layers extend approximately from 2-3m depth to 13m depth. From 13m to 20m lies very stiff to hard clay having SPT N value of 15 blows/ft to 53blows/ft. The natural moisture content of clay sample is calculated in laboratory. The natural moisture content of clay decreased with increase in depth. Figure 9b shows the natural moisture content profile with depth obtained from all boreholes. The soft Bangkok clay layer, lying from 2m to 13m depth has consistent moisture content of 43% to 87%. This layer of clay is soft to medium stiff clay. The clay layer below 13m has sharp decrease in moisture content from 18% to 34%. This underlying layer is stiff to hard clay layer. These graphs show that Bangkok clay layers is divided into two distinct categories with large variation in their moisture content resulting distinct difference in their properties. However, in each group, their properties are consistent and uniform.

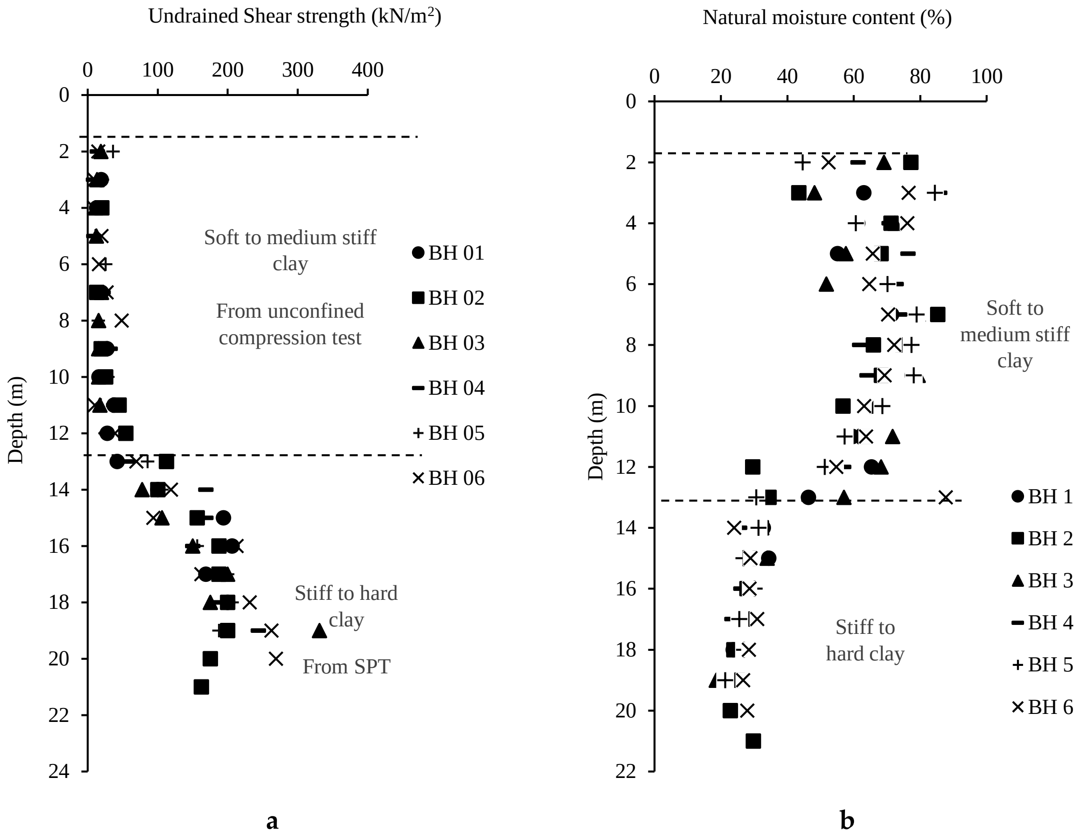


Figure 9. Profile of: **a** Undrained shear strength and SPT N with depth, **b** Natural moisture content from laboratory test

The soil profile is such that the stiffness of clay increases as we proceed to deeper depth. Hence, during SDS test, the value of torque required to penetrate through clay layer increases with increase in depth. The profile of SDS torque along depth from all SDS test is shown in figure 10. The value of average SDS torque (T_{av}) throughout the soft Bangkok clay layer is quite similar and ranges from 8 Nm to 24 Nm. This layer extends from approximately 2m to 13m and correspond to soft to medium stiff clay since it is soft marine clay and intertidal clay deposit. When SDS screw point reaches depth below 13m, it shows sever rise in value of torque. This layer is stiff to hard clay, which had been deposited at Pleistocene epoch. The value of SDS torque in this layer is 32 Nm to 347 Nm.

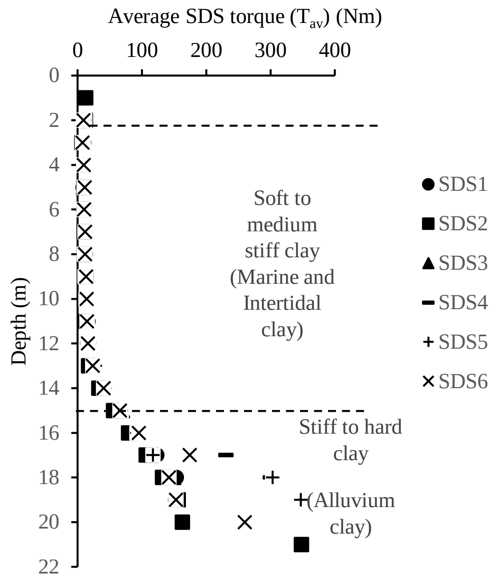
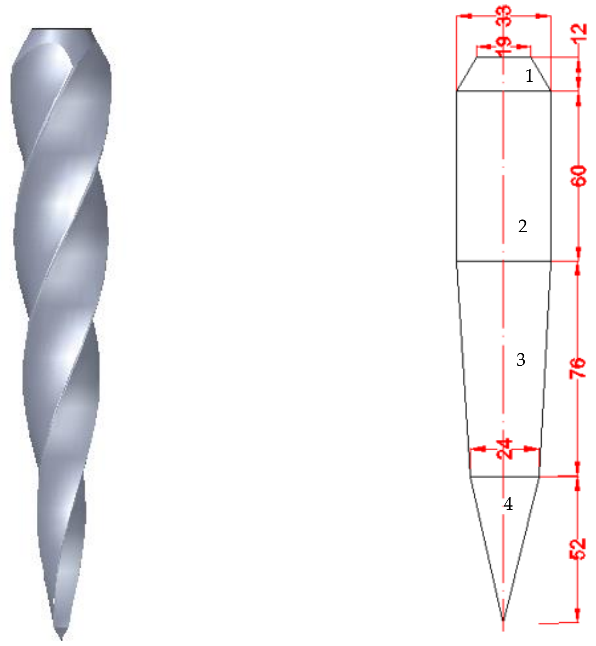


Figure 10. Torque profile from SDS test

3. Results and Discussion

3.1. Derivation of formula for determination of undrained shear strength of clay by Screw Driving Sounding (SDS) technique

The SDS screw is a tapered screw with 4 helices as shown in figure 11a. When rotated on its vertical axis, it creates the 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 an assembled shapes of frustrum on top, cylinder and frustum on middle and cone at bottom as shown in figure 11b. However, this is an approximation and the real shear surface may indeed be along the helix. Figure 11b shows two-dimensional figure of these shapes with their exact dimensions in millimetres.



a **b**

Fig 11. a SDS screw point and **b** SDS screw point depicted in simplified form, dimensions in millimetres

The torque (T) required to penetrate through the soil is equal to the sum of resisting moments from each shape, i.e., 1, 2, 3 and rod portion. All SDS parameters such as torque are measured by the SDS machine as an average of 0.25m, however, the length of screw point is just 0.2m. Hence, it is necessary to include the resisting moment from rod with length 0.05m.

$$T = M_1 + M_2 + M_3 + M_4 + M_5$$

Where;

T = torque

M_1 = Resisting moment from shape 1

M_2 = Resisting moment from shape 2

M_3 = Resisting moment from shape 3

M_4 = Resisting moment from shape 4

M_5 = Resisting moment from 5 cm length of rod

Shape 1: the frustrum:

The uppermost part of the screw is a frustrum as shown in figure 12 with:

upper radius (r_u) = 9.5 mm = 0.0095 m

lower radius (r_l) = 16.5 mm = 0.0165 m

moment arm (r_p) = 0.0095+(0.0165-0.0095)/2 = 0.013

Height (h) = 12mm = 0.012m

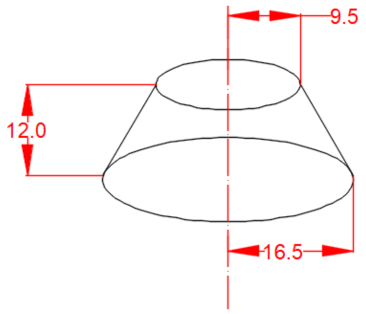


Figure 12. Top most part of simplified screw point as frustrum, dimensions in mm

Resisting moment due to shape 1 (M_1) is:

M_1 = Force × perpendicular distance

= (C_u× surface area) ×perpendicular distance

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

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

= C_u ×1.5×10^{-5}

Shape 2: the cylinder:

The middle part of the screw is a cylinder as shown in figure 13 with:

radius (r) = 16.5 mm = 0.0165 m

Height (l) = 60mm = 0.06m

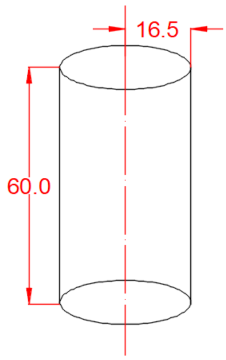


Figure 13. Middle portion of SDS screw point as a cylinder, dimensions in mm

Resisting moment from shape 2 is (M_2):

M_2 = (Cu× surface area) ×perpendicular distance

$= C_u \times 2\pi r l \times r$

$= C_u \times 2\pi \times 0.0165 \times 0.06 \times 0.0165$

= C_u ×1.026×10^{-4}

Shape 3: the frustum:

The next middle part of the screw is a frustrum as shown in figure 14 with:

upper radius (r_u) = 16.5 mm = 0.0165 m

lower radius (r_l) = 12 mm = 0.012 m

moment arm (r_p) = 0.012+(0.0165-0.012)/2 = 0.01425

Height (h) = 52mm = 0.052m

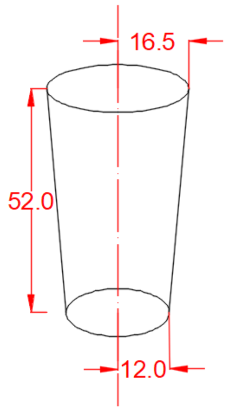


Figure 14. Middle part of simplified screw point as frustrum, dimensions in mm

Resisting moment due to shape 3 (M_3) is:

M_3 = Force × perpendicular distance

= (C_u× surface area) ×perpendicular distance

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

$= C_u \times \{\pi \times (0.0165 + 0.012) \times \sqrt{(0.0165 - 0.012)^2 + 0.052^2}\} \times 0.01425$

$= C_u \times 6.66 \times 10^{-5}$

Shape 4: the cone:

The lowermost part of the screw is a frustrum as shown in figure 15 with:

radius (r) = 12 mm = 0.012 m

moment arm (r_p) = 0.012/2 = 0.006m

Height (h) = 76mm = 0.076m

Figure 15. End part of simplified screw point as cone, dimensions in mm

Resisting moment due to shape 4 (M_4) is:

M_4 = Force × perpendicular distance

= (C_u× surface area) ×perpendicular distance

$= C_u \times \{\pi \times r \times \sqrt{r^2 + h^2}\} \times r_p$

$= C_u \times \{\pi \times 0.012 \times \sqrt{0.012^2 + 0.076^2}\} \times 0.006$

$= C_u \times 1.74 \times 10^{-5}$

Resisting moment from the rod portion:

It is crucial to include the resisting moment from 0.05m length of rod as well. This is because the length of screw is only 0.2m, whereas, the torque and all other SDS parameters are taken as an average in 0.25m depth.

radius of rod (r) = 11 mm = 0.011 m

Height of rod (l) = 50mm = 0.05m

Resisting moment from rod portion is (M_5):

M_2 = (C_u× surface area) ×perpendicular distance

= $C_u \times 2\pi r l \times r$

= $C_u \times 2\pi \times 0.011 \times 0.05 \times 0.011$

= $C_u \times 3.8013 \times 10^{-5}$

Now, total torque (T) is:

$$T = M_1 + M_2 + M_3 + M_4 + M_5$$

$$\text{i.e., } T = C_u 2.4 \times 10^{-4} \quad (6)$$

Substituting these values in equation 11,

$$C_u = 4166 \times T \quad (7)$$

The SDS machine measures torque in Nm, however, the undrained shear strength of soils is measured usually in kN/m². Hence, for ease, converting equation 7 such that torque is in Nm and undrained shear strength is in kN/m²,

$$C_u = 4.1 \times T \quad (8)$$

where, T = average corrected torque obtained by SDS in Nm

C_u = undrained sear strength in kN/m²

Equation 8 can estimate the value of undrained shear strength of clay in field by average torque. However, this equation overestimates the value of undrained shear strength when compared with the valued obtained by FVT, UC and UU tests. Hence, correction factor is required to convert this field value of undrained shear strength to correct value. This is done empirically from plasticity index, in case of marine and intertidal clays. Figure 16 shows the average correction factor in case of marine and intertidal clays.

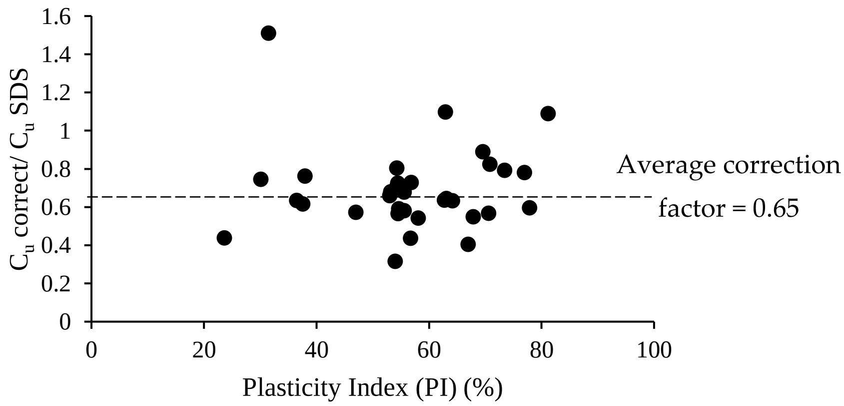


Fig 16. Correction factor for marine and intertidal clays

An average correction factor of 0.65 is obtained from the plot. Hence, the value of undrained shear strength obtained from equation 8 should be multiplied with 0.65 for marine and intertidal clays. The correct value of undrained shear strength is taken as that obtained from unconfined compression test.

3.2. The Correlation Equation or Relation between SDS Penetration resistance and Soil Properties

From soil samples obtained from borehole, common and important soil parameters such as undrained shear strength, SPT N, moisture content and Atterberg's limit are determined. Each of these parameters are either correlated or plotted with suitable SDS parameter to develop a correlation or suitable plot respectively. While doing so, a number of SDS parameters expressed in various forms such as torque, energy, load etc. are examined, which best can correlate with that particular soil property. The correlation or plot between SDS parameters and various soil properties obtained from this research are as follows:

3.2.1. Undrained Shear Strength (S_u)

The undrained shear strength of soil sample obtained from unconfined compression (UC) test unconsolidated undrained (UU) triaxial test and FVT test separately are correlated to the SDS parameter obtained at same depth. It is found that average torque; T_{av} is most suitable parameter for this case. The correlation equation between undrained shear strength from UC test and average torque as well as upper and lower prediction intervals is shown in figure 17.

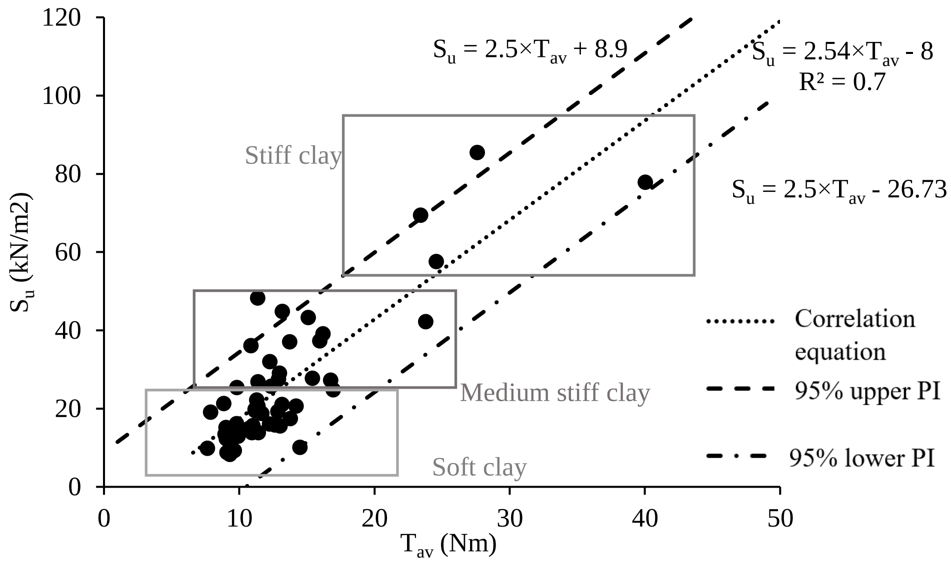


Figure 17. Relationship between the undrained shear strength from UC test and average torque

The correlation equation between the undrained shear strength (S_u) from UC test and average torque (T_{av}) is written as;

$$S_u = 2.5 \times T_{av} - 8 \tag{9}$$

The value of undrained shear strength (S_u) obtained by this equation, by keeping a particular value of T_{av} as input is indeed the mean value of undrained shear strength. With a single value of T_{av}, many values of S_u are possible. The range of value of S_u from a single value of T_{av} can be obtained by the prediction interval (PI). Upper and lower prediction intervals (PI) is calculated for future S_u values. For this, students t-test is used with 95% significance level.

The equation of upper and lower prediction interval bands is written in following equations 10 and 11 respectively:

$$S_u = 2.5 \times T_{av} + 8.9 \quad (10)$$

$$S_u = 2.5 \times T_{av} - 26.73 \quad (11)$$

The undrained cohesion of clay samples was also determined in laboratory by unconsolidated undrained (UU) triaxial test. These values were correlated with corresponding value of average torque as in Figure 18.

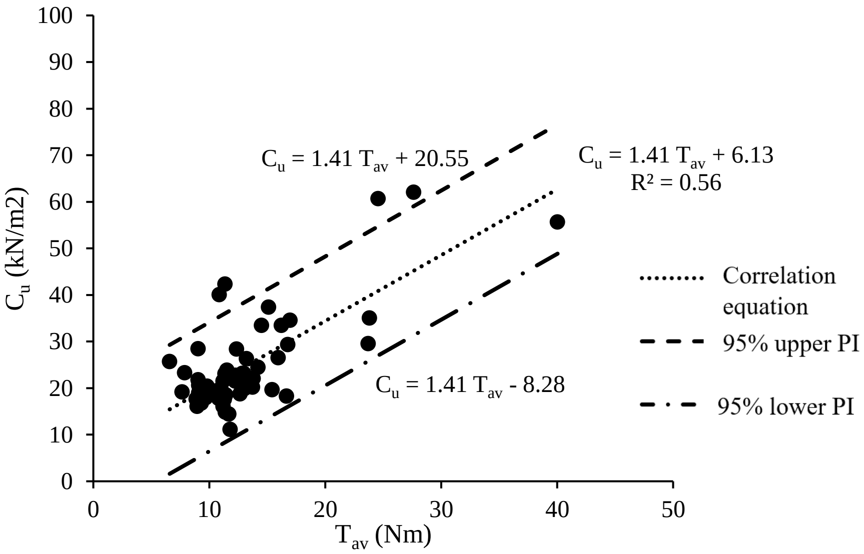


Figure 18. Relationship between the undrained cohesion from UU test and average torque

The correlation equation between the undrained cohesion of clay samples with average SDS torque is;

$$C_u = 1.41 \times T_{av} - 6.13 \quad (12)$$

The upper and lower prediction intervals of the equation is respectively as follows:

$$C_u = 1.41 \times T_{av} - 20.55 \quad (13)$$

$$C_u = 1.41 \times T_{av} - 8.28 \quad (14)$$

The undisturbed undrained shear strength of clay was determined by field vane shear test (FVT), performed in vicinity of SDS test and borehole test. This value was correlated with the average SDS torque and result is shown in figure 19. This value of undisturbed undrained shear strength used in the plot is not applied to any correction factors, so that the designers have freedom to use the correction factor by their choice.

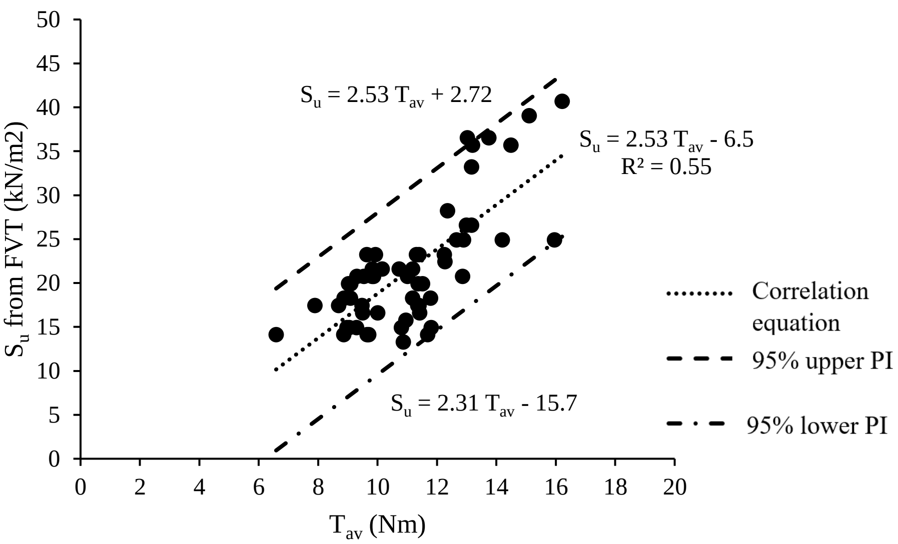


Figure 19. Relationship between the undisturbed undrained shear strength from FVT test and average torque

The correlation equation between the undrained cohesion of clay samples with average SDS torque is;

$$S_u = 2.53 \times T_{av} - 6.5 \quad (15)$$

The upper and lower prediction intervals of the equation is respectively as follows:

$$S_u = 2.53 \times T_{av} - 2.72 \quad (16)$$

$$S_u = 2.53 \times T_{av} - 15.7 \quad (17)$$

22 boreholes with SPT and 22 SDS tests were performed in 8 different locations in Bangkok and vicinity of Bangkok. Unlike the field tests performed in Kasetsart University, these field tests were not performed under controlled environment. The distance between borehole with SPT and SDS test is were not as near as that performed in Kasetsart University. Figure 20 shows the correlation between undrained shear strength from UC test from those boreholes and average torque.

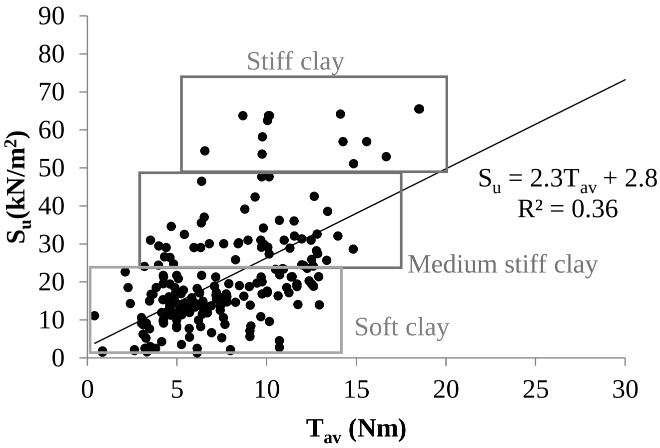


Fig 20. Correlation between the undrained shear strength and average torque

The correlation equation obtained from these tests is:

$$S_u = 2.3 \times T_{av} + 2.8 \quad (18)$$

A linear correlation can be obtained from these data, as suggested by our previous correlations between undrained shear strength and average torque. Higher undrained shear strength indicates stiffer clay demands higher value of torque to penetrate through it. Very low coefficient of determination and large scatter can be observed in the correlation. This is because of various sources of error in the data since the field tests were not performed in a controlled environment as in Kasetsart University.

As the undrained shear strength of clay increases, its resistance to externally applied forces is increased and it behaves stronger. This requires greater torque to penetrate through it. In all three cases, the required torque increases with increase in the undrained shear strength of clay. This correlation is only applicable to soft to stiff clay of Bangkok subsoil, as all the data points used to derive this equation is such. To understand the difference in these three correlation equations better, they are plotted in the same chart which is shown in figure 21.

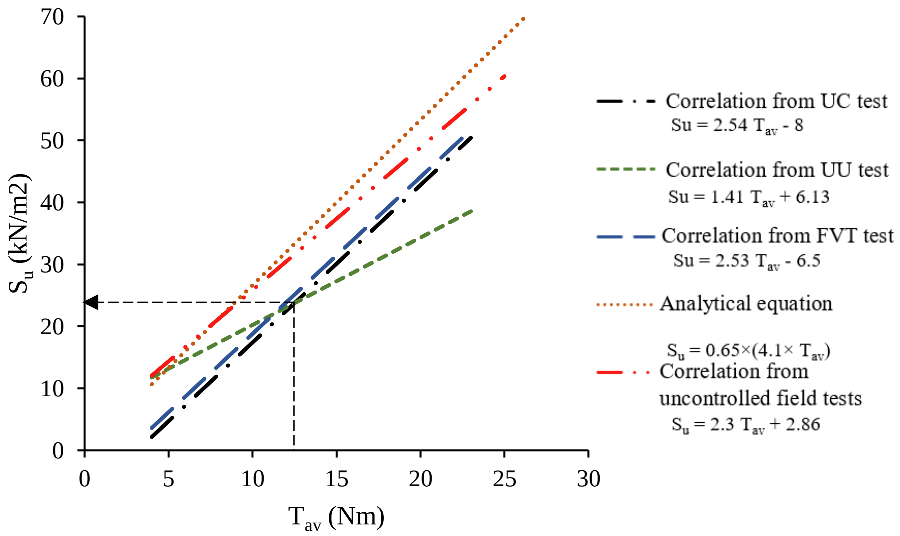


Figure 21. Correlation between the average SDS torque and undrained shear strength obtained from UC, UU and FVT tests

The correlation between average SDS torque and undrained shear strength obtained from UC test, UU test and FVT tests are different. This is because the undrained shear strength of clay is not a unique parameter and depends significantly on the type of test used, the rate of strain, and the orientation of the failure planes [30]. These significantly vary in UU, UC and FVT tests. This results in difference in their correlation equations.

The correlation between the torque and undrained shear strength obtained by UC and UU test are significantly different. The correlation from UU test gives higher undrained shear strength for clay for clay with undrained shear strength lower than 25 kN/m^2 compared to that from UC test and vice versa. Clays having undrained shear strength below 25 kN/m^2 are soft clays. In UU test, the sample is subjected to the confining pressure, due to which, undrained shear strength is greater than from UC test, which has no confining pressure. However, in stiffer clays, the effect due to confining pressure does not make the sample prominently stiffer than it really is, since it is already stiff. There would rather be significant influence of moisture content. Unlike UC test, the sample in UU test is first saturated before the test, which increases the moisture content in the sample. It is obvious to have lesser undrained shear strength for soil with higher moisture content. Stiffer soils have lesser moisture content, and increase in small amount of moisture content on them largely decreases its strength as it becomes softer. Same situation will not be true for soft clays. Soft clays already have higher moisture content and further increase in moisture content will not have equally significant effect on their strength. In addition, the moisture content of clays having undrained shear strength less than 25 kN/m^2 are near the liquid limit. For medium stiff and stiff clays, it is significantly less than liquid limit and rather is in midway between plastic and liquid limit. So, due to saturation of sample in UU test, when moisture content of stiffer clays is increased, it approaches near liquid limit or even might exceed that, decreasing strength of clay sample and hence decreasing required torque. In contrast, since the moisture content in soft clays is already near the liquid limit, increase in water content will not prominently decrease its strength.

According to Yimsiri et al. [30], Bangkok soil deposit is anisotropic and it is stiffer in horizontal direction. Which means, value of undrained shear strength in horizontal direction can be expected to be higher than in vertical direction. It has also been discussed in earlier section, that the shear surface during FVT test is radial and, in that case, the undrained shear strength of soil is from the horizontal direction. In contrast, in case of UC test, the failure surface is at the angle of 45° to horizontal, indicating that the undrained shear strength in that case is the combination of horizontal and vertical direction. This value can be expected to be lesser than what is obtained from FVT test. Hence, the undrained shear strength from FVT is higher than by UC test. In addition, the sample in UC test is disturbed during transportation and handling and loses moisture content, while it is undisturbed and moisture content is preserved during FVT. So, it is expectable for laboratory determined undrained shear strengths to have lesser value than that obtained in field by in-situ tests. While using correlation equations to estimate the undrained shear strength of clay, it is best to use the one obtained from FVT as it excludes the soil disturbance as well as loss in natural moisture content in the sample.

This correlation from above specifically deals with Bangkok clay which is uniform and homogeneous by nature and has quite consistent values of Engineering properties. All the data points are marine or intertidal clays, with soft to stiff consistency and formed during Holocene Epoch. However, the correlation between the undrained shear strength and SDS torque in equation 1 by Yoshida et al. [16] consisted of Japanese alluvium clay, alluvium silt and peat. In addition to this, since there is difference in mineralogy, microstructure, depositional environment and history of Bangkok clay and alluvium clay, equation 1 cannot give accurate result. Due to these reasons, for application of SDS technique on sites with Bangkok clay, these equations gives better and relevant results.

Since different equations are obtained from different tests, hence, an attempt has been made to convert all equations into a same baseline. Figure 22 shows equations which can be used to obtain the undrained shear strength from UC test by using equations 8, 12, 15 and 18.

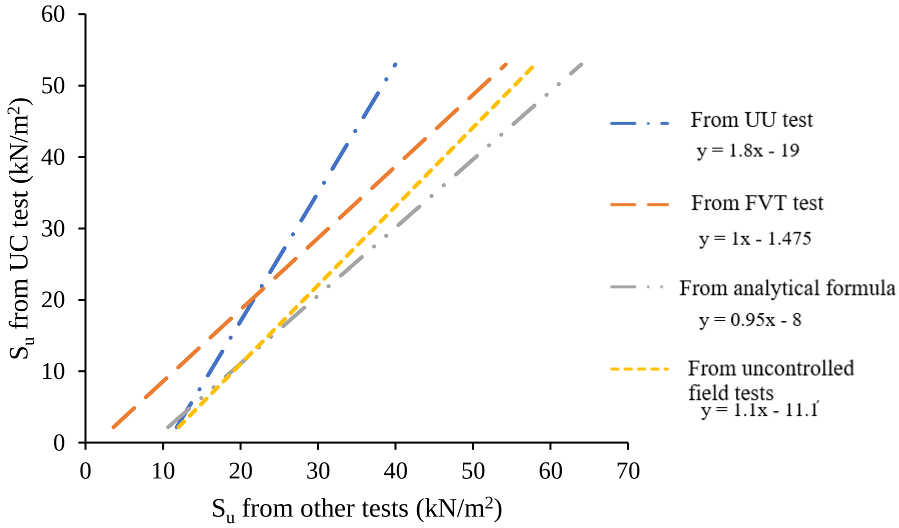


Figure 22. Undrained shear strength obtained from other tests converted to undrained shear strength from UC test

3.2.2. SPT Number of Blows (N)

SPT test is one of the most popular in-situ tests in the world. A large number of equations have been developed between various Engineering soil properties and SPT N in past research. The ability to estimate N directly from SDS parameter will help SDS test result to connect with numerous Engineering properties of soil. This research attempts to estimate the number of blows of stiff to hard clay, directly from the SDS penetration resistance. Figure 23 indicates the relation between N value and average SDS torque.

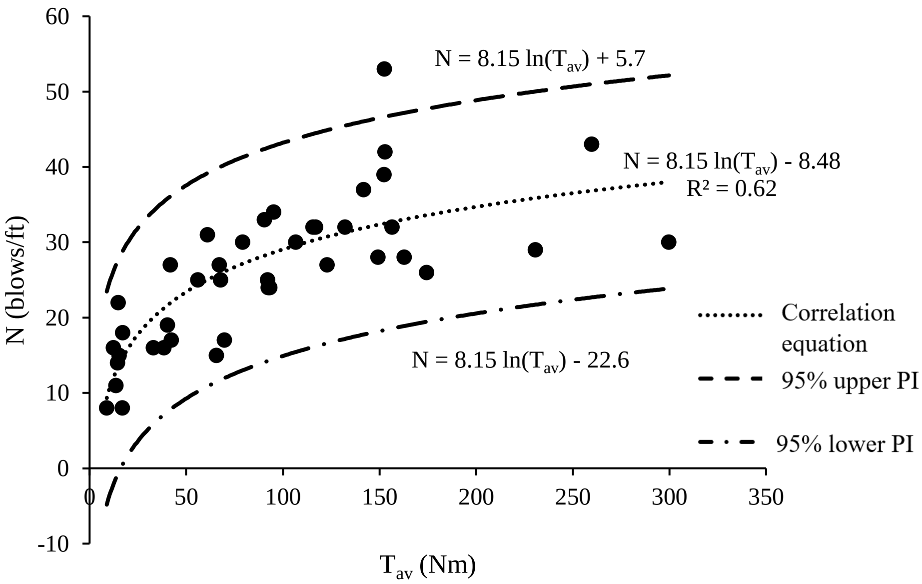


Figure 23. Relationship between SPT blow count and penetration energy

This equation can be written as follows;

$$N = 8.15 \times ln(T_{av}) - 8.48 \quad (19)$$

The upper and lower prediction intervals were calculated with 95% significance level. The equation of 95% upper and lower prediction intervals are given in equation 20 and 21 respectively.

$$N = 8.15 \times ln(T_{av}\ ) + 5.7 \quad (20)$$

$$N = 8.15 \times ln(T_{av}) - 22.6 \quad (21)$$

The equation suggests that higher value of N requires more torque. Higher number of blows in clay indicates that it is stiffer, denser and harder which makes difficult for screw point to penetrate, requiring higher amount of torque. Since SPT test is not significant for soft clay, the data points obtained in this equation are stiff to hard clay layers, which is formed in Pleistocene period. The scatter in the plot is due to difference in shear surface between these tests, as well as difference in penetration mechanism of SPT and SDS test. SPT applies dynamic loading whereas penetration in SDS is by static loading.

The nature of correlation between SPT N and $E_{0.25}$ from Tanaka et al. [12] was a linear equation. The data from clay, silt, sand, organic silt, loam of Japanese alluvium clay is used in order to generate that equation. The data from sand have significant effect on this equation. Also, the clay samples used are only soft clays. However, the equation developed in this research, as shown in equation 19 uses 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 is different from alluvium clay. Equation 19 exclusively deals with Bangkok clay deposit. Due to this reason, the equation developed in this research gives better result when tests are performed for Bangkok clay deposit.

3.2.3. Moisture Content (w_c)

The natural moisture content of clay is plotted with the penetration energy ($E_{0.25}$) and shown in figure 24.

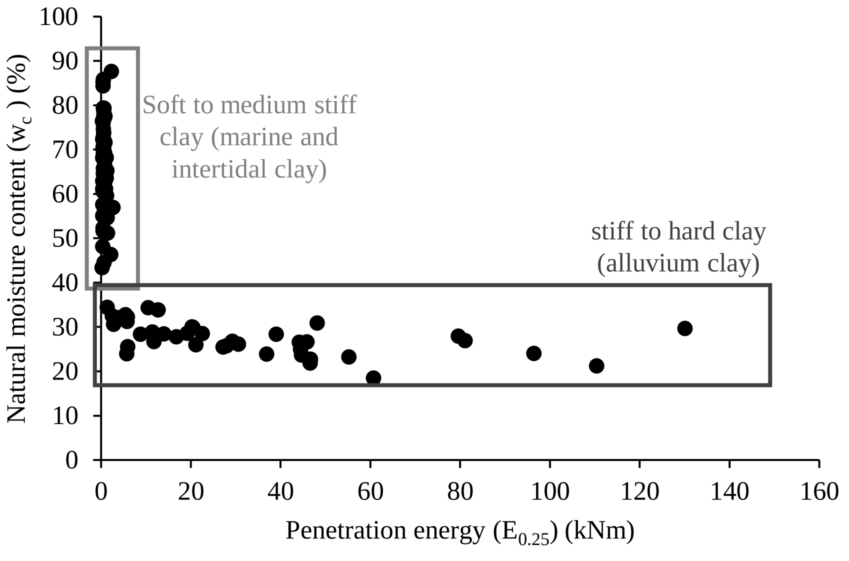


Figure 24. Variation of between natural moisture content with penetration energy

It can be observed very clearly that the energy required to penetrate increases tremendously with decrease in moisture content of clay. Moisture content of a clay sample isa crucial clay parameter. Clay samples in the plot can be divided into two distinct groups which is as specified as in figure 4b. The clay whose moisture content is above 40% is soft to medium stiff clay, which is marine or intertidal clay. They were formed in Holocene period in saline environment. The moisture content of these clay layers is very high which is near their liquid limits or higher than that. They are either in liquid state or even if they are in plastic state, they have considerably higher moisture content and is about to achieve liquid state. So, very small amount of penetration energy is enough to penetrate through it. Further increase in moisture content in these clay layers would not have profound effect on its strength and similar value of penetration energy is required to penetrate through these clays. Hence, penetration energy is insensitive to moisture content for marine and intertidal clays. However, the soil having moisture content below 40% is very stiff to hard clay. This is alluvium clay layer and was deposited in Pleistocene period, in fresh water environment, and was formed before overlying layer was formed in Bangkok plain. These clays have significantly low moisture content which is near to plastic limit or even less than that. They are either in semi solid state or have just entered plastic state. This indicates that they are dry and stiff, and requires more penetration energy than marine and intertidal clays to disintegrate the lump and intrude the SDS screw through it. Penetration energy is very sensitive to moisture content of this layer. This is because addition of even small amount of moisture on it can change its state or have huge effect on its strength, so significantly lesser penetration energy would be enough to penetrate through it.

3.2.5. Consistency Index (CI)

The consistency index indicates the degree of firmness of clay. It provides information on the state of clay i.e., within or outside plastic state or liquid state. Figure 25 shows the plot of penetration energy with consistency index.

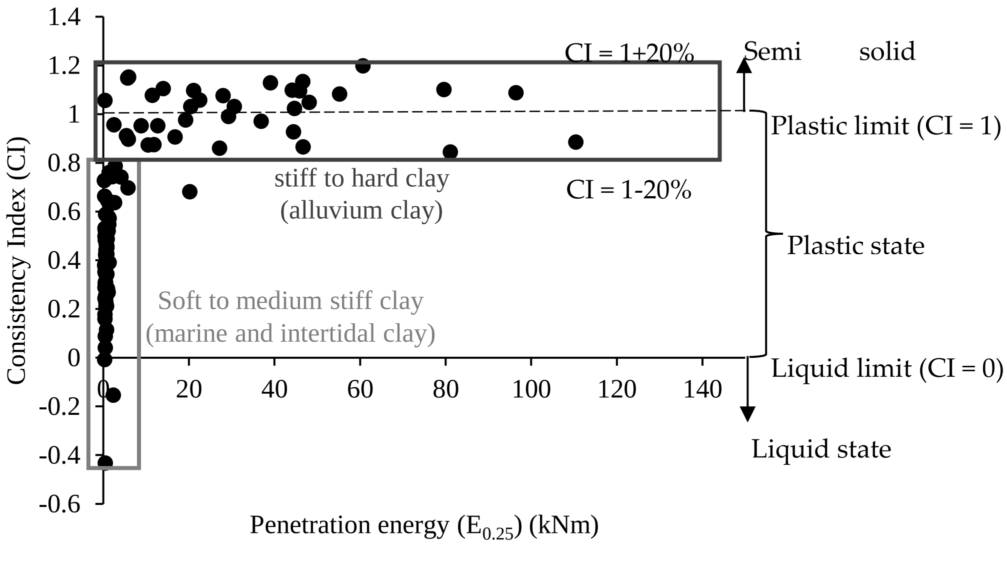


Figure 25. Variation of between consistency Index with penetration energy

As per the plot, higher values of consistency index correspond to higher value of penetration energy. Higher consistency refers to stiffer soil, which will require higher penetration energy to penetrate through. The prominent point of bend in the plot, i.e., consistency index value of 0.8 correspond to the moisture content of 40%. This indeed indicates the difference in types of clay deposit, environment of formation and state of these clay layers, based on moisture content, as discussed in previous section of plot between SDS parameter and moisture content. Most of the alluvium clays have consistency index of more than 1, which indicates that they are in semi solid or solid state. The value of CI of some alluvium clays even being less than 1, almost approaches 1. This indicates they are very near to plastic limit. Hence, they will require more penetration energy to penetrate through it. Increase in moisture content even by a small amount can change them to plastic state and significantly less penetration energy will be enough. Due to this, penetration energy is very sensitive to the consistency index of alluvium clay. In contrast, all marine or intertidal clays have consistency index less than 1 and some are even lesser than 0. This indicates they are in either plastic or liquid state, which means they require lesser penetration energy by the SDS machine to penetrate through them. In addition, since they already have high moisture content, further minor increase in moisture content in them will not have same level of reduction in penetration energy as in alluvium clays. Hence, penetration energy is insensitive to consistency index of marine and alluvium clay.

4. Concluding Remarks

Following conclusions were obtained from the research:

1. The undrained shear strength of clay can be found directly from SDS average torque, using an analytical formula. However, a correction factor is required which is and average of 0.65 in case of marine and intertidal clays.
2. The correlations between the SDS torque and undrained shear strength of Bangkok clay samples, determined from UC, UU and FVT tests are all linear but, are different from each other. Only marine and intertidal clays samples are used for these correlations.
3. The correlation equations between SDS torque and undrained shear strength obtained from UU and UC test intersect at undrained shear strength value of 25kN/m^2. This value separates the soft clays from stiffer clays. The clays having undrained shear strength less than 25kN/m^2 have their natural moisture content very near to or even greater than their liquid limit. However, the stiffer clays having undrained shear strength greater than 25kN/m^2 have their moisture content rather mid-way between liquid limit and plastic limit. Indicating that they are in plastic state. Greater torque is required to penetrate through these clays. The confining stress and saturation of clay sample in UU test also has significant effect on the correlations.
4. Similarly, anisotropy of Bangkok clay has profound effect on the correlation obtained by FVT test. The shear surface of FVT is cylindrical where strength from horizontal direction is dominant. While in case of UC test, the shear plane is 45° to horizontal and strength from both vertical as well as horizontal direction are equally prominent. Since Bangkok clay is anisotropic and stiffer in horizontal direction, FVT gives higher value of undrained shear strength than UC test. In addition, strength obtained from in-situ tests are usually higher than that obtained from laboratory tests due to disturbance in sample.
5. The correlation between SPT N and SDS penetration resistance is also developed. This equation specifically deals on alluvium clay deposit and excludes marine and intertidal clays. These equations allow prediction of those properties from the SDS parameter directly and quickly without sampling. Due to these correlations, the use of SDS can increase the number of site exploration points, where other field tests are being performed, without spending much time, fortune and effort.
6. The state of clay has significant effect on the behavior of SDS penetration energy. The state and consistency of clay is dependent on formation history and deposition period, in case of Bangkok clay layers. The marine clays and intertidal clays have moisture content near their liquid limit, whereas alluvium clay have moisture content close to plastic limit or even less. Hence, the penetration energy is either highly sensitive or insensitive to the moisture content based on the depositional history respectively.

7. When these equations are to be applied in other clay deposit than Bangkok clays, the consistency and state of clay should be given utmost importance. These equations can or cannot be used in a particular clay deposit, or chosen appropriately, based on its state; semi solid, liquid and plastic state. It is a coincidence that the Bangkok clay layers have two distinct properties of clay state.

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References

1. Orense, R.P.; Mirjafari, Y.; Suemasa, N. Screw driving sounding: a new test for field characterisation. *Geotechnical Research* **2018**, *6*, 28-38, doi:https://doi.org/10.1680/jgere.18.00024.
2. Hara, A.; Ohta, T.; Niwa, M.; Tanaka, S.; Banno, T. Shear modulus and shear strength of cohesive soils. *soils and Foundations* **1974**, *14*, 1-12, doi:https://doi.org/10.3208/sandf1972.14.3_1.
3. Hettiarachchi, H.; Brown, T. Use of SPT blow counts to estimate shear strength properties of soils: energy balance approach. *Journal of Geotechnical and Geoenvironmental Engineering* **2009**, *135*, 830-834, doi:https://doi.org/10.1061/(ASCE)GT.1943-5606.0000016.
4. Sivrikaya, O. Comparison of artificial neural networks models with correlative works on undrained shear strength. *Eurasian Soil Science* **2009**, *42*, 1487-1496, doi:https://doi.org/10.1134/S1064229309130092.
5. Terzaghi, K.; Peck, R.B.; Mesri, G. *Soil mechanics in engineering practice*; John Wiley & Sons: 1967.
6. ASTMD2573-01. Standard test method for field vane shear test in cohesive soil. **2008**.
7. Bjerrum, L. Problems of soil mechanics and construction on soft clays. In Proceedings of the Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, 1974; pp. 111-159.
8. Chandler, R.J. The in-situ measurement of the undrained shear strength of clays using the field vane. In *Vane shear strength testing in soils: field and laboratory studies*; ASTM International: 1988.
9. Tsukamoto, Y.; Ishihara, K.; Sawada, S. Correlation between penetration resistance of Swedish weight sounding tests and SPT blow counts in sandy soils. *Soils and Foundations* **2004**, *44*, 13-24, doi:https://doi.org/10.3208/sandf.44.3_13.
10. Mirjafari, Y.; Orense, R.; Suemasa, N. Soil classification and liquefaction evaluation using Screw Driving Sounding. In Proceedings of the Proc., 5th International Conference on Geotechnical and Geophysical site Characterisation, 2016.

11. Orense, R.; Mirjafari, Y.; Suemasa, N. Geotechnical site characterisation using Screw Driving Sounding method. In Proceedings of the New Zealand – Japan Workshop on Soil liquefaction during Recent Large-Scale Earthquakes, Auckland, NZ., 2013; pp. 11-20.
12. Tanaka, T.; Suemasa, N.; Ikegame, A.; Yamato, S. Classification of strata using screwdriver sounding test. In Proceedings of the The Twenty-second International Offshore and Polar Engineering Conference, 2012.
13. Teerachaikulpanich, N.; Phupat, V. Geological and geotechnical engineering properties of Bangkok clay. In Proceedings of the Proceedings of the Japan National Conference on Geotechnical Engineering The 38th Japan National Conference on Geotechnical Engineering, 2003; pp. 143-144.
14. Horpibulsuk, S.; Yangsukkaseam, N.; Chinkulkijniwat, A.; Du, Y.J. Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. *Applied Clay Science* **2011**, *52*, 150-159, doi:https://doi.org/10.1016/j.clay.2011.02.014.
15. Nutalaya, P.; Rau, J.L. Bangkok: the sinking metropolis. *Episode Journal of International Geoscience* **1981**, *4*, 3-8, doi:https://doi.org/10.18814/epiiugs/1981/v4i4/001.
16. Yoshida, S.; Sugano, Y.; Suemasa, N.; Tanaka, T.; Yamato, S. Sds 試験による粘性土の一軸圧縮強さの推定(その 2). In Proceedings of the 第４７回地盤工学研究発表会 2012.
17. Ohtsubo, M.; Egashira, K.; Koumoto, T.; Bergado, D. Mineralogy and chemistry, and their correlation with the geotechnical index properties of Bangkok clay: comparison with Ariake clay. *Soils and Foundations* **2000**, *40*, 11-21, doi:https://doi.org/10.3208/sandf.40.11.
18. Tanaka, H.; Locat, J.; Shibuya, S.; Soon, T.T.; Shiwakoti, D.R. Characterization of Singapore, Bangkok, and Ariake clays. *Canadian Geotechnical Journal* **2001**, *38*, 378-400, doi:https://doi.org/10.1139/t00-106.
19. Tanaka, H.; Locat, J.J.C.G.J. A microstructural investigation of Osaka Bay clay: the impact of microfossils on its mechanical behaviour. **1999**, *36*, 493-508.
20. Inada, M. Use of results of Swedish weight sounding test. *Soils and Foundations* **1960**, *8*, 13-18.
21. Miki, G. A comparison between some sounding tests on loam plateau. *Soils and Foundations* **1959**, *1*, 14-23.
22. Ueda, Y. On Swedish weight sounding rod. *Soils and Foundations* **1957**, *5*, 9-12.
23. Mirjafari, S.Y.; Orense, R.P.; Suemasa, N. Determination of shear strength parameters using Screw Driving Sounding (SDS). In *Geotechnical Earthquake Engineering and Soil Dynamics V: Slope Stability and Landslides, Laboratory Testing, and In Situ Testing*; American Society of Civil Engineers Reston, VA: 2018; pp. 414-422.
24. Robertson, P.; Campanella, R. *Interpretation of cone penetration tests. Part II: Clay*; 1983; Volume 20, pp. 734-745.
25. Schmertmann, J.H. Measurement of in situ shear strength, SOA Report. In Proceedings of the Proceedings, ASCE Spec. Conference on In Situ Measurement of Soil Properties, Raleigh, NC, 1975; pp. 57-138.
26. Gylland, A.; Thakur, V.; Emdal, A. Extended interpretation basis for the vane shear test. In Proceedings of the 17th Nordic Geotechnical Meeting, Island, 2016.
27. Seah, T.H.; Sangtian, N.; Chan, I.C. Vane shear behavior of soft Bangkok clay. *Geotechnical Testing Journal* **2004**, *27*, 57-66, doi:https://doi.org/10.1520/GTJ11266J.
28. Taiani, B.; Ferlisi, S.; Gylland, A.S. Numerical analyses of field vane tests on soft clays. In Proceedings of the International Workshop on Meterology for Geotechnics, Benevento, Italy, March 17-18, 2016.
29. Ratananikom, W.; Likitlersuang, S.; Yimsiri, S. An investigation of anisotropic elastic parameters of Bangkok Clay from vertical and horizontal cut specimens. *Geomechanics and Geoengineering* **2013**, *8*, 15-27, doi:https://doi.org/10.1080/17486025.2012.726746.

30. Yimsiri, S.; Ratananikom, W.; Likitlersuang, S. Investigation of some anisotropic characteristics of Bangkok Clay. In Proceedings of the Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering 2009; pp. 1068-1071.
31. Sinsakul, S. Late quaternary geology of the lower central plain, Thailand. *Journal of Asian Earth Sciences* **2000**, *18*, 415-426, doi:https://doi.org/10.1016/S1367-9120(99)00075-9.
32. Horpibulsuk, S.; Shibuya, S.; Fuenkajorn, K.; Katkan, W. Assessment of engineering properties of Bangkok clay. *Canadian Geotechnical Journal* **2007**, *44*, 173-187, doi:https://doi.org/10.1139/t06-101.
33. Nutalaya, P.; Phienwej, N.; Gupta, A. Flooding and land subsidence of Bangkok. *Physiogeography of Southeast Asia* **2002**.
34. Balasubramaniam, A.; Chaudry, A. Deformation and strength characteristics of soft Bangkok clay. *Journal of the Geotechnical Engineering Division* **1978**, *104*, 1153-1167, doi:https://doi.org/10.1061/AJGEB6.0000685.
35. Bergado, D.; Singh, N.; Sim, S.; Panichayatum, B.; Sampaco, C.; Balasubramaniam, A. Improvement of soft Bangkok clay using vertical geotextile band drains compared with granular piles. *Geotextiles and Geomembranes* **1990**, *9*, 203-231, doi:https://doi.org/10.1016/0266-1144(90)90054-G.
36. Alditra, D.F.; Chaiprakaikeow, S.; Soralump, S. Study of VCM Improved Soft Soil Properties Using Non-Destructive and Destructive Techniques. *Geosciences* **2020**, *10*, 300, doi:https://doi.org/10.3390/geosciences10080300.
37. Oonchittikul, S. Performance of bored piles in Bangkok subsoils. M. Eng. Thesis, Asian Institute of Technology, Thailand, 1990.
38. (GERD), G.E.R.a.D.C. Bangkok Soft Clay Thickness Zonation Map. Available online: http://www.gerd.eng.ku.ac.th/Map/Map14.jpg (accessed on
39. Soralump, S. *Documentary Photography Book Geohazards from Geotechnic's View*; 2011.