PENETRATION TEST PARAMETERS AND THEIR CORRELATIONS FOR SOILS FROM SELECTED LOCATIONS OF BANGLADESH

INDRAJIT KUMAR PAUL

M. Engineering THESIS

DEPARTMENT OF CIVIL ENGINEERING
MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY
DHAKA, BANGLADESH

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil Engineering

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DECLARATION

I hereby declare that the study reported in this thesis entitled as above is my own original work and has not been submitted before anywhere for any degree or other purposes. Further, I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged and cited in the reference section.

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Department of Civil Engineering MIST, Dhaka

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By

Indrajit Kumar Paul

DEDICATON

Dedicated to my most reverend mother and to the memory of my beloved father.

ABSTRACT

Penetration Test Parameters and Their Correlations for Soils from Selected Locations of Bangladesh

Local geological information plays an important role in determining the soil parameters required for designing of foundations. Cone penetration test (CPT) and standard penetration test (SPT) are the most widely used penetration test methods in investigating subsoil condition of a site. Though both the methods, in principles, determines the similar soil parameters and their extent, yet there are marked difference in acquiring the subsoil information. The CPT is a continuous method of penetration using static loading, while SPT is a dynamic and intermittent method of investigation. There are many relations reported by various investigators and they are, however, based on broad qualitative categories of soil. With these concerns, the present study was mainly aimed at finding the relations of the soil parameters obtained from both the investigation methods and engineering soil classes. In total 24 CPT tests were conducted at a site within the proximity SPT borehole's locations of radial distances of 6 m. Soil profiles were prepared using both CPT and SPT data, and similar types of soil were isolated from all the soil profiles for statistical analysis. If case where no consensus soil profiles were obtained SPT profile was given preference. Five classes of soil were considered for investigation like sand and silty sand (SM), silt of low plasticity (ML), silt of high plasticity (MH), clay of low plasticity (CL) and clay of high plasticity (CH).

The analyses indicated that strong linear correlations existed between field SPT N-value, and both CPT cone resistance and sleeve friction for non-plastic silty sand (SM). For non-plastic silt (ML), silt of high plasticity (MH) and clay of low plasticity (CL), moderate linear correlations were obtained. For clay of high plasticity (CH), a moderate linear correlation was observed between field SPT N-value and CPT cone resistance, however, a very weak correlation was found between SPT N-value and CPT sleeve friction. For sandy soil CPT and SPT were found to assess reasonably identical soil profiles. Some deviations were noticed in identifying finer soil layer like silt and clay.

সারসংক্ষেপ

Penetration Test Parameters and Their Correlations for Soils from Selected Locations of Bangladesh

মাটির দৃঢ়তা শক্তি বা ভারবহন ক্ষমতা নির্ধারন তথা ফাউন্ডেশন ডিজাইনের ক্ষেত্রে ভূতাত্ত্বিক ও জিওটেকনিক্যাল তথ্যের গুরুত্ব অপারিসীম। কোন স্থানের ভূ-গর্ভস্থ মাটির দৃঢ়তা বৈশিষ্ট্য যে সকল প্রক্রিয়ায় নির্ণয় করা যায় তার মধ্যে দুইটি ভেদন প্রতিবন্ধকতা (পেনিট্রেসন রেজিস্টেনস) পরীক্ষা যথা কোন্ পেনিট্রেসন পরীক্ষা (CPT) ও স্ট্যান্ডার্ড পেনিট্রেসন পরীক্ষা (SPT) অন্যতম। কোন্ পেনিট্রেসন পরীক্ষা (CPT) সাধারনত স্থির বা চাপ শক্তি এবং স্ট্যান্ডার্ড পেনিট্রেসন পরীক্ষা (SPT) ঘাত বা গতি শক্তি দ্বারা সম্পন্ন করা হয়। আবার, CPT পরীক্ষা কোন নির্ধারিত গভীরতা পর্যন্ত নিরবিচ্ছিন্ন ভাবে করা হয় যার জন্য মাটিতে কোন গর্ত (বোরহোল) করার প্রয়োজন পড়ে না, পক্ষান্তরে মাটিতে গর্ত (বোরহোল) করে বিভিন্ন অর্ন্তবর্তী গভীরতায় SPT পরীক্ষা সম্পন্ন করা হয়। এ ছাড়াও SPT পরীক্ষায় মাটির নমুনা প্রত্যক্ষভাবে সংগ্রহ করা যায়, কিন্তু CPT পরীক্ষায় প্রাপ্ত তথ্য বিশ্লেষণ পূর্বক পরোক্ষভাবে মাটির ধরন অনুমান করা হয়। এই সব ভিন্নতার কারনেই এ দুইটি পদ্ধতির মাধ্যমে সম্পন্ন পরীক্ষা দ্বারা মাটির দৃঢ়তা বৈশিষ্ট্য নির্ধারন ও মাটির স্তর বিন্যাসে (সয়েল প্রোফাইল) ভিন্নতা থাকা যেমন অস্বাভাবিক নয়, তেমনি তাদের মধ্যে কোন সাদৃশ্য আছে কিনা তাও গবেষণা করা যাইতে পারে। অতীতে গবেষকগন বিভিন্ন দেশে তাদের মাটির উপর গবেষণা পরিচালনা করেছেন, কিন্তু বাংলাদেশের মাটির উপর এ সক্রান্তে গবেষণা খুবই কম, বিশেষ করে বিভিন্ন সংসক্তি (কোহেসিভনেস) ও দানা বা কণা দ্বারা ঘটিত মাটিস্তরের উপর। এসব বিষয়গুলি বিবেচনা করেই, CPT ও SPT এ দুটি পেনিট্রেসন পরীক্ষায় প্রাপ্ত তথ্যের মধ্যে কোন সাদৃশ্য বা সম্পর্ক আছে কিনা তা নির্ণয়ের জন্য বর্তমান গবেষনাটি হাতে নেওয়া হয়। বাংলাদেশের একটি প্রকল্পস্থানে ৩০ মিটার গভীরতার ২৪ টি CPT পরীক্ষা হয় এবং প্রতিটি CPT স্থানের সন্নিকটে ৬ মিটার ব্যাসার্ধের মধ্যে SPT পরীক্ষাও করা হয়। উভয় পরীক্ষার তথ্যের ভিত্তিতে মাটির স্তর বিন্যাস করা হয় এবং বিভিন্ন ধরনের মাটির জন্য তথ্যগুলি পৃথক করা হয়। প্রকল্প স্থানের ভূ-গর্ভস্থ মাটির স্তরে সংসক্তিহীন বালি মাটি (SM), কম সংসক্তির মিহিদানার মাটি (ML), বেশি সংসক্তির মিহিদানার মাটি (MH), কম সংসক্তির সূক্ষ্মকণার মাটি (CL) এবং বেশি সংসক্তির সূক্ষ্মকণার মাটি (CH), এই পাঁচ শ্রেণির মাটি পাওয়া যায়।

কোন্ পেনিট্রেসন পরীক্ষা (CPT) এবং স্ট্যান্ডার্ড পেনিট্রেসন পরীক্ষা (SPT) পরীক্ষা থেকে প্রাপ্ত তথ্য পরিসংখ্যানগত বিশ্লেষণে দেখা যায় যে, সংসক্তিহীন (কোহেসনলেস) বালি মাটির (SM) ক্ষেত্রে SPT N-মানের সাথে CPT পরীক্ষার কোন্ পেনিট্রেসন প্রতিবন্ধকতা (কোন্ পেনিট্রেসন রেজিস্টেনস) ও স্লিভ ফ্রিক্সান

প্রতিবন্ধকতা উভয়েরই শক্তিশালী সরল সম্পর্ক বিদ্যমান। পক্ষান্তরে, কম সংসক্তির মিহিদানার মাটি (ML), বেশি সংসক্তির মিহিদানার মাটি (MH) ও কম সংসক্তির সূক্ষ্মকণার মাটির (CL) ক্ষেত্রে মাঝারি ধরনের সরল সম্পর্ক রয়েছে। অন্যদিকে, বেশি সংসক্তির সূক্ষ্মকণার মাটির (CH) ক্ষেত্রে CPT কোন্ পেনিট্রেসন রেজিস্টেনস এর মাঝারি রৈখিক সম্পর্ক পরিলক্ষিত হলেও, SPT N এর সাথে CPT স্লিভ ফ্রিক্সান এর খুবই দুর্বল সম্পর্ক পাওয়া যায়। মাটির স্তর বিন্যাস (সয়েল প্রোফাইল) নির্ধারণে সংসক্তিহীন বালি মাটির (সেন্ড) জন্য CPT এবং SPT তে প্রায় একই ধরনের বিন্যাস পরিলক্ষিত হয়। মিহিদানার মাটি (সিল্ট) এবং সূক্ষ্মকণার মাটির (ক্লে) স্তর বিন্যাসে দুইটি পেনিট্রেসন পরীক্ষার ক্ষেত্রে কিছু অমিল পাওয়া যায়।

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TABLE OF CONTENTS

LIST OF MAIN ABBREBRIATIONS AND NOTATION

ASTM	American Society for Testing and Materials
BNBC	Bangladesh National Building Code
BUTM	Bangladesh Universal Transverse Mercator
CPT	Cone Penetration Test
CPTU	Cone Penetration Test with Pore water pressure
DMT	Dilatometer Test
SPT	Standard Penetration Test
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
WOH	Weight of Hammer
WOR	Weight of Rod
A_s	Sleeve area (normally 150 cm^2)
A_T	Tip area (normally 10 cm^2)
C_B	Correction factor for borehole diameter
C_N	Vertical effective stress correction factor
C_R	Correction factor for rod length
C_S	Correction factor for sampler geometry
D_r	Relative density
E_R	Energy ratio = ES/E60
e_{max}	Void ratio in the loosest state
e_{min}	Void ratio in the densest state
F	Non-dimensional friction
FR or R_f	Friction ratio
F_s	Sleeve force
f_s	Sleeve friction
F_T	Tip force
f_1	An empirical factor
I_C	Soil behavioral type

N	Field-measured SPT blow count
N_{60}	Energy and procedure-corrected blow count
$(N_1)_{60}$	Corrected SPT to a standard effective stress
q_c	Cone resistance (end bearing)
SPT	Standard penetration test
s_u	Undrained strength
φ'	Friction angle
σ'_{vo}	Vertical effective stress

CHAPTER 1
INTRODUCTON

1.1 General

Mitchell et al. (1978) provided several explanations for the growing interest in using in situ testing techniques over 40 years ago, including the following: (a) the ability to determine properties of soil deposits that cannot easily be sampled in the undisturbed state; (b) ability to test a larger volume of soil than can be tested conveniently in the laboratory; and (c) ability to avoid some of the challenges of laboratory testing, such as sample disturbance and the proper simulation of in situ stress.

Engineers should not expect a single in situ test to provide the answer to all geotechnical problems. Just as different laboratory tests are used to obtain specific soil properties, different in situ tests have been developed for the same purpose. The Standard Penetration Test (SPT) and Cone Penetration Test (CPT) are the examples of most commonly used in situ tests used in this part of the world including Bangladesh. However, like all other tests, these in situ tests also have a number of limitations. It is important that engineers understand both the advantages and the limitations of these tests, and their relationships. Geotechnical engineering often requires acute engineering judgment especially about the engineering properties of soil that calls for the use of many tools like SPT and CPT values for geotechnical design.

Local soil parameters are always helpful for a geotechnical professional to think about foundation design analysis. Though, nowadays geotechnical professionals are emphasizing to use of the Cone Penetration Test (CPT) data for the foundation design. Nevertheless, CPT test is comparatively expensive, and the field procedures are time consuming. Hence, it is not possible to conduct CPT at every site due to cost. CPT is a continuous process for measuring various soil parameters. But, in CPT test, the biggest difficulty is soil visualization. Moreover, there is a lack of experienced people for this work. On the other hand, Standard Penetration Test (SPT) is the most comprehensive used test for determining soil shear strength parameter of soil. SPT test is not more expensive than the CPT test. Besides, it requires less time to complete the work. In the SPT test, we can easily visualize and categorize the soil. But it is impossible to do that type of characterization in the CPT test. Therefore, it is high time to develop a relationship between SPT and CPT, depending on local soil conditions. Many researchers from different countries around the world have proposed the relationship between SPT and CPT according to the soil type of their country. Accordingly, in this study, I focused on developing a correlation between SPT and CPT from selected sites in Bangladesh soils.

1.2 Background and Rationale

Standard Penetration Test (SPT) is the most common method of soil investigation technique that can be applied in fields (Kara and Gunduz, 2010, Shahien and Abatal, 2014). Though, many foundation designs are based on SPT values, yet SPT has some disadvantages as it cannot often times generate accurate results due to sudden deviations in measured resistance due to human-error or subtle changes in soil characteristics (Kara and Gunduz, 2010). On the other hand, Cone Penetration Test (CPT) has become a well-established choice for conducting soil investigations; it can generate reliable information at a swift pace and it can be considered as an excellent complement to SPT for field inspection (Jarushi. AlKaabim and Cosentino, 2015). At present, geotechnical professionals have gained sufficient expertise to utilize local SPT data for foundation design. Therefore, it is also important to use CPT data for the aforesaid purpose. In order to achieve this, a consistent relation between SPT and CPT parameters is needed to be established (Akca, 2003). Numerous researches around the world conducted study on SPT-CPT correlations for soils from various geographic and geological locations to serve their purpose. For instance, in one study, the authors first reviewed the existing SPT-CPT correlations by considering historical progression, influencing factors, variance in past correlations and the existing correlations. Then, they carried out SPT and CPT tests within the Nile Delta of Egypt. They found their existing correlation generally coincided with the previous ones but still, they felt the need to update SPT-CPT correlations for the silty sand deposits of the Nile River Delta (Shahien, and Abatal, 2014). For Turkey soil, relationships between cone penetration resistance (qc) and SPT-N value were explored. The researchers (Kara and Gunduz, 2010) found lower $n = q_c / N$ ratio than that of the values they found in other external sources. On the other hand, they found higher values for power (Superscript) correlations. Although, correlation coefficients were found lower than that obtained from literatures due to Adapazari soil being heterogeneous (Kara and Gunduz, 2010). In a study to determine SPT-CPT correlations for granular soils, the authors emphasized the importance of difference between these two field tests. They stated SPT-N value should be corrected for the energy level. They also suggested the correction of cone resistance due to its unequal area and excess pore pressure (Chin et al., 1990). Robertson et al. (1983) proposed a method to determine Standard Penetration Test (SPT) N-values from Cone Penetration Test (CPT) by taking into account soil grain size and SPT energy input. The authors also discussed the issues with SPT and how those issues related to SPT-CPT correlations. Then, they presented recent data which included energy measurement during SPT. Finally, the authors included a chart to estimate mean grain size from CPT data Robertson et al, (1983). In a report on CPT and SPT Based Liquefaction Triggering Procedure, the authors mainly re-examined the aforementioned process for cohesionless soils. They also considered CPT based procedure along with an evaluation of the effects of variation in the magnitude of scaling factor on the SPT based method (Boulanger and Idriss, 2014).

It revealed that all these studies involved huge data on different penetration tests on a particular location to yield reliable correlations. Unfortunately, in the past, not many CPT tests were carried out to measure the properties of soils from Bangladesh. However, the recent trend in this respect is encouraging. Neither not many studies have been reported. As such, it is felt necessary that a study should be conducted on the relationship between SPT and CPT parameters for soils from Bangladesh, so that correlated parameters could be used to assess the soil parameters performing the simple SPT test instead of those from expensive CPT tests.

1.3 Objective of the Study

The present study aims at the following objectives.

(i) To find the relationship between CPT cone resistance and SPT values for selected location soils of Bangladesh.

(ii) To find a method of identifying soil depending on CPT resistances of Bangladesh soil.

1.4 Organization of the Thesis

This thesis reports primarily the relationship between SPT and CPT values in the context of Bangladesh soil conditions. The field test results are analyzed and findings are reported in five chapters. Chapter 1 introduces the hypothesis of the study. Chapter 2 presents the theoretical background and existing literature on the topic. Chapter 3 explains the test and data analysis program and procedures. Chapter 4 provides results and their relevant discussions. Finally, Chapter 5 summarizes the results in the form of conclusions. This chapter also suggests the scope of further studies related to the present investigation.

CHAPTER 2
LITERATURE REVIEW

2.1 General

Explorations below the surface frequently come across difficult or impossible soils to sample using traditional drilling and sampling techniques. Unconsolidated sands and silts below the water table, incredibly soft or sensitive clays, and highly weathered or structured materials, like surficial crusts or residual soils, are typical examples. Drilling and sampling may occasionally be hampered by uncommon groundwater conditions such as artesian or other. In these situations, penetration tests, such as the Standard Penetration Test (SPT) or the Cone Penetration Test (CPT)/Piezocone (CPTU), may yield more accurate results than laboratory studies carried out on defective materials. To distinguish between soft and firm zones, penetration tests, possibly the oldest and most popular type of in situ testing, involve pressing or driving a rod, point, or sampler into the earth. The relationship between the soil characteristics acquired from these penetration tests, SPT and CPT, has been investigated by numerous researchers throughout the world. The current work's main focus is the correlations between soil characteristics measured by SPT and CPT. Following sections present the fundamental ideas or mechanics underlying these in-situ test procedures as well as the relevant literature.

2.2 Standard Penetration Test (SPT)

Leutenegger (2021) provides an excellent and vivid description on the background, mechanism, equipment to be used, test procedure and test results to be obtained from the test SPT. They are being reproduced with slight modifications and presented as under.

2.2.1 Background of SPT

A dynamic penetration test called the SPT is used to gauge how difficult it would be to drive and install a thick-walled tube. In addition, the test is a sampling procedure that obtains a soil sample where the penetration occurs. The fact that it is the only in situ test to offer a model for soil classification and other index testing distinguishes it from all other tests, in the opinion of many engineers.

The history of SPT is presented by Fletcher (1965), Broms and Flodin (1988), and Rogers (2006), starting with Charles R. Gow's invention of the technique in or around 1902 (Fletcher 1965) when he employed a 25 mm (1 inch) open pipe driven into the earth to collect a soil sample. Until now, wash boring methods based on site-erected tripod equipment have been the main method used for soil exploration in the United States. A 50 kg (110 lb) weight was used to retrieve soil samples to force an open pipe into the ground. The Gow Co. joined the Raymond Concrete Pile Co. in 1922 (Anon, 2004) and over the following few years, Gow and H.A. Mohr are said to have continued to refine and modify the sampling process.

Around the same time as the 63.5 kg (140 lb) weight and 760 mm (30 in.) drop were standardized mainly by the firm and others, the 50 mm (2 in.) split spoon sampler was created. The test's record was the number of strikes needed to move the sampler 0.3 meters (12 inches) away. Up until around 1945, when industry-standard "A" size drill rods were produced, the sampler could only be advanced 300 mm (12 in) overall utilizing a 25 mm (1 in) drive pipe. A ball check valve was added to the sampler's top to reduce sample loss.

Parsons (1954) made one of the most significant changes to the test, noting the blows needed for each of three consecutive 150 mm (6 in) increments and taking the lowest total of the two increments for a penetration distance of 300 mm (12 in). The initial 150 mm (6 in.) increment, which many people refer to as a "seating" increment, is still taken even though this technique is no longer in use. The test measurement known as the "N-value" is obtained by adding the blows from the second and third 150 mm (6 in.) driving increments.

In order to provide a correlation with expertise in the design and construction of caisson foundations, Fletcher (1965) claims that the first goal of the SPT was to quantify the density of soil formations using a uniform approach. The apparatus described by Fletcher (1965) demonstrated some apparent differences from contemporary SPT apparatus: (i) there was no internal relief inside the sample barrel; (ii) a 24 in. long spoon was used; (iii) a pin weight hammer was shown as standard equipment; and (iv) a hardwood cushion block was used between the hammer and drive rods.

Modifications to the equipment and procedure to bring the test to the present day (2020) configuration will be discussed subsequently and should be obvious to the reader in comparison to the 1950s and 1960s arrangement of the test. The equipment and procedure used to conduct the SPT was standardized in 1958 in test procedure ASTM D1586.

Some geotechnical engineers feel that the SPT has outlived its usefulness for site investigations and geotechnical design and perhaps should be retired given that there are other options available. Some reasons given for this are that the test is outdated, the test results are too variable, and there are more advanced in situ techniques available such as the CPT/CPTU or DMT. For many years, a number of issues plagued the SPT:

(i) The test was considered highly variable (i.e., equipment and procedures varied too much);
(ii) Test results were historically too dependent on the operator; and
(iii) Control of the test has generally been taken away from engineers and given to drillers.

However, the SPT has some advantageous attributes that make it useful for many routine site investigations:

(i) The test concept, arrangement, and equipment are relatively simple, robust, and inexpensive;
(ii) The equipment is readily available from most drillers around the world and is easily adaptable to most drill rigs;
(iii) The procedure is relatively easy to carry out, and testing may be performed at reasonably frequent intervals, often being performed continuously in the upper layers of soil or the primary zone of influence for foundations;
(iv) A soil sample is usually obtained for visual/manual identification and index property evaluation;
(v) The test has a wide range of applicability, from weathered rock and gravelly sands to soft insensitive clay;
(vi) The test data are simple to collect and the test results are reduced rapidly in the field.

There is also an argument by some engineers that the SPT is a "one-number test", that is, the SPT only gives a single number to use in assessing soil behavior.

2.2.2 SPT Test Mechanism

According to the test procedure, a split tube soil sample barrel with the requisite dimensions must be driven a required distance using a specified amount of impact energy. Fig. 2.1 displays the current test's schematic. A falling weight or hammer with a mass of 63.5 kg (140 lb) is used in the test, and it is allowed to fall freely for 760 mm (30 in) before striking an anvil. Drill rods are attached to the anvil and extend to the tested or sampled depth. With each hammer blow, a sampling barrel, commonly known as a split spoon, is lowered into the soil and affixed to the end of the drill rods.

Typically, three 150 mm (6 in) intervals are marked off on the drill string with chalk, the hammer is raised and lowered, and the number of blows required to advance the spoon is recorded as N0-6, N6-12, and N12-18 for each 150 mm (6 in) increment. ASTM refers to the first 150 mm (6 in.) penetration as a "seating" penetration. The second two 150 mm (6 in.) increments' combined hammer blows are referred to as the SPT N value (with units of blows per 300 mm or blows per ft.) and are used as the test's reference measurement. As required by ASTM D1586 (2018), it is crucial to record and report the incremental blow count values for each 150 mm (6 in.) of material.

If the full 450 mm (18 in.) of penetration cannot be achieved, ASTM D1586 (2018) permits the test to be stopped if one of the following conditions is met:

(i) A total of 50 hammer blows have been applied during any one of the three 150 mm (6 in.) increments;

(ii) A total of 100 hammer blows have been applied; or

(iii) There is no observed advance of the sampler during the application of ten successive hammer blows.

The number of hammer blows required to accomplish the desired penetration increment is recorded as the penetration resistance if only partial penetration occurs, for instance, "50 for 2 in." The drill rods and spoon may proceed independently without being driven in exceptionally soft clays. A common name for this is "Weight of Rod" (WOR). It is known as the "Weight of Hammer" (WOH) if the spoon and rods move forward after the hammer has been mounted. When this happens, it is crucial to record the size of the drill rods being utilized as well as the water level inside the boring on the boring logs. The weight that is somewhat buoyant for that distance below the water's surface may be included in the overall mass of the spoon and rods.

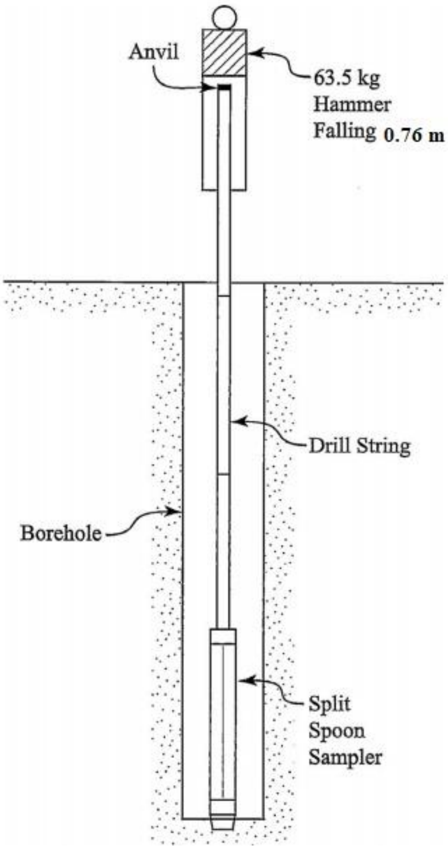


Fig. 2.1 Schematic of Standard Penetration Test (after Leutenegger, 2021)

The amount of soil collected for that drive is noted after the spoon is brought to the surface and opened. We call this recovering. The ASTM protocol includes recording the recovery, which should be done on the boring logs. The recovery ratio can be utilized to help evaluate the SPT data qualitatively. For instance, if the recovery ratio is continuously low in deposits with coarse grains, this may indicate the presence of large gravel or cobbles that are too numerous to fit inside the spoon. After recording the Recovery, the soil is typically sent back to the office or lab and put into watertight containers like glass jars or bags for preservation, or it is covered in plastic and aluminum foil.

2.2.3 Test Equipment of SPT

The SPT's mechanics, which were discussed in the preceding part, represent a very straightforward idea; nevertheless, because the exam is regarded as so specific, how it is carried out might vary considerably. These are a consequence of the several test instruments that have been and are still used in the field to conduct the test. The four main parts of the test apparatus are the drop weight or hammer with an anvil, a string of drill rods connecting the sampler to the hammer, and a barrel sampler, as shown in Fig. 2.1.

2.2.4 Test Procedure of SPT

The ASTM D 1586 (2018) and ASTM D 6066 (2011) specifications describe the test methods and apparatus used to conduct the SPT. The SPT is a reference test used internationally and covered in ISO 22476-3 (2005).

2.2.5 Factors Affecting SPT Results

The SPT aims to have the test response reflect variations in soil behavior rather than variations in test methodology. A variety of circumstances can influence the outcomes of the SPT. The test was conducted in a more-or-less rudimentary manner. The results indicated significant variability due to the historical variability in drilling equipment, procedures, personnel, etc. The energy is mainly uncontrollable and varies significantly from drop to drop in drop hammer systems using a rope and cathead, which leads to unpredictable effects. However, many of these problems have been resolved by employing a calibrated automatic hammer. Only calibrated hammers should be utilized when performing the SPT for the following three reasons:

(i) Automatic hammers provide a repeatable operator-independent known energy.

(ii) A fully enclosed automatic hammer is much safer for the drill crew;

(iii) Automatic hammers provide increased productivity in the drilling operation.

The SPT N-value can be influenced by factors other than energy, according to a number of studies (Fletcher 1965; Schmertmann 1978; Decourt 1989; Kulhawy and Trautmann 1996). Almost all of these variables fall into one of two categories: (i) differences in the equipment and (ii) variances in the operator or procedure. The remaining factors are compiled in Table 2.1 in the event that a calibrated automatic hammer is employed.

Table 2.1: Factors other than hammer energy that may influence SPT results (after Leutenegger, 2021)

Variation Type	Item of variation	Description
Equipment variations	Sampler dimensions	Variations in exact sampler dimensions vary around the world. Sampler should conform to the latest ASTM standard and should be measured before use
	Liners/no liners	Use of liners vs. no liner but spoon with internal relief increases blow counts
	Use of damaged or deformed tip on sample spoon	Damaged shoe may change blow counts
	Using damaged drill rods	Drill rods that are slightly bent or otherwise damaged tend to reduce energy transfer giving artificially high N-values
Procedural variations	Inadequate cleaning of the borehole	SPT is only partially made in original soil. Sludge may be trapped in the sampler and compressed as the sampler is driven, increasing the blow count
	Failure to maintain sufficient hydrostatic head in the boring	The water table in the borehole must be at least equal to the piezometric level in the sand, otherwise the sand at the bottom of the borehole may be transformed into a loose state
	Using a too large pump	Too high a pump capacity will loosen the soil at the base of the hole causing a decrease in blow count
	Over-washing ahead of casing	Low blow count may result in dense sand since sand may be loosened by over-washing
	Drilling method	Drilling technique (e.g., cased holes vs. mud stabilized holes) may result in different N-values for the same soil. The SPT was originally developed from wash boring techniques. Drilling procedures which seriously disturbs the soil will affect the N-value, e.g., drilling with cable tool equipment
	Rate of testing	In saturated soils, a fast rate of testing may increase pore water pressures.
	Plugged casing	High N-values may be recorded for loose sand when sampling below groundwater table. Hydrostatic pressure causes sand to rise and plug casing

Table 2.1: Factors other than hammer energy that may influence SPT results (after Leutenegger, 2021)

Variation Type	Item of variation	Description
	Loose drill rod connections	Energy losses can occur from loose rod connection giving artificially high N-values
	Marking drive increments	Drive marks should be made after the spoon and drill string has been just set on the bottom of the borehole but before the hammer is attached or rods are released
	“Seating” the spoon before marking the rods	There is no such thing as “seating” of the spoon before marking the three 0.15 m (6 in.) incremental drive lengths
	Sampler plugged by gravel	Artificially high blow counts result when gravel plugs sampler; resistance of loose sand could be highly overestimated
	Carelessness in counting the blows and measuring penetration	Poor observations of incremental blow counts may produce errors in N-values.
	Using drill holes that are too large	Holes greater than 100 mm (4 in.) in diameter are not recommended. Use of larger diameters may result in decreases in the blow count from stress relief at bottom of hole
	Attitude of operators	Blow counts for the same soil using the same rig can vary, depending on who is operating the rig, and perhaps the mood of operator and time of day

2.2.6 Corrections of SPT Values

It is required to convert the test findings to a standard energy level because the SPT blow count is directly related to the hammer system energy. This will enable accurate comparison of test results between various hammer systems and accurate interpretation of the test data. In order to take into account, the hammer energy, rod length, borehole diameter, and sampler shape, adjustments are made to the field SPT N-value.

2.2.6.1 Corrections for Hammer Energy, Equipment, and Drilling: N to N_{60}

A reference value of 60% of the theoretical free-fall energy is utilized to bring N-values to a standard reference point based on a number of recommendations. The 60% energy level was also the foundation for various correlations for various soil parameters because it indicates a reasonable average energy level that has been applied since the 1960s using conventional SPT equipment. In order to rectify the field recorded N-values to a reference energy level of 60% and take into account the sampler geometry, drill rod length, and borehole diameter, a variety of correction factors have been included. Thus, the following definition of the energy-corrected blow count is possible:

$$N_{60} = N E_R C_B C_s C_R \tag{2.1}$$

Where,

N_{60} = Energy and procedure-corrected blow count

N = Field-measured blow count

E_R = Energy ratio = ES/E60

C_B = Correction factor for borehole diameter

C_S = Correction factor for sampler geometry

C_R = Correction factor for rod length

Recommended values for these adjustment factors are shown in Table 2.2. SPT N-values obtained from field measurements must always be corrected using Eq. (2.1) and presented as corrected blow counts, N_{60}.

Table 2.2: Recommended average SPT correction factors: N to N_{60} (after Leutenegger, 2021)

Borehole Diameter	**C_B**
65 mm – 115 mm (2.5 in.–4.5 in.)	1.00
150 mm (6 in.)	1.05
200 mm (8 in.)	1.15
Sampler	**C_s**

Table 2.2: Recommended average SPT correction factors: N to N_{60} (after Leutenegger, 2021)

Sampler without liner			1.00
Sampler with liner or barrel diameter same as shoe diameter			0.83
Drill Rod Length			**C_R**
< 3m (10ft)			0.75
3 m – 4 m (10 ft. – 13 ft.)			0.80
4 m – 6 m (13 ft. – 20 ft.)			0.90
6 m – 10 m (20 ft.– 30 ft.)			0.95
>10 m (>30 ft.)			1.00
Hammer and Drop Mechanism			
North America	Automatic	--	1.40
	Safety	Rope and cathead	1.00
	Donut	Rope and cathead	0.75
Japan	Donut	Trip	1.30
	Donut	Rope and cathead	1.10
China	Donut	Trip	1.00
	Donut	Rope and cathead	0.90
United Kingdom	Safety	Trip	1.00
	Safety	Rope and cathead	0.80

2.2.6.2 Correction for Overburden Stress in Sands: N_{60} to $(N_1)_{60}$

The SPT N-value will rise with depth in a homogeneous sand deposit with a fixed void ratio or relative density since the mean effective stress also rises with depth. Therefore, the N-value must be adjusted for the impact of this fluctuating stress level to produce a single characteristic value that depicts a single relative density. A correction factor is typically used to offer a constant effective stress reference to accommodate this. As listed in Table 2.3, numerous overburden correction variables have been proposed. The general format for applying a correction factor is as follows:

$$(N_1)_{60} = C_N N_{60} \tag{2.2}$$

Where,

N_{60} = Energy-corrected blow count

$(N_1)_{60}$ = Corrected blow count to a standard vertical effective stress level

C_N = Vertical effective stress correction factor

Table 2.3: Suggested SPT overburden correction factors for sands: N_{60} to $(N_1)_{60}$ (after Leutenegger, 2021)

Formula for C_N	Units of σ'_{vo}	References
$C_N = 50/(10 + \sigma'_{vo})$	psi	Gibbs & Holtz (1959)
$C_N = 1/(1 + 2\sigma'_{vo})$; $\sigma'_{vo} \leq 15$	ksf	Bazaraa (1967)
$C_N = 4/(3.25 + 0.5\sigma'_{vo})$; $\sigma'_{vo} > 15$		
$C_N = 0.77 \log_{10}(20/\sigma'_{vo})$	kg/cm^2, tsf	Peck et al. (1974)
$C_N = 1 - 1.25 \log_{10}(\sigma'_{vo})$	kg/cm^2, tsf	Seed (1976)
$C_N = 1.7/(0.70 + \sigma'_{vo})$	kg/cm^2, tsf	Tokimatsu &Yoshimi (1983)
$C_N = (1/\sigma'_{vo})^{0.5}$	kg/cm^2, tsf	Liao & Whitman (1986)
$C_N = 2/(1 + \sigma'_{vo})$; For NC medium loose fine sand	kg/cm^2, tsf	Skempton (1986)
$C_N = 3/(2 + \sigma'_{vo})$; For NC dense coarse sand		
$C_N = 1.7/(0.7 + \sigma'_{vo})$; For OC fine sand		

Skempton's proposed correction factors are the only ones that consider gradation, as seen in Table 2.3. The adjustment factor recommended by Liao and Whitman (1986) seems to be the one that is most frequently employed. Simple and typically in the middle of the other suggested correction variables, it is a good choice. The phrase $(N_1)60$ refers to an effective vertical stress of 1 kg/cm^2 (1 tsf), for which the correction factor equals 1. When employing the SPT in fine-grained soils, there is insufficient data to support the use of overburden correction factors. To estimate undrained shear strength in medium to stiff clays (N>10), Oskorouchi and Mehdibeigi (1988) recommended applying an overburden correction factor to SPT N-values (Leutenegger, 2021).

2.2.7 Interpretation of Soil Properties from SPT-Value

Numerous researchers have connected different SPT values with a wide range of cohesive and cohesionless soil qualities. Researchers discovered a link between specific soft/weak rock properties and SPT readings. In that regard, SPT is a flexible and frequently used test. The following is a list of some of the correlation items. Some of the significant correlations are then described. The complete list is in Leutenegger (2021).

For cohesionless soil;

(i) Relative density

(ii) Friction angle

(iii) Elastic modulus

(iv) Constrained modulus

(v) Small-strain shear modulus

(vi) Shear wave velocity

(vii) Liquefaction potential

For cohesive soil;

(i) Undrained shear strength

(ii) Stress history

(iii) Insitu lateral stress

(iv) Elastic modulus of soil

(v) Small-strain shear modulus

2.2.7.1 Relative Density of Cohesionless Soil

Several early correlations between SPT N-values and the relative density, D_r, of coarse-grained soils were given when the SPT was conducted using either a safety hammer or a donut. Variations in the composition, geologic origin, stress history, moisture conditions, and techniques and equipment utilized for coarse-grained soils affect these correlations differently (Leutenegger, 2021). For instance, Gibbs and Holtz's (1957) correlation used a spoon with a fixed internal diameter and no relief. As a result, the blow counts may be higher than those that would have been obtained by using a spoon with internal relief. Leutenegger (2021) lists several correlations that were created after 1975.

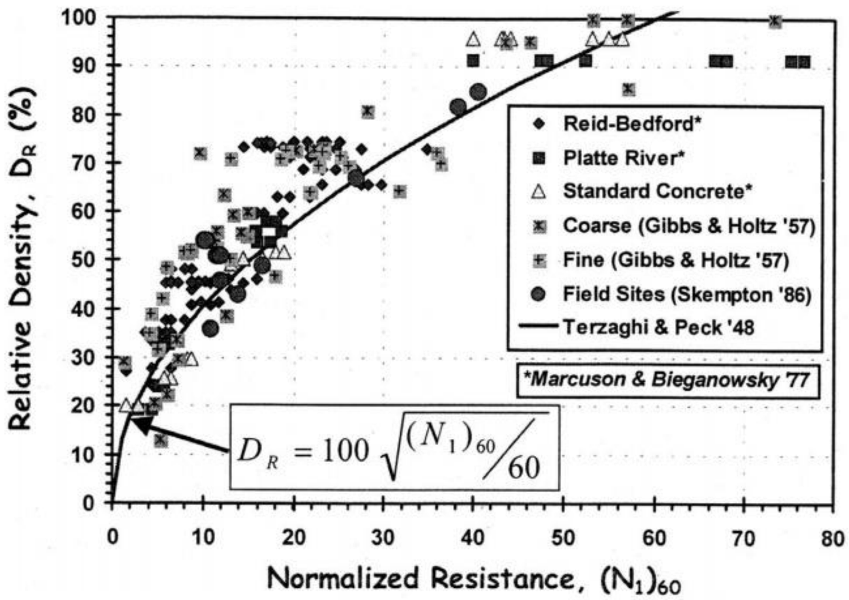


Fig. 2.2: Correlation between SPT $(N_1)_{60}$ and relative density (After NHI, 2002).

Given variations in grain-size distribution, age, stress history, geologic origin, etc., and variations in field procedures employed for obtaining N-values, no single expression can be utilized to characterize the relationship between SPT blow counts and relative density for all sands. A method for determining relative density from N-values that accounts for gradation, as seen by the difference in the void ratio $(e_{max} - e_{min})$, was proposed by Cubrinovski and Ishihara (2001). Using energy and stress-corrected blow counts, $(N_1)_{60}$, various correlations are shown in Fig. 2.2.

2.2.7.2 Friction Angle of Cohesionless Soil

By providing an estimate of the drained friction angle, φ', the SPT data may help determine the shear strength of granular soils. It should be understood that the value is not fixed but varies for the stress level, stress path, loading conditions, etc., and that any estimate does not account for these variables. Several ideas have been put forth by different researchers for determining SPT N-values. A comparison between SPT $(N_1)_{60}$ results and those derived from triaxial compression testing is shown in Fig. 2.3. This connection seems to be used. Engineers should exercise caution when calculating the friction angle in sands from N values. Any relationships should be supported by local knowledge of foundation performance.

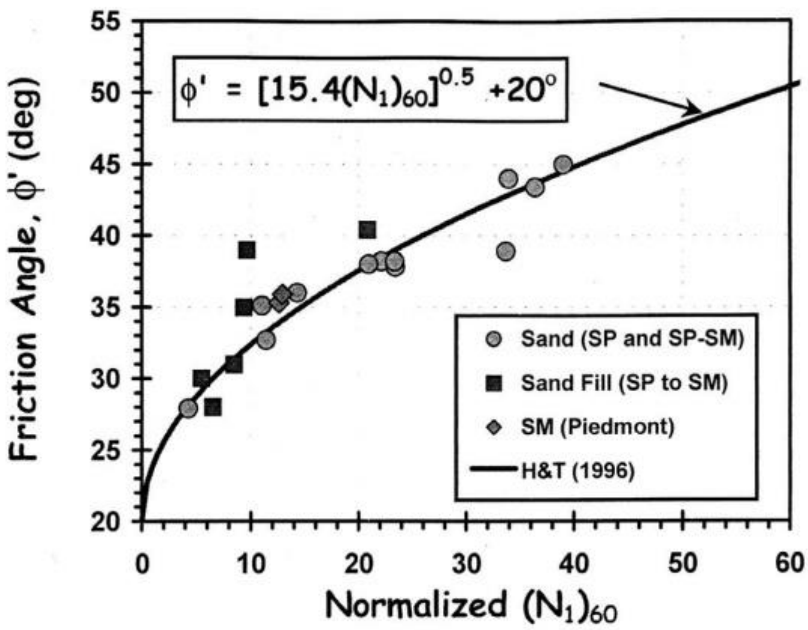


Fig. 2.3: Correlation between $(N_1)_{60}$ and φ′ (After NHI, 2002).

2.2.7.3 Undrained Shear Strength in Cohesive Soil

Using N to estimate the undrained shear strength is one of the practical applications of SPT in fine-grained soils. It may be expected that the results of the SPT would indicate a more or less linear increase in N values with increasing depth in soft to extremely soft typically cemented clays. Increasing effective stress and undrained strength would be consistent with this. A constant N/σ'_{vo} would result from dividing the normalized N value by the vertical effective stress, σ'_{vo} indicating a constant normalized undrained shear strength.

A straightforward chart connecting SPT N-values to fine-grained soils' consistency (unconfined compressive strength) can be found in most soil mechanics or foundation engineering texts. A list of various relationships is presented in Figure 2.4. Alternatively, the unconfined compressive strength (UCS) can be calculated using the SPT N-value. It should be noted that most of these correlations employ the "uncorrected" SPT N-values and, as a result, can vary based on the correlation's development system. Only a small amount of research has been done to link clay strength from the energy-corrected SPT N-value, N_{60}. The link suggested by Stroud (1974) for the association between N-values and the undrained strength of stiff intact clays is as follows:

$$s_u = f_1 N \quad (2.4)$$

Where, f_1 = an empirical factor

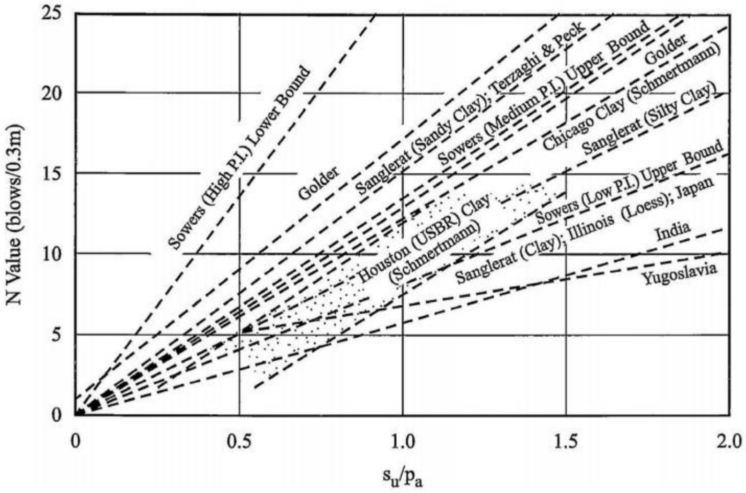


Fig. 2.4 Comparison of historic reported correlations between SPT N-value and undrained shear strength. (After Kulhawy and Mayne 1990).

The SPT results from which the N-values were derived were based on the modern practice so that the parameter f_1 is more properly defined as:

$$f_1 = s_u/N_{60} \quad (2.5)$$

2.3 Cone Penetration Test (CPT) and Piezocone Test (CPTU)

Cone Penetration Tests have been utilized for over 70 years in many regions of the world to ascertain site stratigraphy, assess strength traits and other soil attributes, and design foundations, among many other uses. Cone tests are incredibly adaptable and have many qualities that make them ideal for in-situ testing. The test has a straightforward premise and can be executed easily. Cone tests have a wide range of uses and can be utilized in various soil types.

Numerous studies have been published on CPTs, cone testing, data interpretation, and cone design applications. The CPT/CPTU is helpful for a quick and more thorough study of the intricate soil layering frequently missed during conventional test drilling and sampling because it offers a nearly continuous record of the stratigraphy. In general, over the past 10 to 15 years, the empirical interpretation of CPT/CPTU data has reached an advanced stage of maturity (Leutenegger, 2021).

2.4 Mechanics of CPT/ CPTU

The CPT is an intrusive, full displacement cylindrical probe pushed from the ground surface with or without a borehole. It is typically made of stainless steel and has a diameter of around 35.7 mm (1.405 in.). The static hydraulic thrust of a standard drill rig or specialized hydraulic pushing rig is used to advance the cone, which has a tip apex angle of 60°, at a pace of 2 cm/s. Fig. 2.5 provides a schematic representation of this idea. Forces or pressures exerted on the cone tip are gauged as the advance progresses. The cone's dimensions and suggested testing methods are covered in ASTM D3441-16 (2016) and ASTM D5778-20 (2020). The International Organization for Standardization has also standardized the CPT and CPTU in ISO 22476-1 (2022).

2.4.1 Mechanical Cones

Early static CPTs were built using straightforward mechanical systems like push rods, cones, and external load cells. According to reports, the "Dutch" CPT was originally applied in the Netherlands to gauge hydraulic fill's thickness and bearing capacity around 1930. One or two men pushed the cone with an apex angle of 60° and an end area of 10 cm2. These only allowed for an exploring depth of around 3 m (10 ft). Cone resistance was measured at the ground's surface using a mechanical load cell or pressure gauge. Most early cones used a dual rod system, pushing the cone forward first with a pair of outside rods and then again with a set of inner rods, only measuring the resistance at the cone tip.

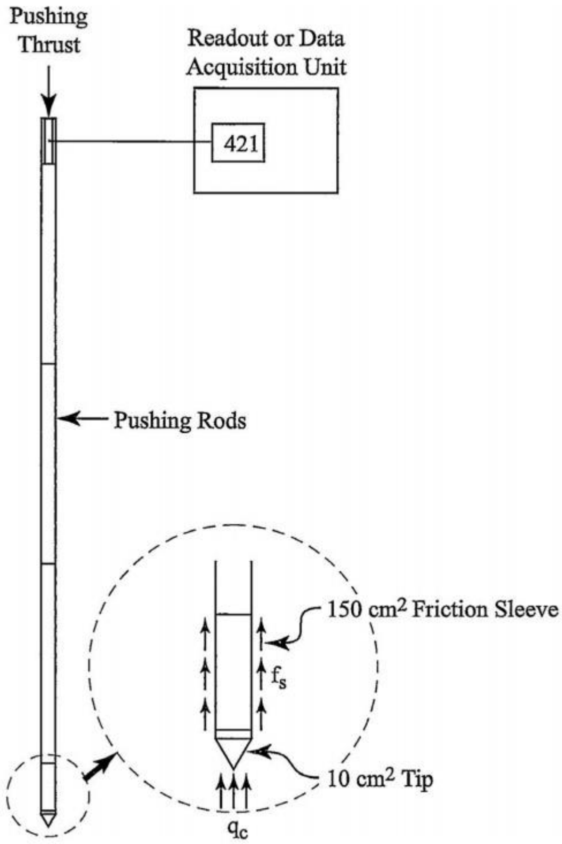


Fig. 2.5: Principle of cone penetrometer testing (After Leutenegger, 2021).

Begemann (1953) modified mechanical cones by proposing a sleeve behind the cone tip to measure the local friction. The name "friction cone" is more often used, while Begemann (1953) referred to this design as the "adhesion jacket cone." Begemann's sleeve had a 150 cm2 surface area.

The cone must first be moved to the test depth by pushing on the outside rods, which calls for another double-rod system. The inner rod is advanced to the test depth, around 40 mm (1.5 in), to measure the tip resistance. The inner rod is still pushed after the initial 40 mm (1.5 in.) push to engage the friction sleeve. The tip and the sleeve are resistant with an additional push of roughly 40 mm. After that, subtraction is used to get the sleeve resistance. The procedure for moving the cone while wearing a friction sleeve is shown in Fig. 2.6.

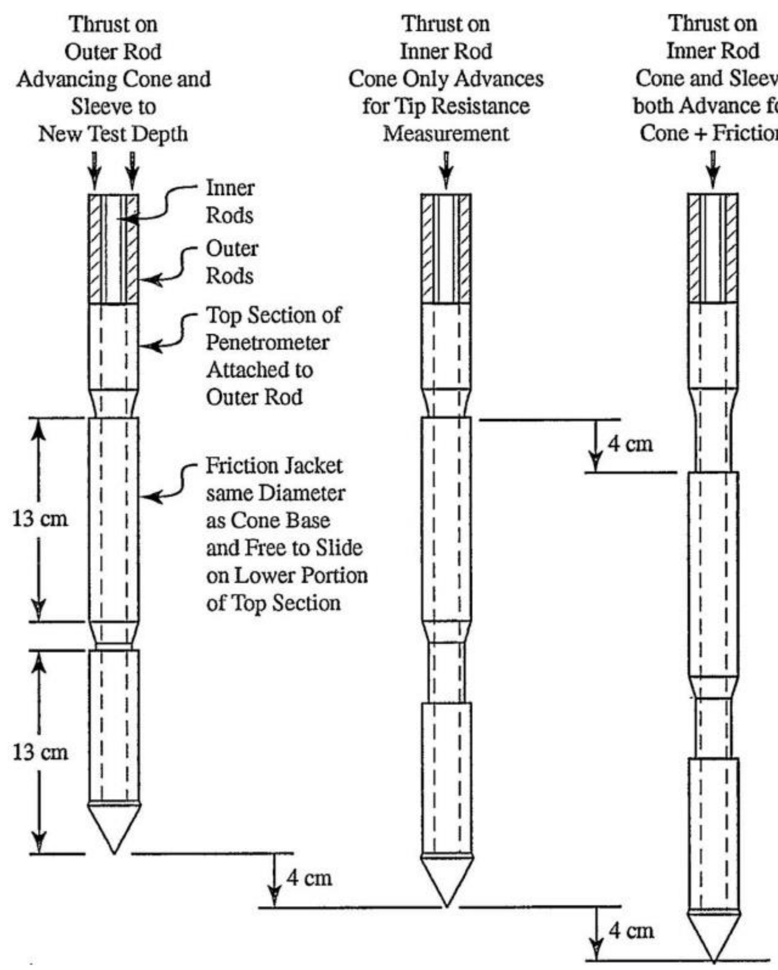


Fig. 2.6: Sequence of advancing a mechanical cone. (After Leutenegger, 2021).

The usage of mechanical cones is relatively impractical due to their numerous shortcomings. The double rod system is complicated and typically requires the fabrication of a unique set of rods; in other words, standard drill rods cannot typically be utilized. Due to the design and construction, earth particles might get inside or stick to some of the sliding parts, which would cause the cone to jam. Frictional losses could also exist in the double rod arrangement.

The mantle cone and friction jacket cone produce discontinuous data rather than a continuous profile since they can only be used to deliver test findings at intervals of approximately 150 mm. When the cone goes over alternating layers of soft and stiff soil or in highly stratified soils, it might be challenging for the operator to read the load cell precisely. Some unique layering may be overlooked when the load changes substantially over comparatively short distances.

2.4.2 Electric Cones

Since the 1970s, electric cones have become more widely used. Load cells are built into the cone body to measure the force at the tip and sleeve. Strain gages are often installed in the load cells. Modern technology has been devised that measures the load and transmits the data to the surface utilizing electrical components. Even cones without a connection have been utilized, instead using a down-hole memory module. Fig. 2.7 depicts a cross-section of a standard electric CPT cone body. Although other sizes are available, the typical electric cone for routine work has a tip area of 10 cm^2 and a friction sleeve area of 150 cm^2.

A computer automatically records the data as the exam progresses. As the cone is advanced, the results are shown in real time so that the operator can immediately see the soil conditions. The information is often shown as a function of depth vs. unit tip and sleeve resistance. These two measurements can assess soil qualities, indicate site stratigraphy, and drive foundation design. Compared to mechanical cones, electric cones have a variety of definite advantages, such as the following: Since only one push rod is needed, almost any rod system can be used. Additionally, the data may be automatically recorded for easier and quicker reporting, the testing interval is closer for better stratigraphic delineation, and the results are typically more reliable because the test is essentially operator-independent. Not every electric cone has the same design. Generally speaking, there are two categories of electric cones: those with tip and sleeve load cells that are intended to be completely independent and those with tip and sleeve load cells that are more or less in series. The latter style is frequently referred to as a "subtraction" cone.

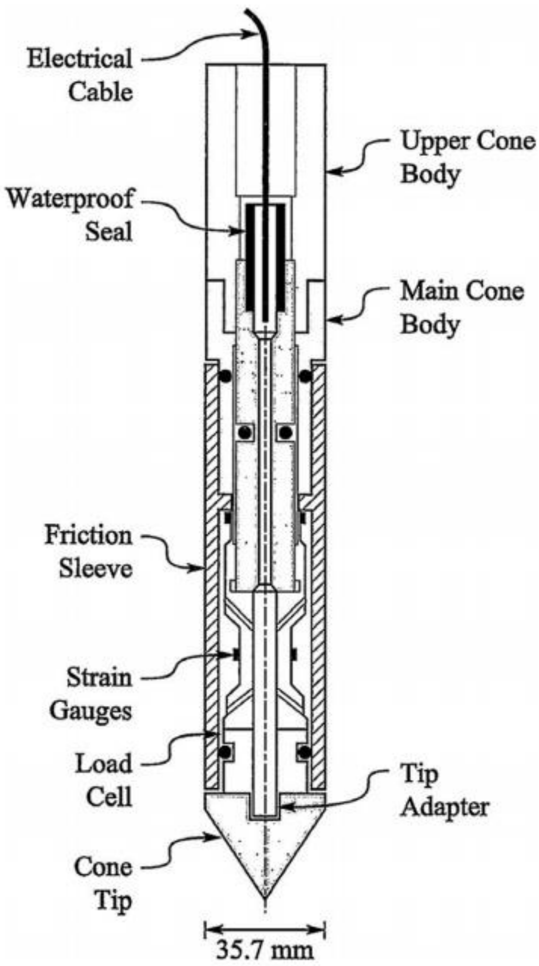


Fig. 2.7: Section through electric cone penetrometer (After Leutenegger, 2021).

The friction sleeve needs to be unrestricted in its motion for an appropriate response. The tip or sleeve resistance, or both, may be incorrect if adequate clearance is not provided at the ends of the sleeve in the design. Additionally, sufficient space must exist between the cone tip and friction sleeve to ensure that tip force transfer is not hindered. In order to prevent water from getting into the load cells, rubber "O" rings are typically employed. Additionally, some sort of soil seal is sometimes utilized at the ends of the friction sleeve to prevent soil from getting between the sleeve and tip or sleeve and body.

Some cones also have an inbuilt inclinometer to track the cone's tilt away from vertical. This measurement is more frequently utilized to warn early about a problem rather than to amend the test findings. Van de Graaf and Jenkel (1982) discussed using data from an internal inclinometer to correct the CPT depth. They demonstrated how depth mistakes of up to 1.2 meters can happen during a CPT sounding at a depth of 30 meters. The likelihood of cone damage or loss often increases if the cone deviates from vertical by more than around 5°. While a gradual deviation could indicate that the rods were not vertical at the start of the test or that the pushing is not vertical, a sharp deviation might indicate that the cone has encountered an obstruction like a cobble or random, uncontrolled fill.

2.4.3 Electrical Piezocone Cones

The CPTU is an electric friction cone primarily constructed the same as a regular electric friction cone, except that it additionally has a pressure transducer positioned inside the cone body to detect soil pore water pressure as the cone advances. It is also referred to as PCPT or CPTu. A further tool for describing the underlying soil conditions is the measurement of pore water pressure. Eliminating the friction sleeve and measuring the pore water pressure and tip resistance is an alternate design for a CPTU.

The Delft Soil Mechanics Laboratory built the first piezocone in 1962, according to Vlasblom (1985), though Janbu and Sennesset (1974) reported the first observations of pore water pressure during cone penetration. Torstenson (1975) and Wissa et al. (1975) unveiled two pore pressure probe variations simultaneously the following year. Although the location of the filter element varied, the probes described by Torstenson (1975) and Wissa et al. (1975) both measured only pore water pressure. The ASTM D5778 (2020) standard test method outlines the tools and processes for performing piezocone testing.

2.4.4 Test Procedures of CPT/ CPTU

ASTM and ISO standardization of the CPT and CPTU. Numerous recommendations in these standards concern the documentation of test results and standardization of cone geometry (including apex angle, tip, sleeve area, etc.). The test is performed with the rate of advance set to 20 mm/s, and the operation is relatively straightforward because just a few external components are needed. Measuring the depth in addition to the cone tip resistance and sleeve friction is necessary. Many electro-mechanical devices may be used to measure depth, and many of them use a reference point and a rotating potentiometer coupled to the cone rods. Advanced systems, such as self-contained cone trucks, frequently require an electrical system. Whatever method is employed, using a consistent, reliable reference point is critical.

2.4.5 Factors Affecting Test Results

The test findings from the CPT can be affected by several circumstances, even though the test equipment and technique are generally stated. In contrast to the SPT, the CPT does not have as many issues or uncertainties simply because of how the test is set up and how data are gathered. The following sections provide a brief overview of several factors that could influence CPT/CPTU findings. In some circumstances, the discussion is purposefully condensed because it is thought that most CPT work will be done with a cone measuring 10 cm2 (1.55 in^2) and having a tip apex angle of 60°. DeRuiter (1982) states that errors can also happen while using electric cones, typically due to calibration or zero load errors. Readings with zero load must be taken before and after each sounding to check for mechanical or electrical issues. The load cells must be calibrated routinely.

2.4.6 Data Reduction and Presentation of Test Results

Data reduction for the CPT/CPTU results is a relatively simple process. By dividing the measured tip load (force) by the cone tip projected end area, the following value is obtained:

$$\mathrm{q_c} = \mathrm{F_T}/\mathrm{A_T} \tag{2.3}$$

Where,

q_c = Tip resistance (end bearing)

F_T = Tip force

A_T = Tip area (normally 10 cm^2)

By dividing the measured sleeve force by the sleeve area, unit sleeve friction, also known as skin friction

$$\mathrm{q_c} = \mathrm{F_T}/\mathrm{A_T} \tag{2.4}$$

Where,

f_s = Sleeve friction

F_s = Sleeve force

A_s = Sleeve area (normally 150 cm^2)

Normal units for q_c and $f_s$are either kg/cm^2 or tons/ft^2. An additional parameter that combines the tip and sleeve measurements is called the friction ratio and is defined as

$$\mathrm{FR\ or\ R_f} = f_s/q_c \times 100\ (\%) \tag{2.5}$$

The data are shown as q_c, f_s, and R_f vs. depth, so it is possible to determine how these parameters vary vertically at the site. Fig. 2.8 illustrates a typical CPT profile produced from an electric cone. Examples of typical CPTU outcomes in soft clay are shown in Figure 2.9.

2.4.7 Interpretation of Results for Stratigraphy of Site

The outcomes of CPT/CPTU can be used to assess site stratigraphy and estimate various particular soil attributes for coarse- and fine-grained soils. The interpretation of specific soil qualities from CPT/CPTU has more or less matured over the last 10–15 years. Although more observations have been added to the database, many empirical correlations have not been significantly altered. The CPT/CPTU measurements frequently show variances in penetration resistance, which can indicate subsurface soil conditions. Looking at the penetration records of q_c or q_t and f_s versus depth is the quickest way to get a preliminary indication of changes in stratigraphy. Significant changes in soil stratigraphy can also be detected with the additional measurement of pore water pressure. The friction ratio may be helpful as a soil-type indicator.

Instead of getting samples from test borings, soil conditions may be identified using the CPT/CPTU data. This method is indirect but based on extensive research and years of experience, even though it occasionally gives false information. There is no tried-and-true method for consistently identifying soils. Also, remember that a CPT's response (i.e., q_c and f_s) is an average response affected by a sizable amount of soil. This makes it nearly impossible to discern extremely thin layers. Since identification is based on soil behavior or response to the test, it is preferred to classify when evaluating soil conditions from CPT/CPTU data.

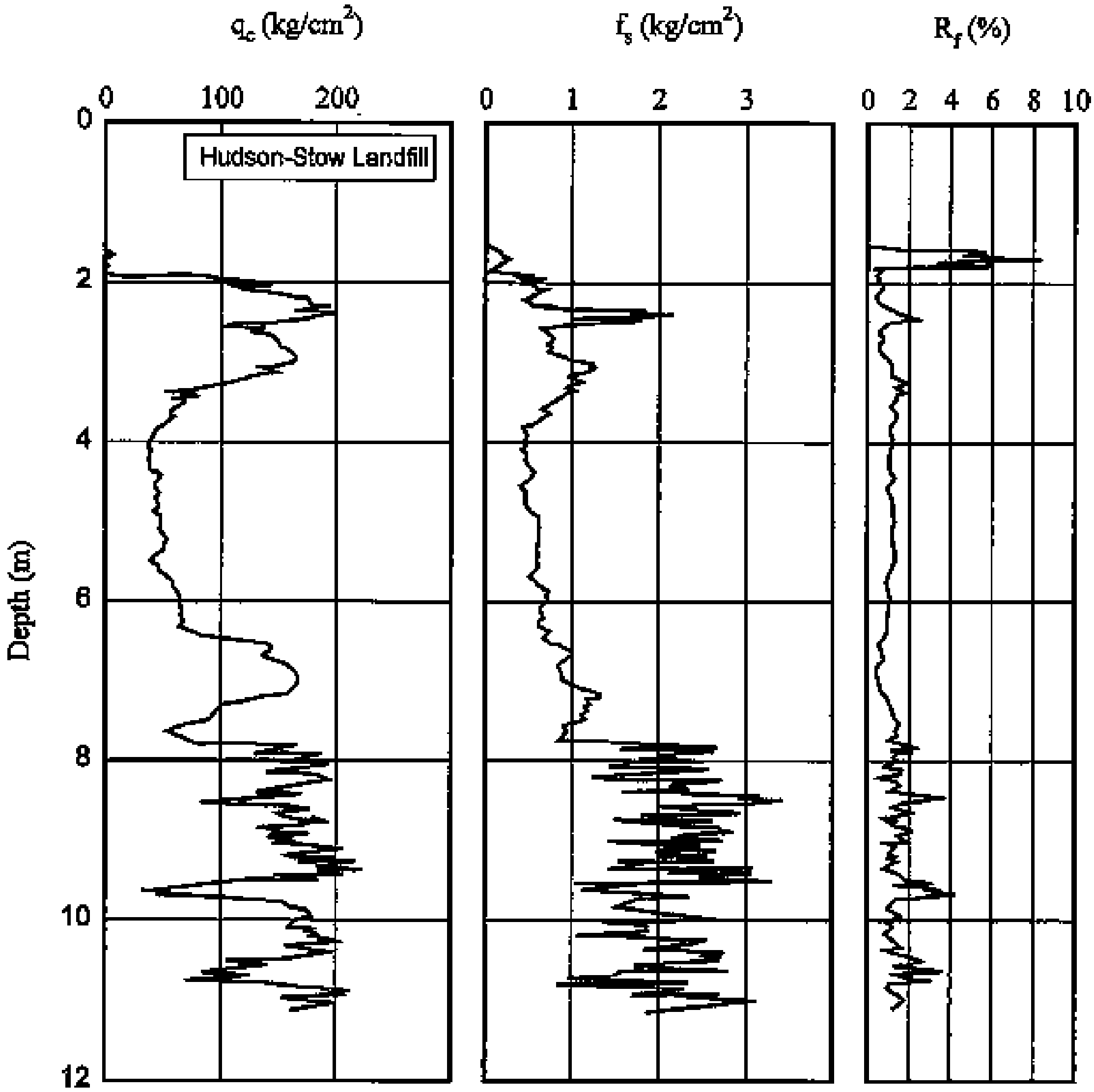


Fig. 2.8: Typical CPT data obtained in sand (After Leutenegger, 2021).

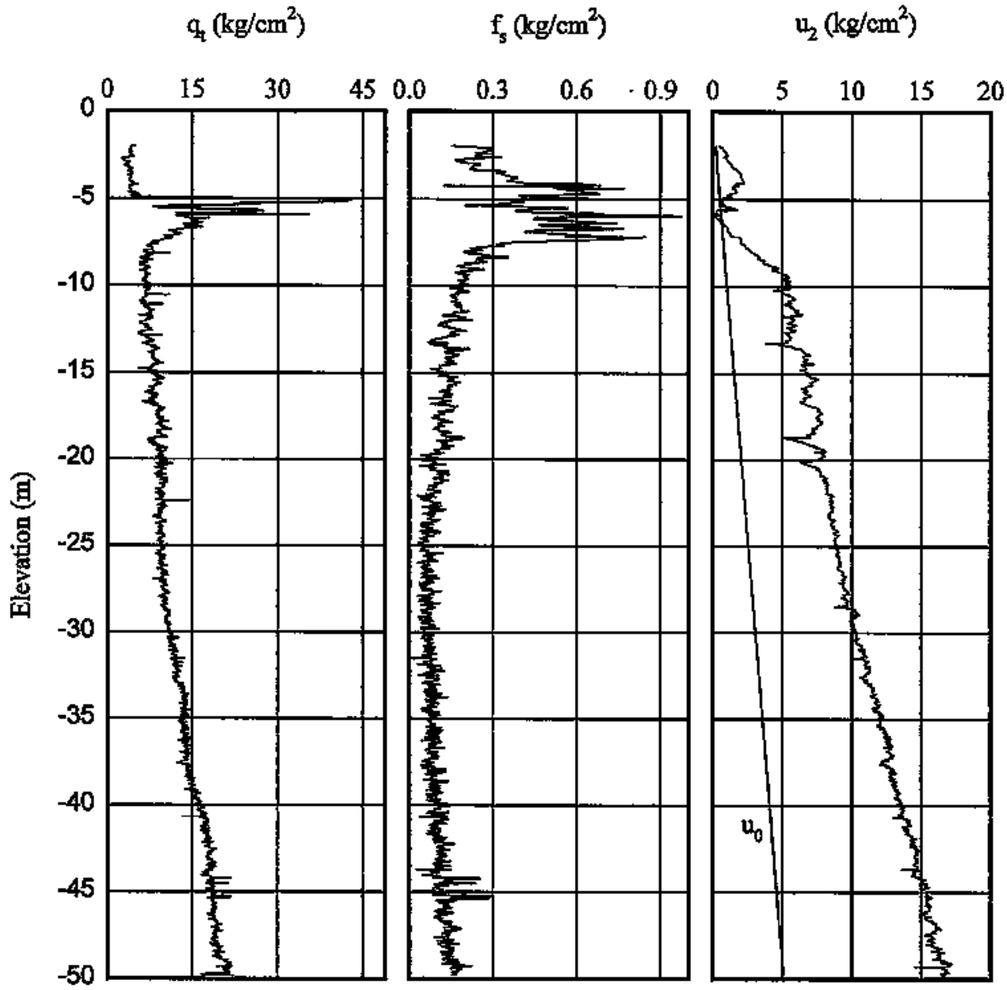


Fig. 2.9: Typical CPTU data obtained in soft clay (After Leutenegger, 2021).

2.4.8 Soil Identification from q_c, f_s, and R_f

Cone tip resistance, q_c, and sleeve friction, f_s, are independently measured by electric cones. These numbers can be combined to define the friction ratio, F_R, as given by Eq. (2.5), even if they have not been corrected for the effects of pore pressure. Begemann (1965) proposed using the sleeve friction and cone tip resistance to create a soil profile. He stated that F_R values less than 2.5% would indicate sand, larger than 3.5% would indicate clays, and between 2% and 4% as mixed composition soils. By combining the friction ratio and cone tip resistance acquired from electric cones, several charts have been proposed in determining the kind of soil (e.g., Douglas and Olsen 1981; Robertson et al. 1986). Most of these graphs take on the overall shape depicted in Fig. 2.10, where tip resistance and friction ratio are plotted, and zones of soil behavior are suggested.

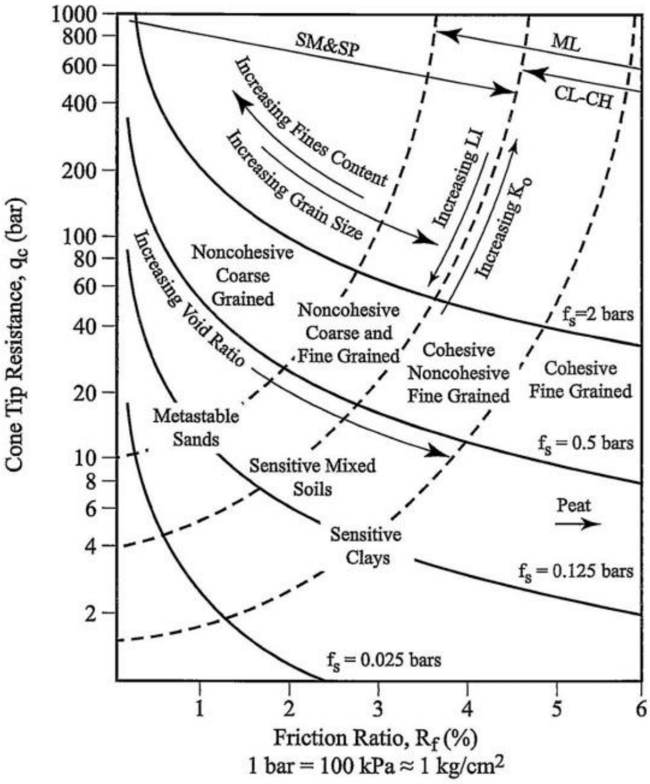


Fig. 2.10: Soil identification chart based on CPT (After Douglas and Olsen (1981).

2.4.9 Soil Behavioral Type from CPTU

To determine a CPTU soil behavioral type, the tip resistance, sleeve resistance, and pore water pressure from the CPTU may be combined. The normalized parameters of CPTU tip resistance and sleeve friction were proposed by Robertson and Wride (1998).

$$I_{CRW} = [\{3.47 - \log(Q_{t1})\}^2 + \{1.22 + \log(F)\}^2]^{0.5} \quad (2.6)$$

Jefferies and Been (2006) suggested I_c as

$$I_C = \left[\left\{3 - \log\left(Q_t\left[1 - B_q\right] + 1\right)\right\}^2 + \{1.5 + \log(F_r)\}^2\right]^{0.5} \quad (2.7)$$

Where, F is the non-dimensional friction ratio denoted by the formula $F = f_s/(q_t - \sigma_{vo})$ and B_q is the observed pore water pressure. Lutenneger (2021) can be cited for more information. Table 2.4 provides values for the soil behavioral type based on I_C and I_{CRW}. A chart created using the CPTU soil behavioral type I_C is shown in Figure 2.11. The CPT index I_C can also be used to measure the percentage of particles (% <No. 200 sieve).

According to Table 2.5 (following Mayne et al. 2009), the content of fines can be approximated.

Table 2.4: Soil behavioral type from CPTU (after Leutenegger, 2021)

CPTU I_c	CPTU I_{CRW}	Soil behaviour type zone	Soil identification
< 1.25	< 1.31	7	Gravelly sands
1.25 – 1.80	1.31 – 2.05	6	Clean to silty sands
1.80 – 2.40	2.05 – 2.60	5	Sandy mixtures
2.40 – 2.76	2.60 – 2.95	4	Silty mixtures
2.76 – 3.22	2.95 – 3.60	3	Clays
> 3.22	> 3.60	2	Organic soils
N/D	N/D	1	Sensitive clays

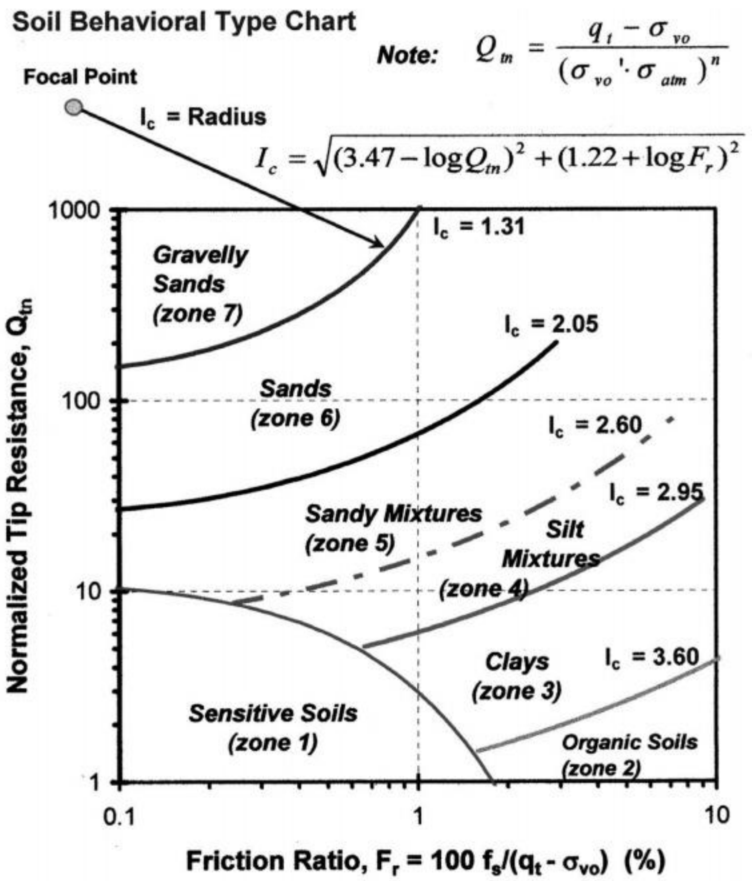


Fig. 2.11: Soil behavioral type chart based on CPTU (After Mayne 2014).

Table 2.5: Estimated Fines content from CPT Index I_C (after Leutenegger, 2021)

I_c	% Fines
< 1.26	0
1.26 – 3.50	$\%\text{Fines} = 1.75 I_C^{3.25} - 3.70$
> 3.50	100

Charts were created when the device's original design was used (without considering pore water pressure), as illustrated in Fig. 2.12. As can be seen, typically, fine soils have lower qc values and greater friction ratio values. This sort of chart has a restriction because it is based on test data from relatively shallow depths, typically less than 30 m.

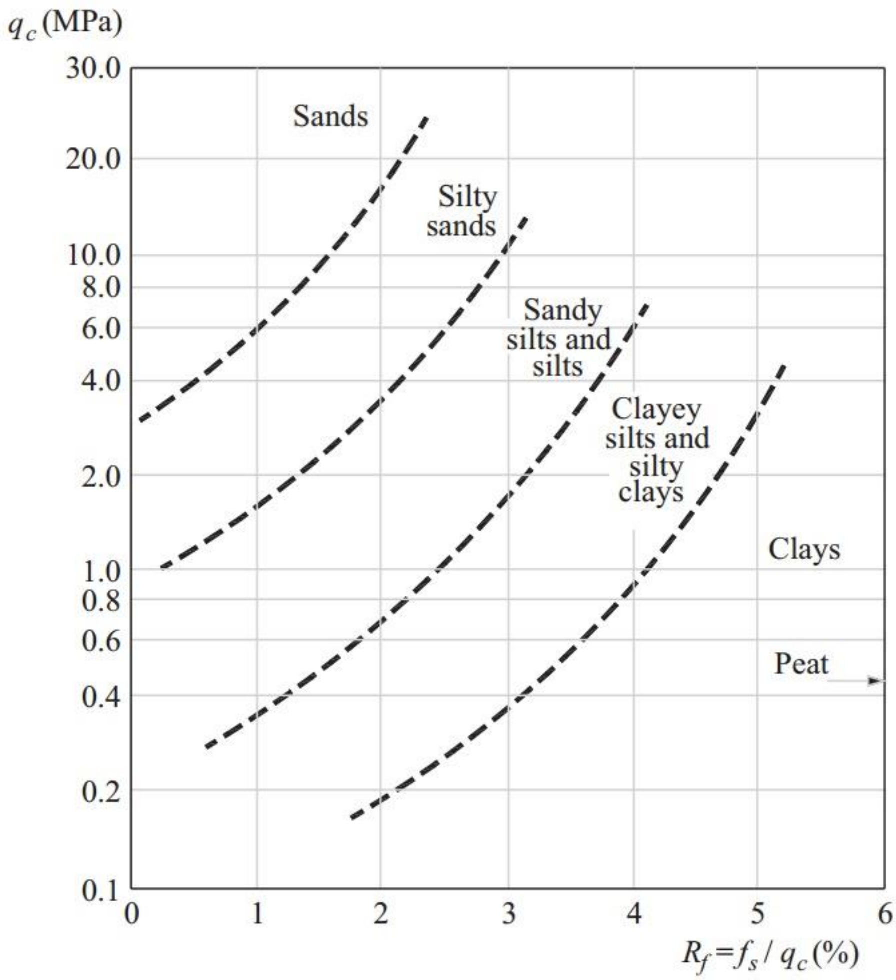


Fig. 2.12: Simplified soil classification chart from CPT results (after Robertson and Campanella, 1983; Reproduced from Fernandes, 2020).

2.4.10 Undrained Shear Strength of Soil from CPT

It has been widely used to estimate the undrained shear strength of clays utilizing both the tip resistance and sleeve friction based on the results of the CPT. Similar to SPT, CPT, and CPTU can be used to determine a number of different soil properties. Information is available in Leutenegger (2021).

2.5 CPT-SPT Relationships

Since SPT and CPT are the most frequently used field tests in most nations, attempts to correlate the parameters N and q_c quickly increased due to their use at the exact location in numerous geotechnical investigation campaigns. Many countries have done significant work with their data on CPT and SPT in the past. Researchers have developed several links to cone resistance q_c versus SPT N-values as a function of factor (n). A few researchers have related additional sleeve friction, f_s . The relationships are presented in Table 2.6.

Table 2.6: Relationship between CPT and SPT parameters (after Kara, 2010)

Author(s)	Soil Types	Relationship
De Alencar Velloso (1959)	Clay and silty clay	$n = q_c/N = 0.35$
	Sandy clay and silty sand	$n = q_c / N = 0.2$
	Sandy silt	$n = q_c / N = 0.35$
	Fine sand	$n = q_c / N = 0.6$
	Sand	$n = q_c / N = 1.00$
Franki piles (1960) From Akca (2003)	Sand	$n = q_c / N = 1.00$
	Clayey sand	$n = q_c / N = 0.6$
	Silty sand	$n = q_c / N = 0.5$
	Sandy clay	$n = q_c / N = 0.4$
	Silty clay	$n = q_c / N = 0.3$
	Clays	$n = q_c/ N = 0.2$
	Coarse sand	$n = q_c / N = 0.2$

Table 2.6: Relationship between CPT and SPT parameters (after Kara, 2010)

Author(s)	Soil Types	Relationship
Meigh & Nixon (1961)	Gravelly sand	$n = q_c / N = 0.3 - 0.4$
(Schmertmann (1970)	Silt, sandy silt and silt-sand mix.	$n = (q_c + f_s)/N = 0.2$
	Fine to medium sand, silty sand	$n = (q_c + f_s)/N = 0.3 - 0.4$
	Coarse sand, sand with gravel	$n = (q_c + f_s)/N = 0.5 - 0.6$
	Sandy gravel and gravel	$n = (q_c + f_s)/N = 0.8 - 1.0$
Barata et al. (1978)	Sandy silty clay	$n = q_c / N = 1.5 - 2.5$
	Clayey silty sand	$n = q_c / N = 2.0 - 3.5$
Ajayi & Balogun (1988)	Lateritic sandy clay	$n = q_c / N = 3.2$
	Residual sandy clay	$n = q_c / N = 4.2$
Chang (1988)	Sandy clayey silt	$n = q_c / N = 2.1$
	Clayey silt, sandy clayey silt	$n = q_c / N *= 1.8$
Danziger & de Valleso (1995)	Silt, sandy silt and silt-sand	$n = (q_c + f_s)/N = 0.2$
	Fine to medium sand, silty sand	$n = (q_c + f_s)/N = 0.3 - 0.4$
	Coarse sand, sand with gravel	$n = (q_c + f_s)/N = 0.5 - 0.6$
	Sandy gravel and gravel	$n = (q_c + f_s)/N = 0.8 - 1.0$
	Silt, sandy silt and silt-sand	$n = (q_c + f_s)/N = 0.2$
	Silty sand	$n = q_c / N = 7.0$
Danziger et al. (1998)	Sand	$n = q_c / N = 5.7$
	Silty sand, Silty clay	$n = q_c / N = 5.0 - 6.4$
	Clayey silt	$n = q_c / N = 3.1$
	Clay, silt and sand mixtures	$n = q_c / N = 1.0 - 3.5$

Table 2.6: Relationship between CPT and SPT parameters (after Kara, 2010)

Author(s)	Soil Types	Relationship
	Clayey sand and silty clay	$n = q_c / N = 4.6 - 5.3$
	Sandy clay	$n = q_c / N = 1.8 - 3.5$
	Clay	$n = q_c / N = 4.5$
Emrem and Durgunoglu (2000)	Turkey soils	$n = q_c/N =$ fine (D_{50})
Akca (2003)	Sand	$n = q_c / N = 0.77$
	Silty sand	$n = q_c / N = 0.70$
	Sandy silt	$n = q_c / N = 0.58$
Bashar Tarawneh (2014)	sand, sandy silt, and silty sand soils	$N = 1.59 + 0.993q_c + 0.069$ effective stress $+ 18.185f_s$
Kara, and Gündüz (2010)	Clay	$q_c = 0.2152N^{0.8252}$ (all data) $q_c = 0.1994N^{0.8535}$ (filtered data)
	Silt	$q_c = 0.3993N^{0.7436}$ (all data) $q_c = 0.3755N^{0.7342}$ (filtered data)
	Sand	$q_c = 0.7094N^{0.7213}$ $(all\ data)$ q_c $0.5334N^{0.809}$ $(filtered\ Data)$
	All	$q_c = 0.2106N^{0.9513}$ $(all\ data)$ $q_c = 0.1877N^{0.9894}$ $(filtered\ Data)$
Feda Aral and Ekrem Gunes (2017)	High plasticity clays (CH)	$q_c / N_{60} = 0.11$
	Moderate plasticity clays (CL)	$q_c / N_{60} = 0.11$
	Clayey sand-silt-uniform SC, SM and SP sand density	$q_c / N_{60} = 0.39$

Table 2.6: Relationship between CPT and SPT parameters (after Kara, 2010)

Author(s)	Soil Types	Relationship
Mominul et al. (2014)	Constant is better suit for Local soil (Existing correlations)	$q_{t1}/(N_1)_{60} = 0.45$
Mehtab Alam 2018	Silty Sand	$q_c = 0.427N$
	Sandy Silt	$q_c = 0.337N$
	Silty Clay	$q_c = 0.319N$
	Lean Clay	$q_c = 0.291N$
Hossain et al. (2020)	Constant better applicable to the local soils instead of D_{50} or f_c-based correlations	$q_{tc}/(N_1)_{60} = 0.45$
Karim et al. (2021)	Sandy soil	$N_{60} = 7.799 + 1.979 \times q_c - 6.371 \times f_s$; where $R^2 = 0.9803$
	Silt-Sand mixed soil	$N_{60} = 2.279 + 3.417514 \times q_c + 106.210 \times f_s$; where $R^2 = 0.7764$
	Clayey soil	$N_{60} = -2.879 + 15.404 \times q_c - 13.784 \times f_s$; where $R^2 = 0.9529$
	Silt-Clay mixed soil	$N_{60} = -2.105 + 14.482 \times q_c + 21.258 \times f_s$; where $R^2 = 0.9313$
Note: q_c/ N in MPa.		

Urmi (2019) conducted a study on geotechnical characterization of riverine and coastal soil of Bangladesh based on the results of CPT and SPT. She proposed several correlations involving SPT N_{160} value, angle of internal friction, φ, CPT q_c and other parameters.

2.7 Concluding Remarks

Literature review suggests that SPT and CPT are being the most widely used field tests in most countries, significant attempts have been done to correlate the parameters N, q_c, φ and others. However, in Bangladesh, only a few studies have been carried out especially using SPT and CPT parameters from the same site locations and for various types of soil. As such, there is a need a study on these aspects.

CHAPTER 3
TEST PROGRAM AND PROCEDURES

3.1 General

For a new construction work at the Ghorashal Polash Urea Fertilizer Project (GPUFP) site at Narsindhi, soil investigations were done in 30 boreholes with SPT measurements. Later 42 SPT boreholes and 24 CPT profiles were also done at the site. As such, 24 CPT profile and 17 SPT boreholes at proximity locations were considered for analysis to find relations of the parameters obtained from both the tests. The proximity pairs of SPT and CPT locations were within a maximum radial distance of 7 m. In the following sections, the test program and procedures are described.

3.2 Project Site

The proposed site is located on the left bank of the Shitalakhya River under Polash upazila of Narsingdhi district. The site is surrounded by Ghorashal power station on the south, the Shitalakha River on the west, countryside on the north and east. The project area is of about 1.10 hector land. Figure 3.1 shows the project location. The SPT borehole and CPT locations are indicated in Figs. 3.2 (a) and 3.2 (b). Their GPS locations are presented in Tables A.1 and A.2 of Appendix- A.

According to FCL (2019), the site is underlain predominantly by soft cohesive layer (recent deposits) from 3.5 m to 6.0 m below. This layer comprises of very soft to soft cohesive inorganic soil. Sub-soil between 5.0 m to 20 m depth comprises of medium to stiff desiccated clay of Pleistocene age (Madhupur clay) underlain by medium to dense non-cohesive sandy strata. Dense non-cohesive sand soil have been encountered at a depth around 23 m to 25 m. Madhupur Tract a large upland area in the central part of Bangladesh. The southern part of this tract is known in Bangla as Bhawal Garh and the northern part as Madhupur Garh. Geologically it is a terrace from one to ten metres above the adjacent floodplains. Though in its present form it is of Pleistocene age its origin may be in the late Miocene, when the bengal basin was being filled in rapidly. The total extent of this Tract is 4,244 sq km. The main section stretches from just south of Jamalpur in the north, to Fatullah of Narayanganj, in the south. This part of Bangladesh has been uplifted several times, resulting in numerous longitudinal faults. The most prominent of these are along the western side, where they can be clearly seen at Mirpur (Dhaka city) and near Ghatail and Madhupur further north. Long fault traces are also extant on the eastern side.

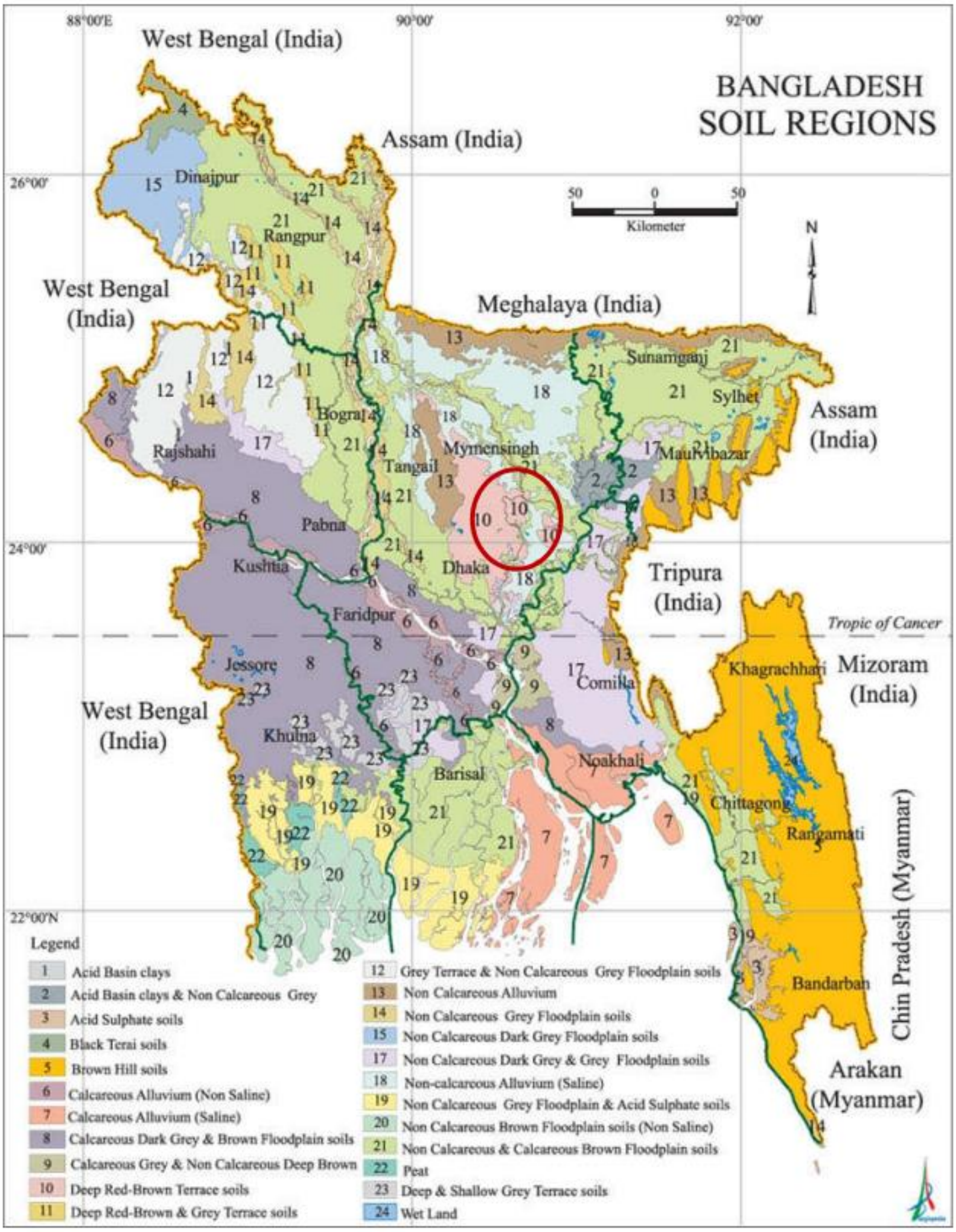


Fig. 3.1: Location map of project site (encircled; after Banglapedia, 2021).

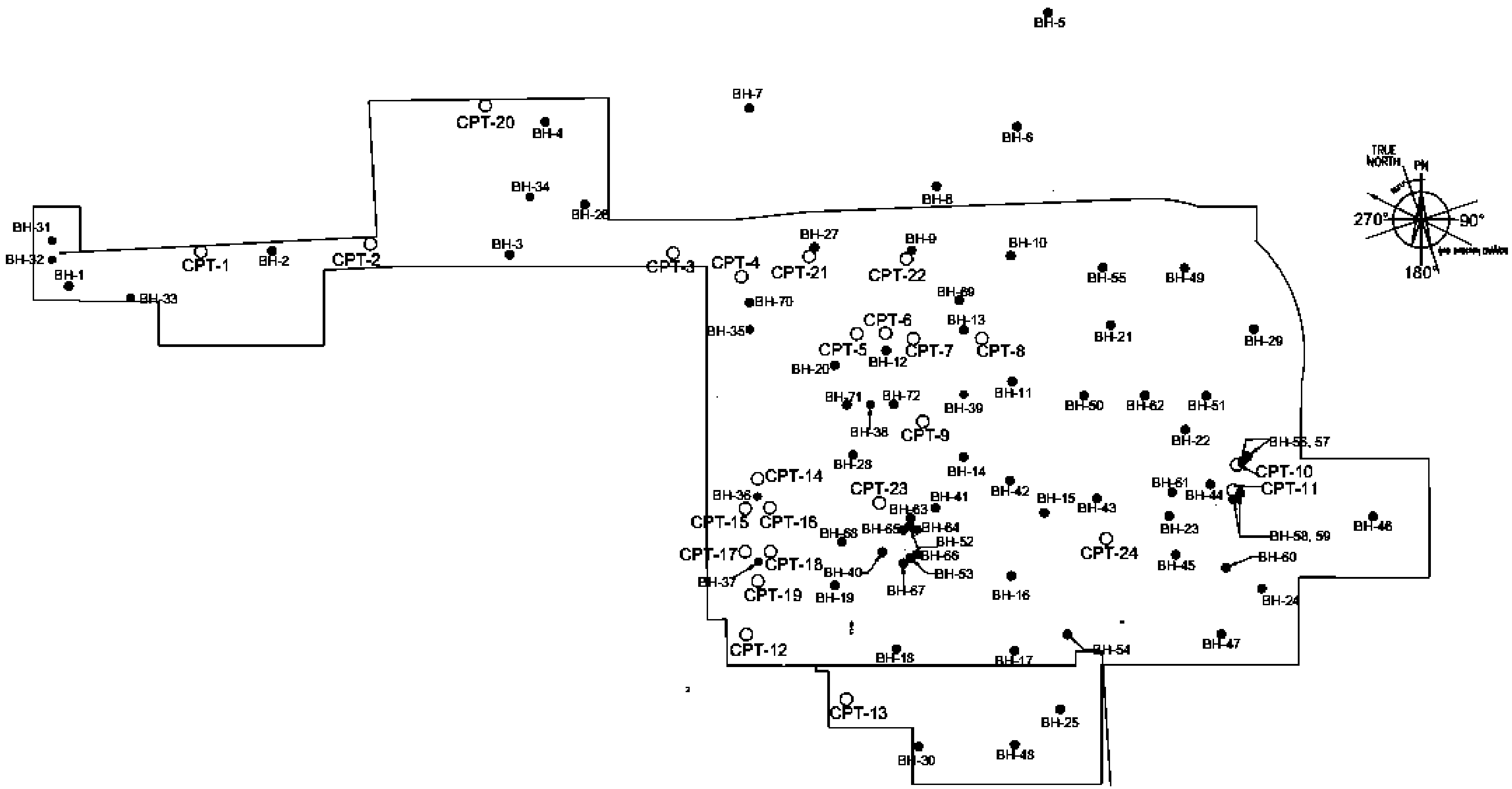


Fig. 3.2(a): SPT boreholes and CPT locations.

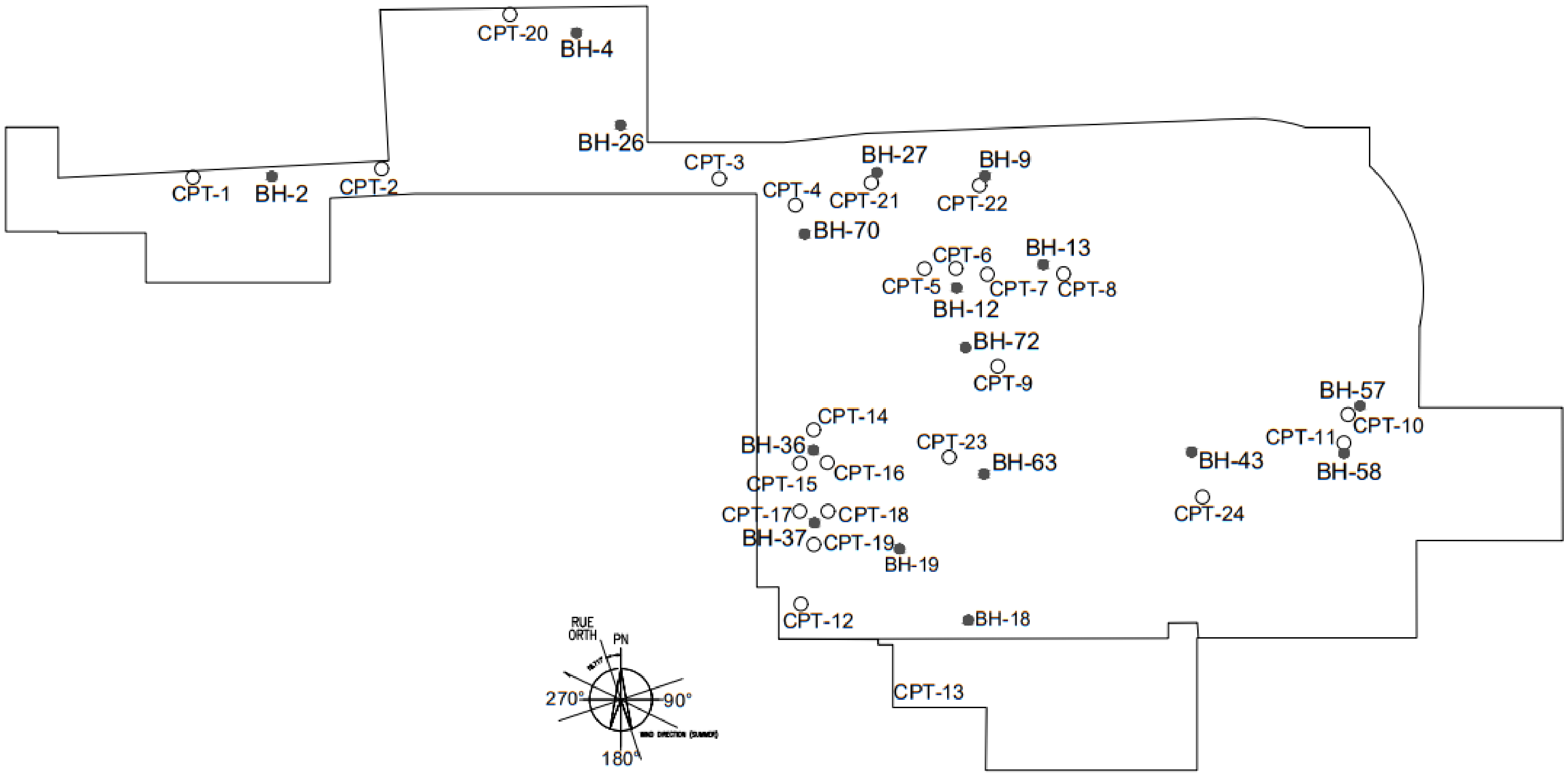


Fig. 3.2(b): 24 CPT locations and 17 proximity boreholes.

3.3 Test Program

A total of seventy-two (72) numbers SPT exploratory boreholes were undertaken at the project site. Twenty-four (24) cone penetration tests (CPT) were also conducted at the site. Liquid limit and plastic limit tests were also carried out on clayey and silty soils for classification purposes. Grain size analysis was also performed on the samples. The main task of the present investigation was to find out relationship between soil parameters obtained from SPT and CPT, for various types of soil. Figure 3.3 outlines the study program.

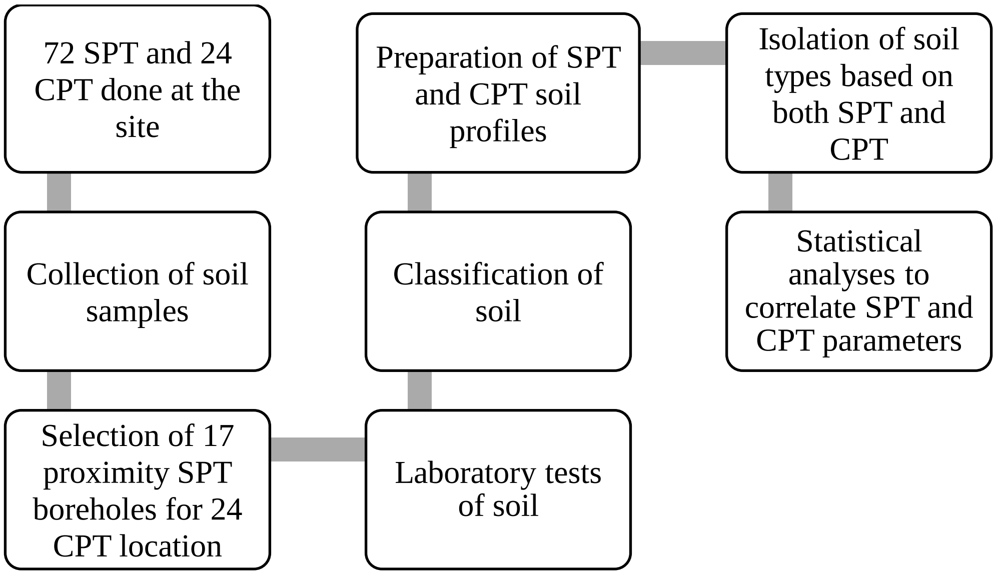


Fig. 3.3: Outline of the study program.

3.3 Test Procedures

In the present study mainly SPT and CPT tests were carried out in the field, and routine classification tests were done following standard ASTM test procedures. In the following sections, the test procedures are briefly described.

3.3.1 Boreholes and Standard Penetration Test (SPT)

ASTM D1586 (2018) was followed in performing the Standard Penetration Test (SPT). The test includes dropping a hammer (automatic trip) weighing 63.5 kg, and the hammer falls freely from a height of 760 mm along the drill pipe to drive the sampler attached at the end of the drill rod. A drilling rig is used for the purpose. The number of blows, necessary to produce the penetration was recorded in three different stages each of 150 mm. The number of blows required in the 2nd and 3rd 150 mm (total of 300 mm) of the penetration of the sampler is called the SPT value (N) and is represented by 'N'. A typical SPT borehole operation is shown in Fig. 3.4.

Fig. 3.4: Typical SPT operation.

The boreholes were drilled to the depth of 22 m to 40 m. During the drilling operation, the N-SPT values were measured, and soil samples were collected as per BNBC (2020) and ASTM D1587 (2018).

A typical bore log is shown in Fig. 3.5. Soils encountered during boring at shallow depths were mainly clay of medium plasticity (CL), silt of low plasticity (ML) and occasionally fat clay (CH). The subsequent deep layers are prevailing non-cohesive by nature consisting of silty soil, sand silt mix and silty fine sand (SM). Whenever the N-SPT values exceed 50 for 300 mm penetration, it was treated as refusal and further N-SPT values were not measured for that depth as per BNBC (2020) and ASTM D1586 (2018). However, measured SPT N-values were used to determine the relationships of cone resistance q_c and sleeve friction f_c up to a depth of 30 m.

BORE LOG

Client	: BCIC
Location	: Ghorashal, Palash, Norsingdi.
Project	: GPUFP Project.
Borehole No.	: 1(ONE)
Boring Depth (m)	: 30.00
G.W.L (m)	: 0.31 m down from EGL
R.L (m)	: 1.98m down from the jetty
Date started	: 4/12/2017
Date completed	: 4/12/2017

Depth (m)	Sample Type & No.	Sample Depth (Thick)	Description of Materials	Bore Log	SPT Blow Count 6"	6"	6"	12"
			EGL					
1.5	D-1	(3.00)	Light Yellowish very soft to soft SILT of low plasticity (ML).		1	0	1	1
3.0	D-2	3.00			1	1	2	3
4.5	D-3		Pale Bluish Ash soft SILT of high plasticity (MH) with trace organic matter.		1	1	2	3
6.0	D-4	(5.38)			1	2	2	4
7.5	D-5	8.38			1	2	2	4
9.0	D-6	(2.12)	Pale Yellowish non-plastic dense silty fine SAND (SM).		8	13	18	31
10.5	D-7	10.50			9	14	20	34
12.0	D-8	(4.50)	Pale Bluish Ash stiff to very stiff SILT of low plasticity (ML).		6	9	15	24
13.5	D-9				4	7	8	15
15.0	D-10	15.00			5	8	9	17
		(1.50)	Pale Bluish Ash non-plastic medium dense SILT (ML) with few sand.					
16.5	D-11	16.50			6	10	13	23
18.0	D-12	(4.07)	Blackish Decomposed organic matter (OL).		2	3	4	7
19.5	D-13	20.57			2	3	5	8
		(0.43)	Pale Bluish Ash very stiff CLAY of medium plasticity (CL).					
21.0	D-14	21.00			6	8	9	17
		(1.50)	Pale Yellowish non-plastic medium dense SANDY SILT (SM).					
22.5	D-15	22.50			6	9	10	19
		(1.50)	Pale Yellowish non-plastic dense silty fine SAND (SM).					
24.0	D-16	24.00			9	15	18	33
		(1.50)	Pale Yellowish non-plastic dense SANDY SILT (SM).					
25.5	D-17	25.50			10	16	20	36
27.0	D-18	(4.50)	Pale Yellowish non-plastic dense to very dense silty SAND (SM).		13	25	25	50 11"
28.5	D-19				14	27	23	50 11"
30.0	D-20	30.00			11	18	25	43

SPT Value

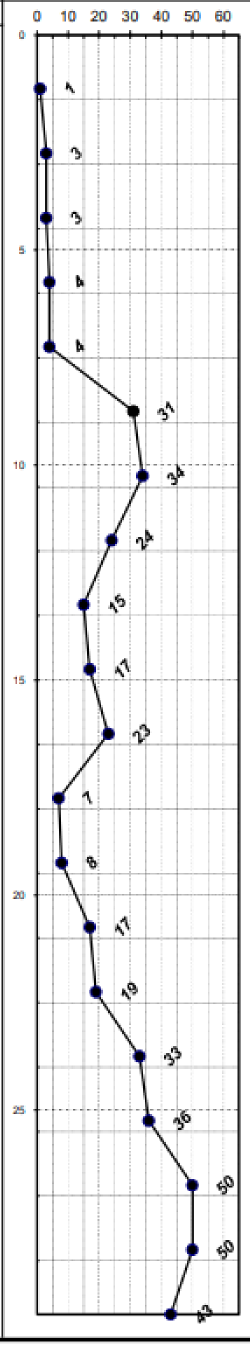


Fig. 3.5: Typical borehole log with SPT values.

3.3.2 Static Cone Penetration Test

Cone penetration tests were carried out using a 15 cm^2 area of electronic cones with 60° apex angle and 225 cm^2 friction sleeve area with a hydraulic pressure system of 200 kN. A total of 24 soundings were performed at different locations. The tests were terminated at 50 m (maximum) below existing ground level and tests were conducted in accordance to ASTM D 5778 (2020). Throughout the test the cone was advanced by applying thrust. A CPT test arrangement is shown picture of Fig. 3.6.

Fig. 3.6: Typical CPT test arrangements.

The data monitoring arrangements are shown in Fig. 3.7. The cone manufactured by GeoMil (n.d.) is a subtraction type cone equipped with instruments to measure (i) Cone pressure, (ii) Sleeve friction, and (iii) Dynamic pore pressure; Furthermore, the cone is also equipped with two inclinometers to monitor its verticality at all times. Depth of the cone was recorded using an opto-electric encoder. All data was recorded for every centimeter automatically in a computer running proprietary software. Prior to commencement of each test, the pressure transducer of the cone was saturated using silicon oil. The cone was calibrated prior to commencement and at the end of each test conforming to the specification using CPTest acquisition software (GeoMil, n.d.), this software also automatically recorded all data from the cone. Tables A.1 and A.2 in

Appendix show the SPT and CPT location coordinates and ground surface elevation of the 24 proximity SPT and CPT locations, as per BUTM (2010).

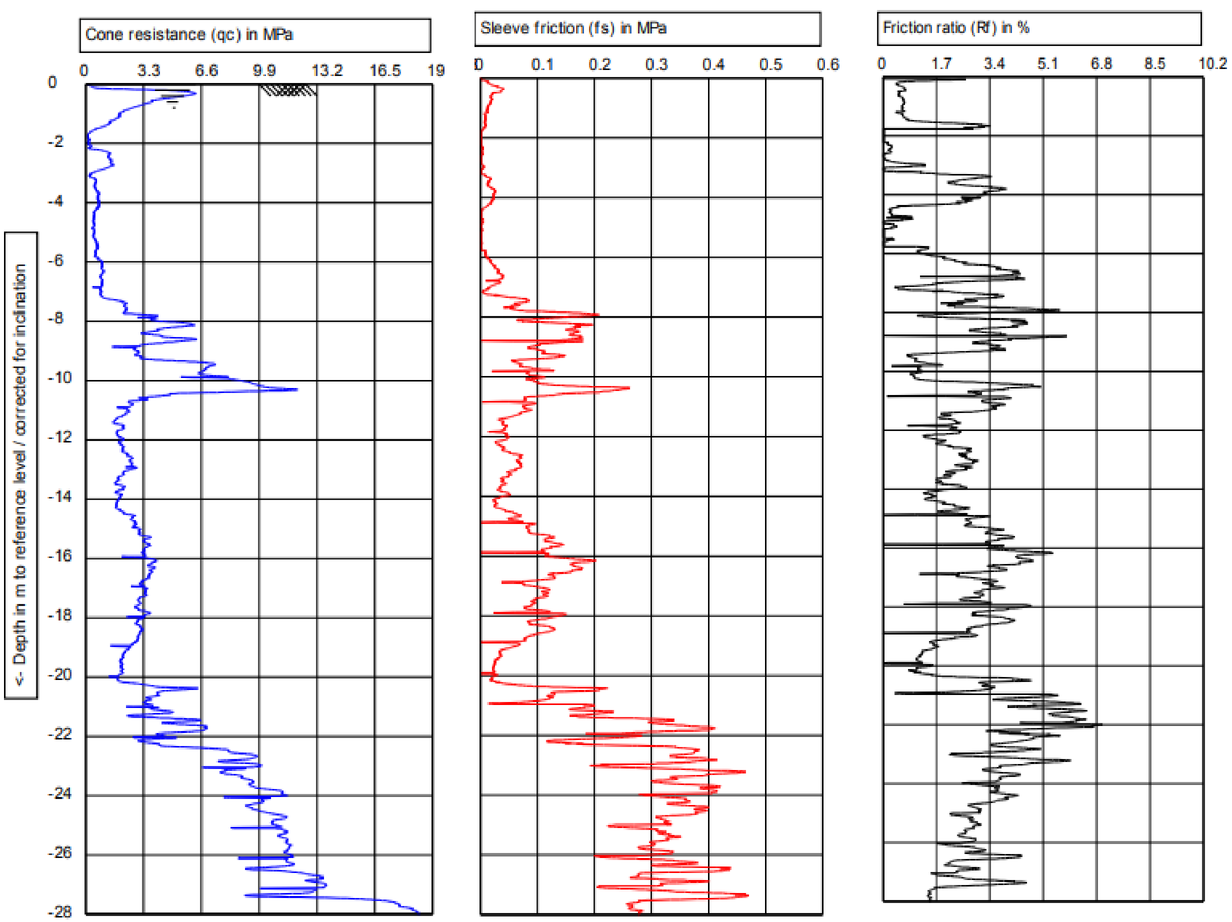
Fig. 3.7: Data monitoring system of CPT.

Typical CPT test results are shown in Fig. 3.8. After completion of the test all collected data has been plotted using CPTask processing software (GeoMil, n.d.), which was also used to estimate engineering parameters from the in-situ test data. This software has been used to estimate following engineering parameters: cone resistance (q_c), sleeve friction (f_s), friction ratio % (F_r) and soil classification. Depending of the "Measured Parameters" the following equations are used to calculate new signals.

$$q_c = kPa = \text{Cone resistance} = \text{Measured parameter}$$

$$f_s = Mpa = \text{Local friction} = \text{Measured parameter}$$

$$R_f\,(\%) = \text{Friction ratio} = (f_s/q_c)\ \times 100(\%)$$



(a) Cone resistance profile. (b) Sleeve friction profile. (c) Friction ratio profile.

Fig. 3.8: Typical CPT test results.

3.4 Soil Profiling

For comparison purposes soil profiles were drawn using both SPT and CPT data. SPT profiling was done using the classification schemes suggested by BNBC (2020), ASTM D2487 (2017) and ASTM D2488 (2018). The CPT soil profiles were prepared using the simplified soil classification chart suggested by Robertson et al. (1983). In CPT soil profiling the following broad classification was considered, Table 3.1. Typical soil profiles as obtained from SPT and CPT data are presented in Fig. 3.9. All the soil profiles as considered in this investigation are presented in Figs. B.1 to B.24 of Appendix- B.

In CPT test method, continuous readings of cone resistance q_c and sleeve friction f_s are usually taken. In SPT, however, tests are usually performed at 1.5 m intervals for N values. As such, for comparison purposes, CPT results are interpolated or synchronized at each 1.5 m intervals. The data were isolated for various types of USCS soil classes. Statistical analyses of the data were done to correlate field SPT N-value with CPT cone resistance and CPT sleeve friction for various types of soil. Excel spread sheet was used for the statistical analysis where data were plotted and regressed to find the relations.

Table 3.1: Broad soil classification for profiling as used in the present investigation

Robertson et al. (1983) soil class	Broad soil classification for profiling
Sand, Silty sand	Sand
Sandy silt and clayey Silt	Silt
Silty clay and Clay	Clay
Silty organic, clayey organic and organic, peat	Organic

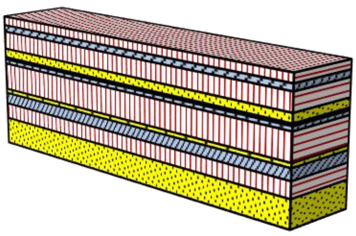
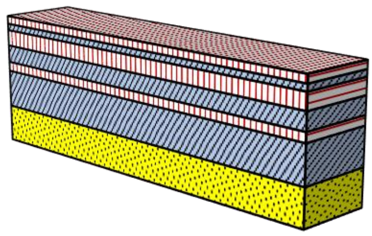
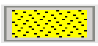
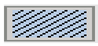
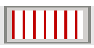
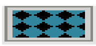
<table>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">(a) CPT Soil Profile.</td><td colspan="2">(b) SPT Soil Profile.</td></tr>
<tr><td colspan="4">Legend:</td></tr>
<tr><td>Sand</td><td></td><td>Clay</td><td></td></tr>
<tr><td>Silt</td><td></td><td>Organic</td><td></td></tr>
</table>

Fig. 3.9: Typical CPT and SPT soil profies.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 General

The present study was concerned with the relationships of SPT and CPT parameters. SPT tests were performed in boreholes and at the proximities 17 SPT boreholes (within a maximum radial distance of 6.0 m), 24 CPT tests were also performed up to a depth of 30 meters. Both SPT and CPT soil profiles were prepared using the standard procedures. Once both the profile gave the consensus soil types, field SPT N-value, CPT cone resistance q_c and sleeve friction f_s were graphically plotted and statistically analyzed using excel spread sheet. The efficiency of the statistical correlations is expressed in terms of correlation coefficient (R^2) as per the suggestions of Allwright, (2023). In this study, the following five types of soil were considered using classification test results (grain size and consistency limits) to determine the relationships.

(i) Non-plastic silty sand (SM)

(ii) Silt of low plasticity and non-plastic sandy silt (ML)

(iii) Silt of high plasticity (MH)

(iv) Clay of low plasticity or silty clay (CL)

(v) Clay of high plasticity (CH)

4.2 Non-plastic Silty Sand (SM)

A total of 147 data of non-plastic silty sand (SM) has been isolated from all the 17 SPT borehole and 24 CPT profiles. The data are presented in Table C.1 of Appendix C. The field SPT N-values are plotted against CPT cone resistance (q_c) and also against sleeve friction (f_c) values. They are shown in Figs. 4.1 and 4.2 respectively. It has been observed that both cone resistance and sleeve friction have positive linear relationship with field SPT N-value in a range of 0 to 75. Statistical analysis yielded the trend line with limiting zero intercept, having strong correlation coefficients. The relations may be expressed as equations (4.1) and (4.2) respectively.

For cone resistance $q_c(kPa) = 290.1N \qquad R^2 = 0.777 \qquad (4.1)$

For sleeve friction $f_s(kPa) = 5.2N \qquad R^2 = 0.767 \qquad (4.2)$

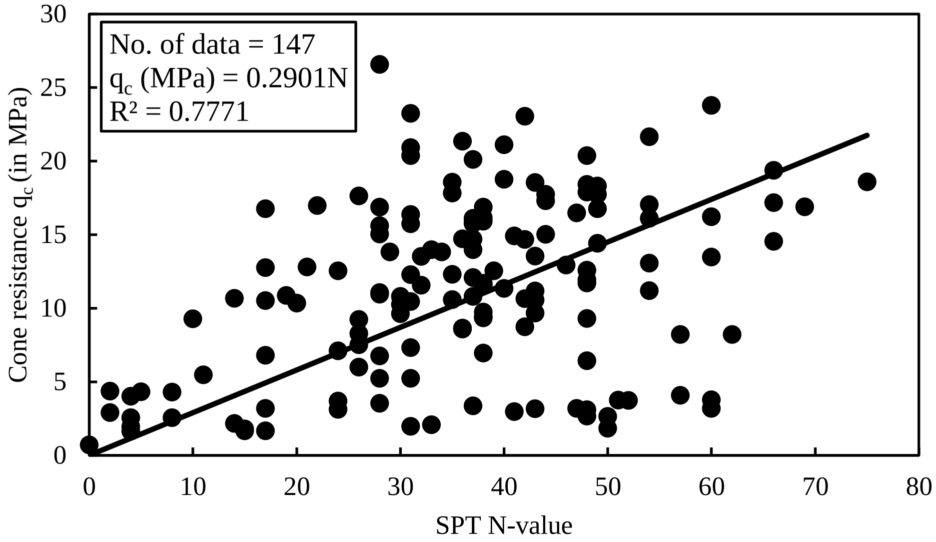


Fig. 4.1: SPT and CPT cone resistance relation for non-plastic silty sand (SM) soil.

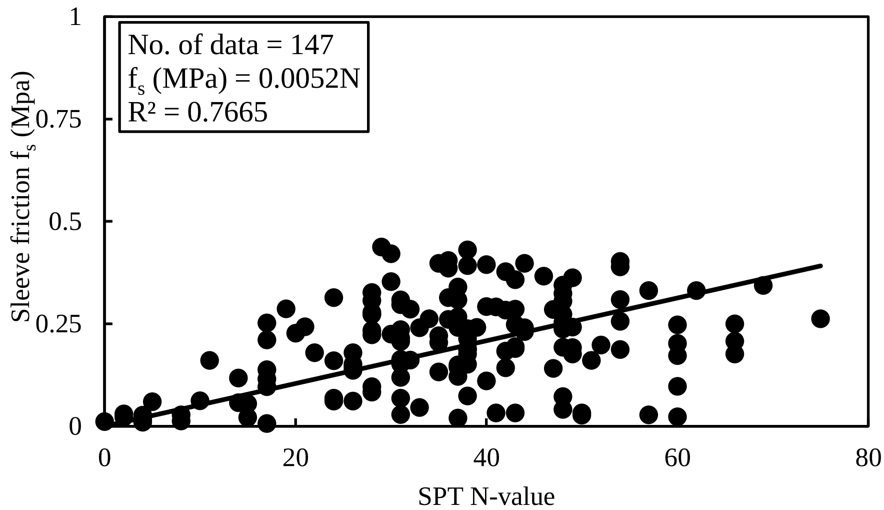


Fig. 4.2: SPT and CPT sleeve friction relation for non-plastic silty sand (SM) soil.

The relation of cone resistance was compared with the findings of the previous investigators, and are presented in Fig. 4.3. It shows that the relation for SPT N-value and CPT cone resistance obtained from the present investigation agrees well with the findings of Kara and Gunduz (2010), and Aral and Gunes (2017). Some other investigators estimate higher values of cone resistance against SPT N-value, Fig. 4.3.

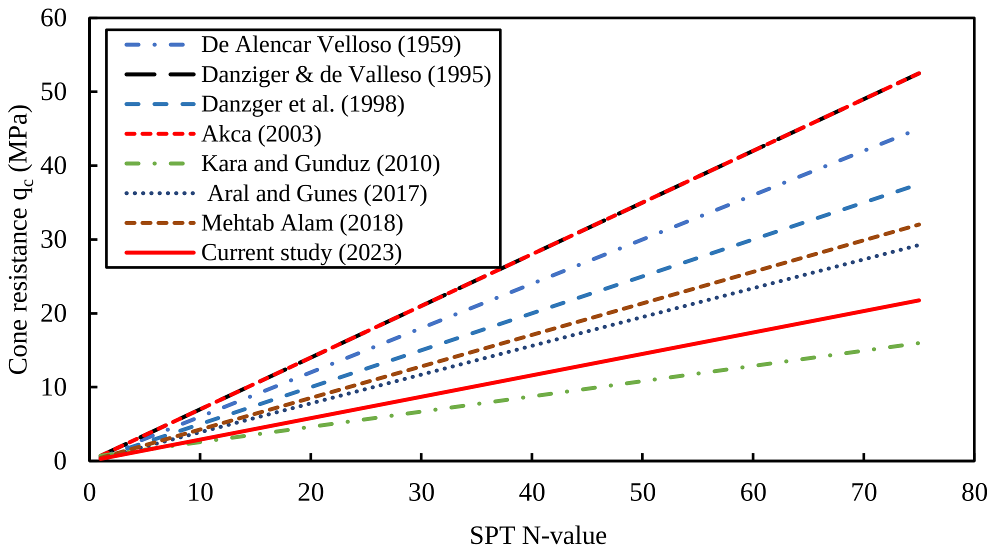


Fig. 4.3: Comparison of SPT and CPT relationships with results obtained for non-plastic silty sand (SM) soil.

Published literature on the direct correlation of CPT skin resistance and SPT values happened to be a very few. However, some investigators (Schmertmeann, 1970; Denziger & de Valleso, 1995) reported similar relation of SPT N-value with combined CPT cone resistance and sleeve friction, $(q_c + f_s)$. According to them SPT CPT, relations can be described as $(q_c + f_s)(in\ kPa) = (300\ to\ 400)N$. The results of $(q_c + f_s)$ as obtained from present investigation are plotted against SPT N-value in Fig. 4.4.

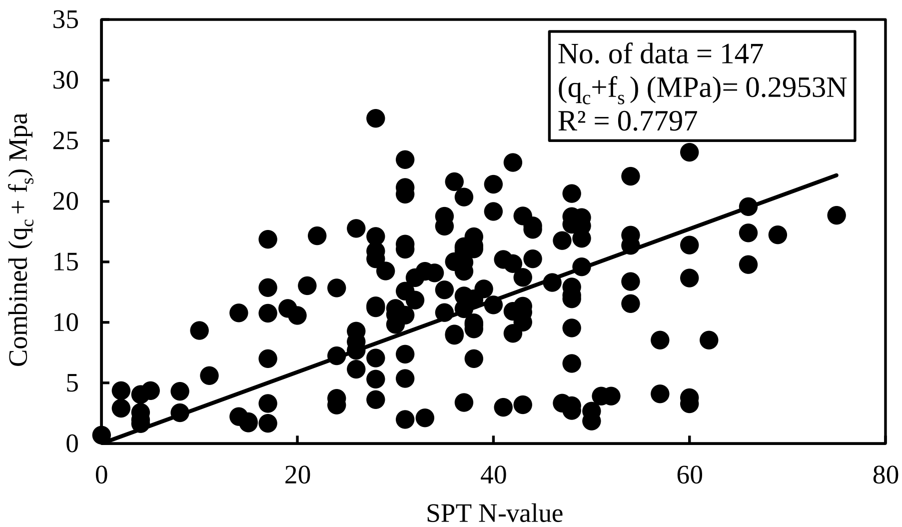


Fig. 4.4: SPT N-value and CPT $(q_c + f_s)$ relation for non-plastic silty sand (SM) soil.

A strong correlation was obtained that may be represented by eq. (4.3).

$$(q_c + f_s)\ (in\ kPa) = 295N \qquad R^2 = 0.797 \tag{4.3}$$

While compared with the findings of previous investigator, Fig. 4.5, the present investigation was found to agree with the lower limit values given by Schmertmeann (1970) and Denziger & de Valleso (1995). This may be because of presence of significant amount of fines in the sand (SM) samples encountered in the present investigation.

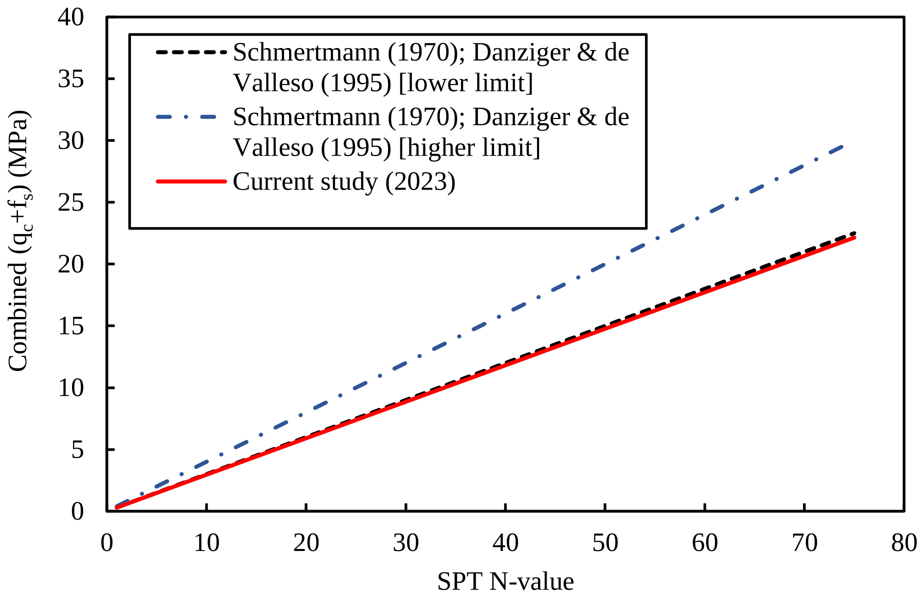


Fig. 4.5: Comparison of SPT N-value and CPT $(q_c + f_s)$ relation for non-plastic silty sand (SM) soil.

4.3 Silt of Low Plasticity and Non-Plastic Sandy Silt (ML)

From all 17 SPT borehole and 24 CPT profiles, 85 sets of data have been identified for low plastic silty and non-plastic sandy silt (ML) soil. The data are presented in Table C.2 of Appendix C. The field SPT N-values are plotted against CPT cone resistance (q_c) and also against sleeve friction (f_c) values. They are shown in Figs. 4.6 and 4.7 respectively. It has been observed that both cone resistance and sleeve friction have positive linear relationship with field SPT N-value in a range of 0 to 60. Statistical analysis yielded the trend line with limiting zero intercept, having good correlation coefficients. The relations may be expressed as equations (4.4) and (4.5) respectively.

For cone resistance $q_c(kPa) = 168\ N$ $R^2 = 0.558$ (4.4)

For sleeve friction $f_s(kPa) = 4.3\ N$ $R^2 = 0.510$ (4.5)

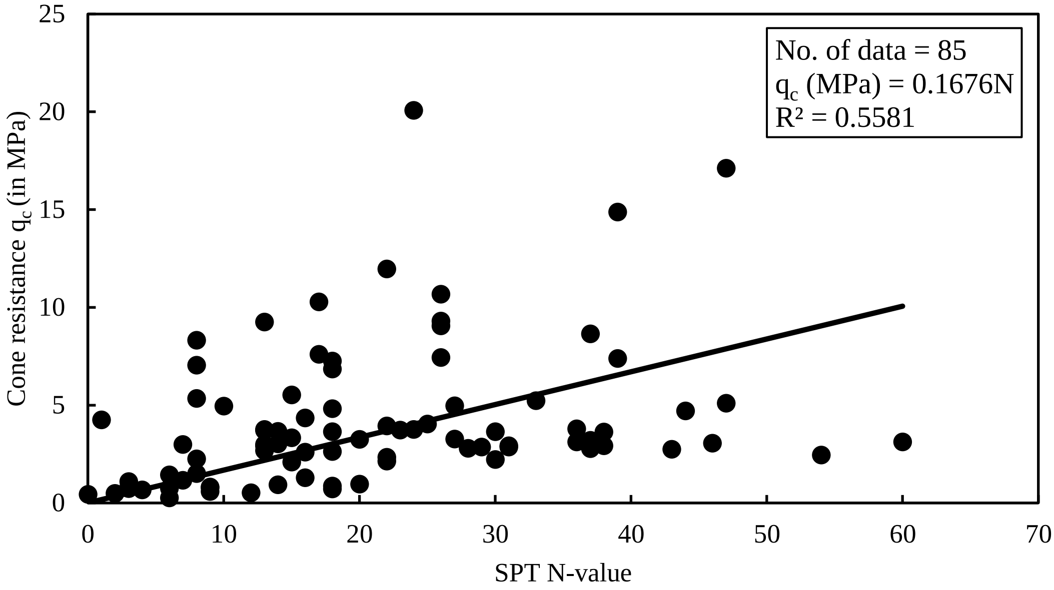


Fig. 4.6: SPT N-value and CPT cone resistance relation for low plastic silt and non-plastic sandy silt (ML).

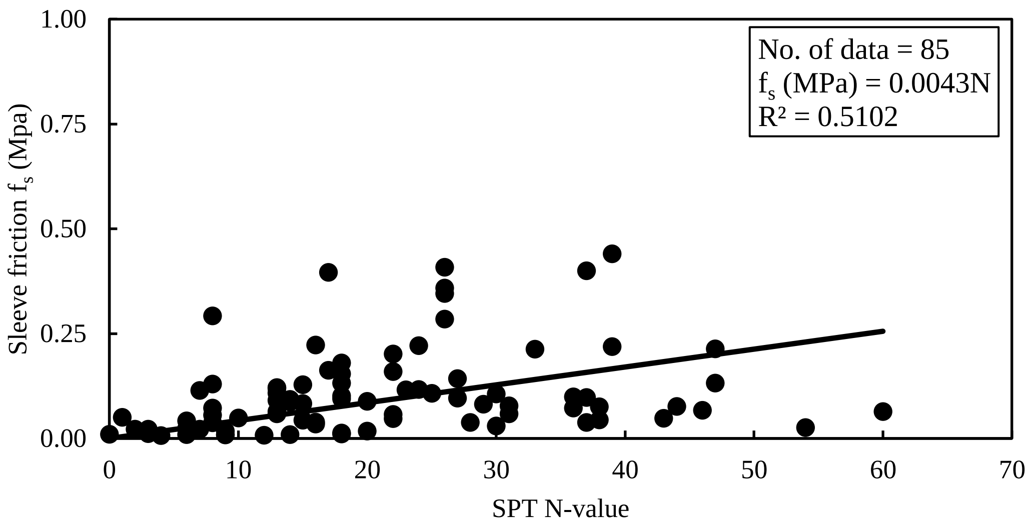


Fig. 4.7: SPT N-value and CPT sleeve friction relation for low plastic silt and non-plastic sandy silt (ML).

The relation of cone resistance was compared with the findings of the previous investigators, and are presented in Fig. 4.8. It shows that the relation for SPT N-value and CPT cone resistance obtained from the present investigation agrees well with the findings of Kara & Gunduz (2010), and Chang (1998). Other investigators estimates higher values of cone resistance, Fig. 4.8.

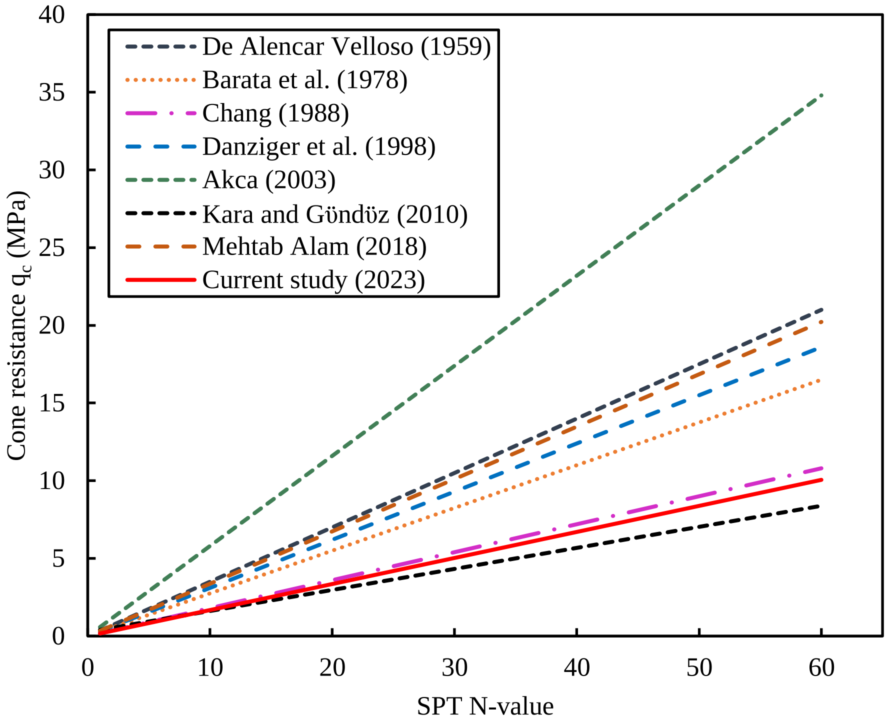


Fig. 4.8: Comparison of SPT N-value and CPT cone resistance relations for silt of low plasticity and non-plastic silty sand (ML) soil.

Some investigators (Schmertmeann, 1970; Denziger & de Valleso, 1995) reported relation of SPT N-value and combined CPT cone resistance and sleeve friction, $(q_c + f_s)$. According to them SPT CPT, relations can be described as $(q_c + f_s)(in\ kPa) = 200\ N$. The results of $(q_c + f_s)$ as obtained from present investigation are plotted against SPT N-value in Fig. 4.9. A correlation was obtained that may be represented by Eq. (4.6). However, the correlation is not very strong as indicated by the correlation coefficient (R^2) of 0.560.

$$(q_c + f_s)\ (in\ kPa) = 172\ N \qquad R^2 = 0.560 \qquad (4.6)$$

Figure 4.10 compares the findings of previous investigator with that of the present investigation. Interestingly, the present investigation agrees well with the findings of Schmertmeann (1970) and Denziger & de Valleso (1995).

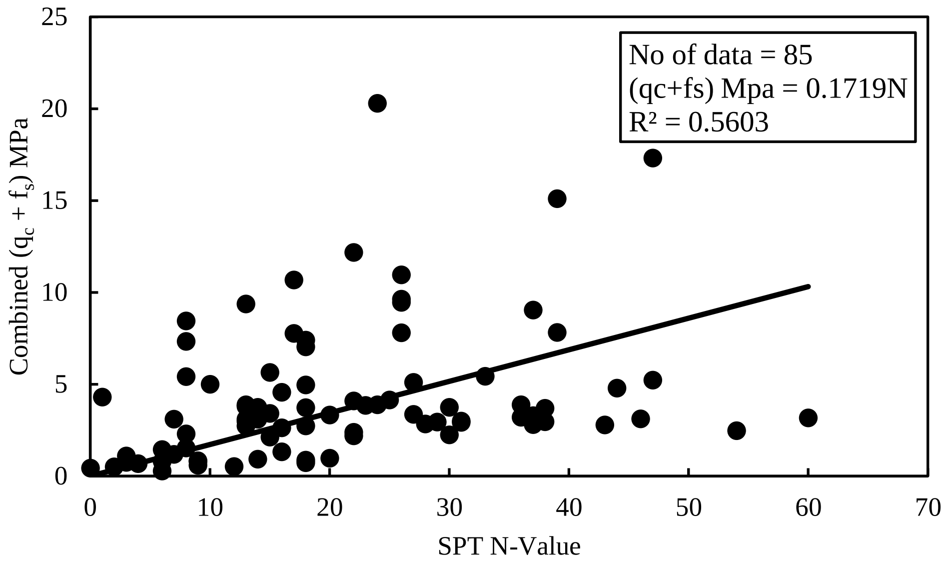


Fig. 4.9: SPT N-value and CPT $(q_c + f_s)$ relation for silt of low plasticity and non-plastic sand silt (ML) soil.

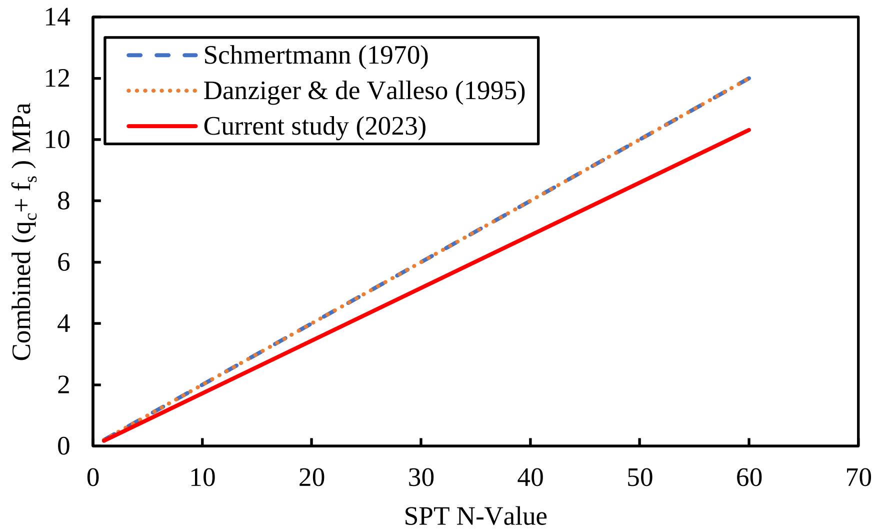


Fig. 4.10: Comparison SPT N-value and CPT $(q_c + f_s)$ relation for silt of low plasticity and non-plastic sand silt (ML) soil.

4.4 Silt of High Plasticity (MH)

There were 43 data sets has been isolated from all the 17 SPT borehole profiles for determining the SPT-CPT relationships in the soil of silt of high plasticity (MH). The data are presented in Table C.3 of Appendix C. The field SPT N-values are plotted against CPT cone resistance (q_c) and also against sleeve friction (f_c) values. They are shown in

Figs. 4.11 and 4.12 respectively. It has been observed that both cone resistance and sleeve friction have positive linear relationship with field SPT N-value in a range of 0 to 53. Statistical analysis yielded the trend line with limiting zero intercept, having good correlation coefficients. The relations may be expressed as Eqs. (4.7) and (4.8) respectively. However, the correlation is not very strong as indicated by the correlation coefficients (R^2) of 0.556 and 0.468.

For cone resistance $\quad q_c(kPa) = 112\ N \qquad R^2 = 0.556 \qquad$ (4.7)

For sleeve friction $\quad f_s(kPa) = 2.6\ N \qquad R^2 = 0.468 \qquad$ (4.8)

The reported literature involving the relations of SPT N-value with both CPT cone resistance and friction for high plastic silty soil (MH) may be a very few. The present study proposes the relations given by Eqs. (4.7) and (4.8) respectively for cone resistance and sleeve friction.

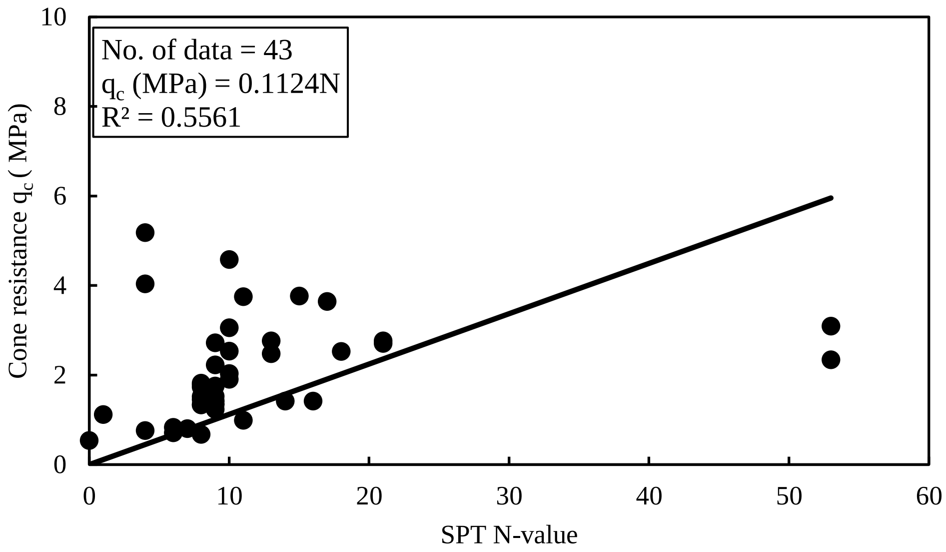


Fig. 4.11: SPT N-value and CPT cone resistance relation for silt of high plasticity (MH).

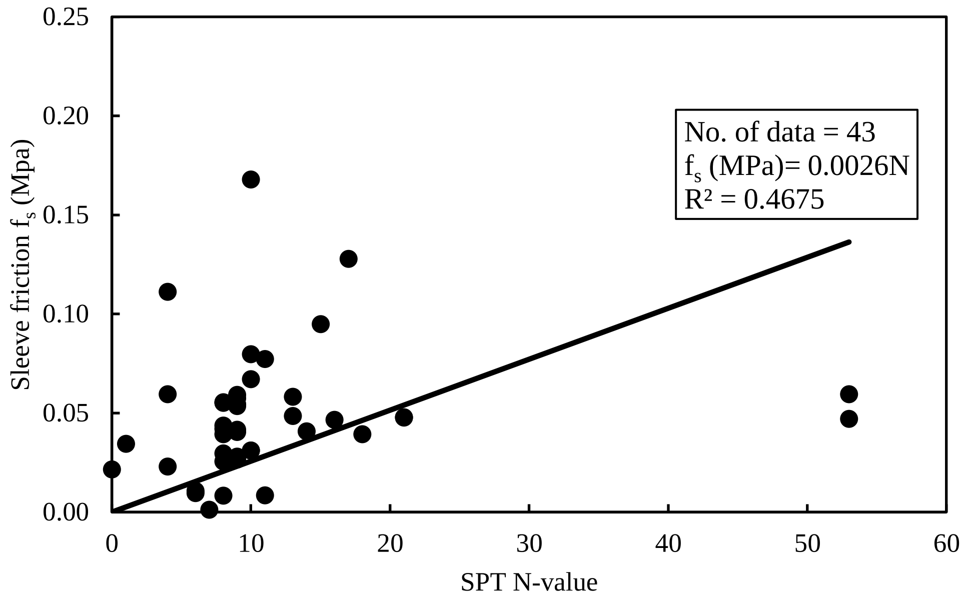


Fig. 4.12: SPT N-value and CPT sleeve friction relation for silt of high plasticity (MH).

4.5 Clay of Low Plasticity or Silty Clay (CL)

A large number of 182 data were used for clay soil of low plasticity (CL). The data are presented in Table C.4 of Appendix C. The field SPT N-values are plotted against CPT cone resistance (q_c) and also against sleeve friction (f_c) values. They are shown in Figs. 4.13 and 4.14 respectively. It has been observed that both cone resistance and sleeve friction have positive linear relationship with field SPT N-value in a range of 1 to 51. Statistical analysis yielded the trend line with limiting zero intercept, having good correlation coefficients. The relations may be expressed as Eqs. (4.9) and (4.10) respectively.

For cone resistance $$q_c(kPa) = 210\,N \qquad R^2 = 0.602 \tag{4.9}$$

For sleeve friction $$f_s(kPa) = 5.8\,N \qquad R^2 = 0.548 \tag{4.10}$$

The relation of cone resistance was compared with the findings of the previous investigators, and are presented in Fig. 4.15. The SPT N-value and CPT cone resistance relation obtained and as represented by Eq. (4.9) agrees well with the findings of Aral and Gunes (2017), and Alam (2018). Other investigators estimates higher values of cone resistance, Fig. 4.15.

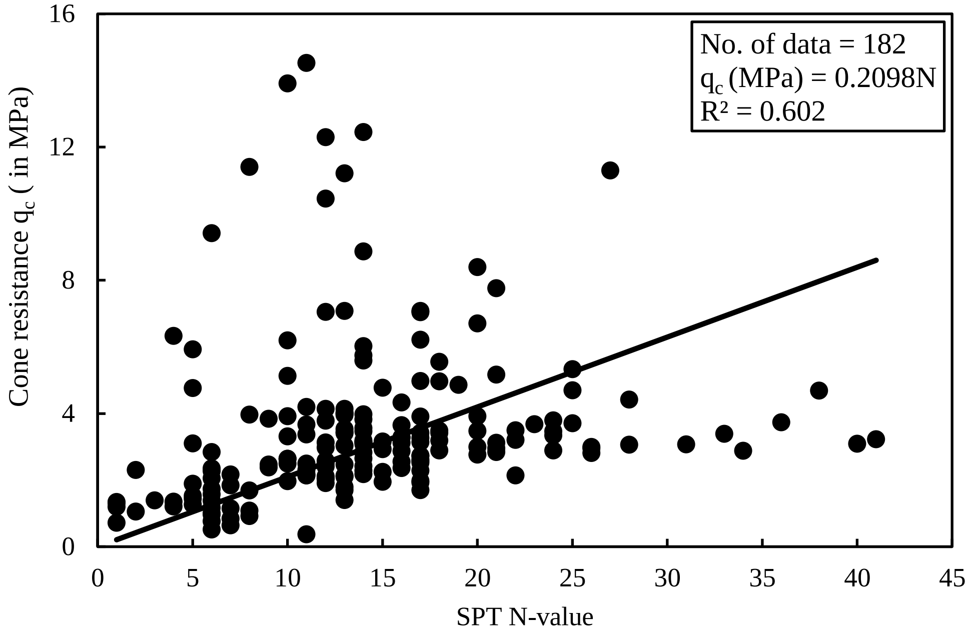


Fig. 4.13: SPT N-value and CPT cone resistance relation for silty clay and clay of low plasticity (CL).

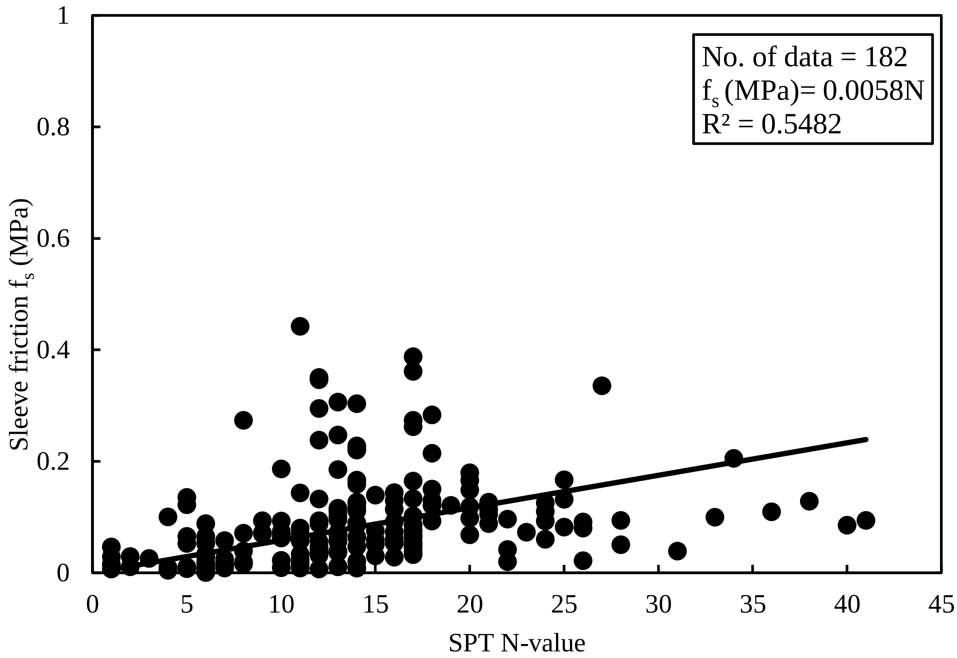


Fig. 4.14: SPT N-value and CPT sleeve friction relation for silty clay and clay of low plasticity (CL).

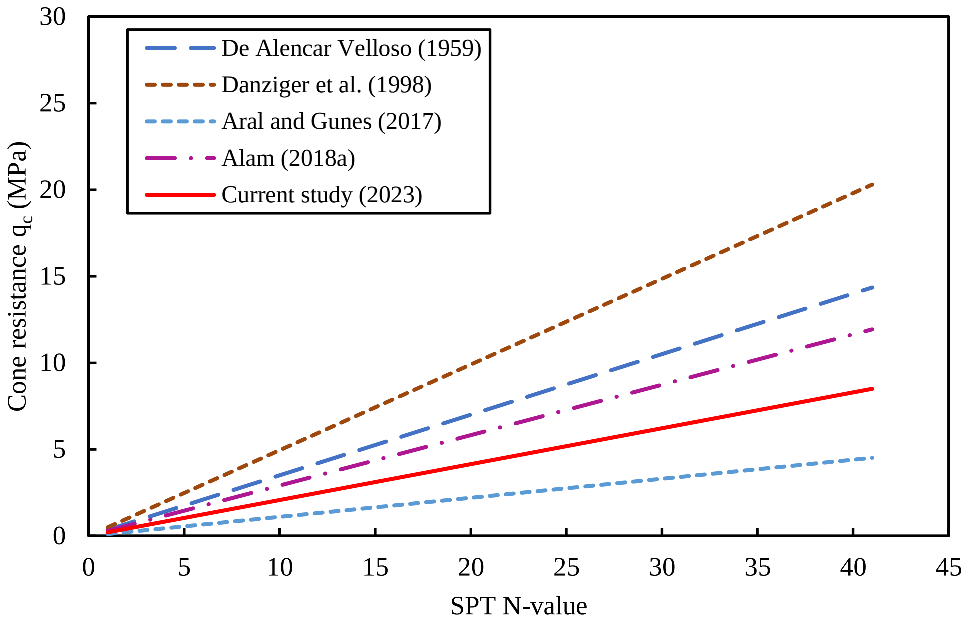


Fig. 4.15: Comparison of SPT N-value and CPT cone resistance relations for silty clay and clay of low plasticity (CL).

4.7 High Plastic Clay (CH)

There were 14 data sets for defining the SPT-CPT relationships in the soil of clay of high plasticity (CH). The data are presented in Table C.5 of Appendix C. The field SPT N-values are plotted against CPT cone resistance (q_c) and also against sleeve friction (f_c) values. They are shown in Figs. 4.16 and 4.17 respectively. It has been observed that both cone resistance and sleeve friction have positive linear relationship with field SPT N-value in a range of 3 to 22. Statistical analysis yielded the trend line with limiting zero intercept, having a strong to good correlation coefficient for cone resistance and sleeve friction, respectively. The relations may be expressed as Eqs. (4.11) and (4.12) respectively.

For cone resistance $\quad q_c(kPa) = 211\ N \qquad R^2 = 0.751 \qquad$ (4.11)

For sleeve friction $\quad f_s(kPa) = 8.4\ N \qquad R^2 = 0.719 \qquad$ (4.12)

The relation of cone resistance was compared with the findings of the previous investigators, and are presented in Fig. 4.18. The SPT N-value and CPT cone resistance relation obtained and as represented by Eq. (4.11) suggests a different relation while compared to the findings of other investigators, Fig. 4.18. However, this new relation gives an in between values as compared to the other investigators.

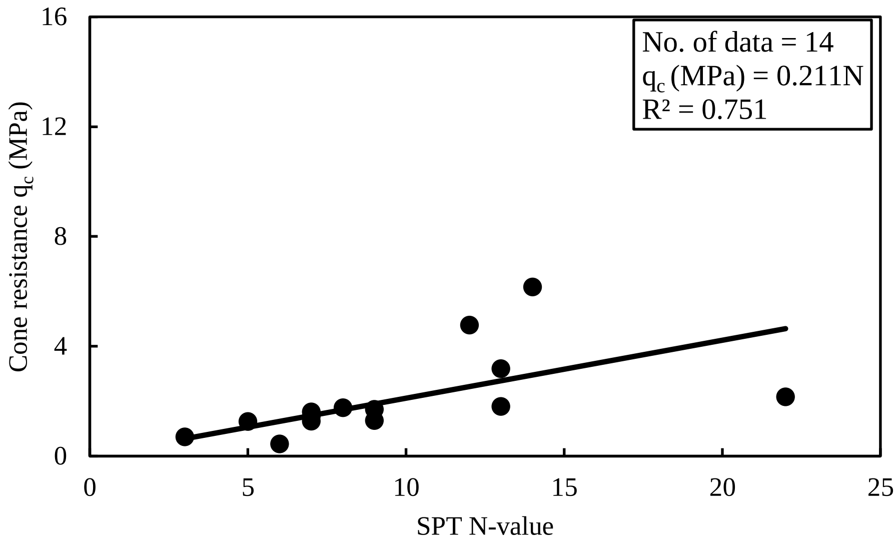


Fig. 4.16: SPT N-value and CPT cone resistance relation for high plastic of clay (CH).

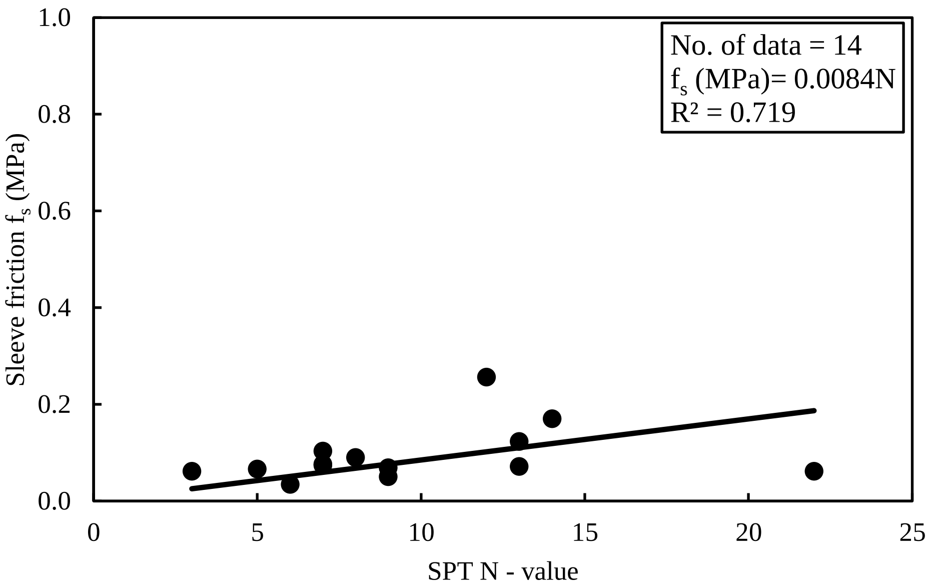


Fig. 4.17: SPT N-value and CPT sleeve friction relation for high plastic clay (CH).

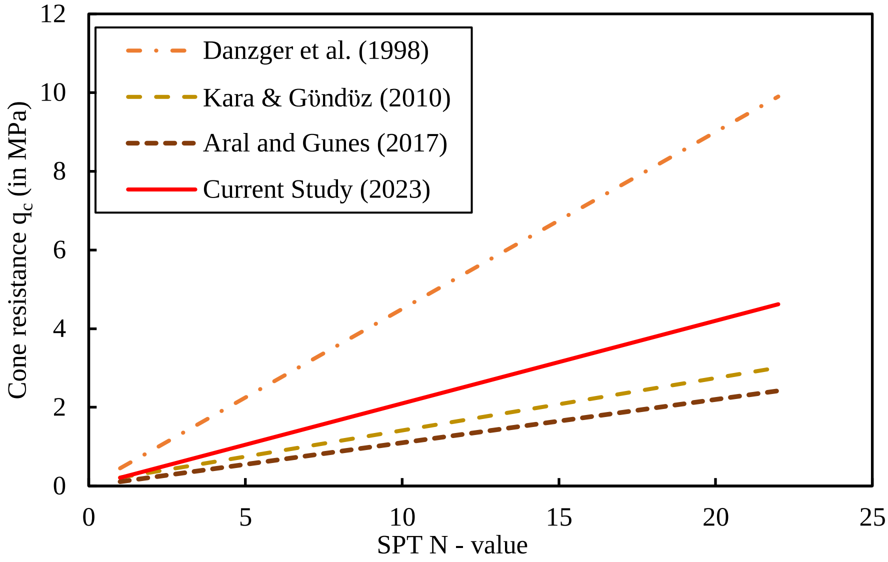


Fig. 4.18: Comparison of SPT N-value and CPT cone resistance relations for high plastic clay (CH).

4.8 Summary of SPT-CPT Relations Obtained

The present study proposes various relationships of field SPT N-value with CPT cone resistance, CPT sleeve friction and combinations. For the sake of easy comparison, the cone the relations are reproduced in summary form in Tables 4.1 and 4.2.

Table 4.1: SPT N-value and CPT cone resistance relations obtained in the present study

SL No.	Soil class	No. of data sets	Relationship between q_c and N (SPT) values	Correlation coefficient (R^2)	Eq. No.
1	Non-plastic silty sand (SM)	147	q_c (kPa) = 290 N	0.777	(4.1)
2	Silt of low plasticity and non-plastic sandy silt (ML)	85	q_c (kPa) = 168 N	0.558	(4.4)
3	Silt of high plasticity (MH)	43	q_c (kPa) = 112 N	0.556	(4.7)
4	Silty clay and clay of low plasticity (CL)	182	q_c (kPa) = 210 N	0.602	(4.9)
5	High plastic clay (CH)	14	q_c (kPa) = 211 N	0.751	(4.11)

Table 4.2: Relation of field SPT N-value and CPT sleeve friction and combinations as obtained from the present study

SL No.	Classification of the soil	No. of data sets	Relationship between f_s and N (SPT) values	Correlation coefficient (R^2)	Eq. No
1	Non-plastic silty sand (SM)	147	f_s (kPa) = 5.2 N	0.767	(4.2)
			$(q_c + f_s)$ (kPa) = 295 N	0.797	(4.3)
2	Silt of low plasticity and non-plastic sandy silt (ML)	85	f_s (kPa) = 4.3 N	0.51	(4.5)
			$(q_c + f_s)\ (kPa) = 172\ N$	0.56	(4.6)
3	Silt of high plasticity (MH)	43	f_s (kPa) = 2.6 N	0.468	(4.8)
4	Silty clay and clay of low plasticity (CL)	182	f_s (kPa) = 5.8 N	0.548	(4.10)
5	High plastic clay (CH)	14	f_s (kPa) = 8.4 N	0.719	(4.12)

4.9 Interpretation of Soil Profiles

In the present study soil profiles were drawn using both SPT and CPT data. All the soil profiles as considered in this investigation are presented in Figs. B.1 to B.24 of Appendix-B. As mentioned earlier, in Section 3.4, the CPT soil profiles were tried to prepare using various methods suggested by different investigators and the simplified soil classification chart, Fig. 2.12, suggested by Robertson et al. (1983) was found to yield reasonably identical results of soil profiling while compared to that SPT. Because of too many minor soil classifications used by the other methods, it was found awkward to prepare a reasonably consensus CPT soil profiling with that of SPT. It was observed that both CPT and SPT give comparable soil profile for sandy soil while using Robertson et al. (1983) method of interpretation of CPT results. However, generally found that while Robertson et al. (1983) CPT method interprets a soil as clay, SPT identifies it as silty soil, and the vice versa has also been noticed.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 General

This present study was carried out to in an attempt correlate the CPT parameters, cone resistance and sleeve friction, with the standard penetration test N-value for various types of subsoil classes from a selected location of Bangladesh. In total 24 CPT tests were conducted at a project site within a SPT boreholes proximity location of radial distances of 6 m. Soil profiles were prepared using both CPT and SPT data, and similar types of soil were isolated for statistical analysis. The following sections provide the outcome of the study as conclusions and suggestions for future work in this context.

5.2 Conclusions

The major outcome of the study can be summarized as follows:

(i) Strong linear correlations were found to exist between field SPT N-value, and both CPT cone resistance and sleeve friction for non-plastic silty sand (SM). The correlation may be proposed in terms of equations (4.1) and (4.2). In both the cases (cone resistance and sleeve friction), the correlation coefficient (R^2) was larger than 0.75.

(ii) For soil types like silt of low plasticity and non-plastic sandy silt (ML), silt of high plasticity (MH) and clay of low plasticity or silty clay (CL) moderately strong correlations were obtained with correlation coefficients (R^2) larger than 0.50. The correlations may be proposed as equations (4.3) through (4.11). All these correlations are summarized in Table 4.1.

(iii) For clay soil of high plasticity (CH), strong (0.751) and good (0.719) linear correlations of field SPT N-value were observed with CPT cone resistance and sleeve friction respectively. The relations may be proposed as Eqs. (4.11) and (4.12).

(iv) For sandy soil CPT and SPT were found to yield reasonably identical soil profile while using the simplified soil classification chart suggested by Robertson et al.

(1983). While compared the soil profiles, it was observed that both CPT and SPT gave comparable results for sandy soil. However, in general, while Robertson et al. (1983) method of CPT interprets a soil as a clay, SPT identifies that one as a silty soil; the vice versa was also found to be true. Though they did not happen in all the cases.

5.3 Recommendations for Further Study

The present study involves CPT and SPT test data only of a particular site of Bangladesh and the study was limited to the relations of field SPT N-value, CPT cone resistance and sleeve friction for a broad soil classification. The study may be extended on the following aspects.

(i) To generalize the proposed relations in the context of Bangladesh, extensive study may be carried out using soils from various locations of Bangladesh.

(ii) The other parameters of like soil index properties may be considered in the investigation.

(iii) The CPT with pore pressure measurement and SPT with various corrections may be considered.

(iv) A fully research dedicated test scheme may be designed for performing CPT and SPT in the proximity locations at various sites.

(v) Study may also be carried out to find relations among parameters obtained from CPT, SPT and dynamic cone penetration test (DCP).

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APPENDIX- A

NORTHING AND EASTING OF SPT AND CPT LOCATIONS

Table A.1: Northing and easting of the 17 SPT borehole locations

Sl. No	Bore Hole ID	True north coordination (BUTM-2010)		GPUFP coordination		Location	RL (m)
		Easting-X (m)	Northing-Y (m)	Easting-X (m)	Northing-Y (m)		
1	BH-2	565,068.268	2,653,377.249	-	-	-	-
2	BH-4	565,388.712	2,563,413.591	-	-	-	-
3	BH-9	565,714.850	2,653,158.765	-	-	-	-
4	BH-12	565,655.031	2,653,066.313	-	-	-	-
5	BH-13	565,740.702	2,653,060.508	-	-	-	-
6	BH-18	565,563.456	2,652,761.345	-	-	-	-
7	BH-19	565,522.794	2,652,846.969	-	-	-	-
8	BH-26	565,400.473	2,653,316.703	-	-	-	-
9	BH-27	565,617.829	2,653,195.049	-	-	-	-
10	BH-36	565,474.664	2,652,961.582	4,938.181	5,185.940	NH_3 tank	8.181
11	BH-37	565,452.290	2,652,895.254	4,938.274	5,115.940		8.156
12	BH-43	565,817.107	2,652,844.141	5,300.200	5,184.598	Process compressor house	7.93
13	BH-57	565,975.065	2,652,824.834	5456.000	5217.000	01-T-701	7.764
14	BH-58	565,963.065	2,652,800.393	5456.000	5217.000	01-T-301	7.859
15	BH-63	565,621.511	2,652,887.607	5101.000	5163.000	02-T-501	7.934
16	BH-70	565,533.389	2,653,160.456	4929.983	5393.141	Raw water treatment house	8.327
17	BH-72	565,620.099	2,653,016.046	5058.447	5284.193	Raw water treatment unit	7.824

Table A.2. Northing and easting of 24 CPT locations

Sl. No	CPT ID	True north coordination (BUTM; 2010)		GPUFP coordination		Location	RL (m)
		Easting- X (m)	Northing- Y (m)	Easting- X (m)	Northing- Y (m)		
1	CPT 1	564,996.583	2,653,400.576	4,344.513	5,448.304	Corr./ Conveyor	7.267
2	CPT 2	565,170.331	2,653,350.370	4,525.182	5,456.508	Corr./ Conveyor	7.304
3	CPT 3	565,472.617	2,653,236.570	4,848.000	5,445.729	Corr./Conveyor	8.066
4	CPT 4	565,531.907	2,653,189.641	4,919.214	5,420.307	Raw Water Tank	8.018
5	CPT 5	565,630.530	2,653,090.919	5,044.300	5,358.454	Potable water tank	7.553
6	CPT 6	565,659.424	2,653,082.713	5,074.300	5,359.954	Demi. Water tank	7.954
7	CPT 7	565,686.073	2,653,067.877	5,104.300	5,354.454	Process Con. Tank	7.943
8	CPT 8	565,755.373	2,653,044.925	5,177.300	5,354.954	Costic Soda Tank	7.936
9	CPT 9	565,667.069	2,652,980.762	5,114.256	5,265.847	Polish water tank	7.768
10	CPT 10	565,969.978	2,652,830.387	5,449.400	5,220.627	M. Solution Tank	7.709
11	CPT 11	565,957.399	2,652,806.037	5,445.300	5,193.527	M. Tank	7.704
12	CPT 12	565,415.868	2,652,826.002	4,926.001	5,038.663	NG Flare	7.741
13	CPT 13	565,494.933	2,652,726.744	5,032.736	4,970.026	Comm. Building	8.258
14	CPT 14	565,481.203	2,652,980.883	4,938.181	5,206.319	NH_3 Tank	7.842
15	CPT 15	565,458.207	2,652,954.103	4,924.994	5,173.575	NH_3 Tank	7.858
16	CPT 16	565,483.166	2,652,945.793	4,951.300	5,173.714	NH_3 Tank	7.894
17	CPT 17	565,443.394	2,652,911.218	4,924.725	5,128.205	NH_3 Tank	7.945
18	CPT 18	565,469.259	2,652,902.302	4,952.085	5,128.061	NH_3 Tank	8.006
19	CPT 19	565,445.970	2,652,876.309	4,938.368	5,095.696	NH_3 Tank	8.029
20	CPT 20	565,333.668	2,653,450.412	4,647.778	5,603.673	Bag Storage	8.358
21	CPT 21	565,609.373	2,653,187.378	4,993.309	5,443.022	Bulk Urea Storage	7.999
22	CPT 22	565,706.359	2,653,150.126	5,097.120	5,438.862	Bulk Urea Storage	7.563
23	CPT 23	565,594.980	2,652,913.384	5,067.600	5,178.900	Granulation House	7.919
24	CPT 24	565,811.163	2,652,795.637	5,310.135	5,136.751	NH_3 REF Struc.	8.305

APPENDIX- B

CPT-SPT PROXIMITY LOCATIONS SOIL PROFILES

Table B.1: CPT and proximity SPT Borehole locations

Sl. No.	CPT Location ID	Proximity SPT BH No.	Sl. No.	CPT Location ID	Proximity SPT BH No.
1	CPT 1	BH 2	13	CPT 13	BH 18
2	CPT 2		14	CPT 14	BH 36
3	CPT 3	BH 26	15	CPT 15	
4	CPT 4	BH 70	16	CPT 16	
5	CPT 5	BH 12	17	CPT 17	BH 37
6	CPT 6		18	CPT 18	
7	CPT 7		19	CPT 19	
8	CPT 8	BH 13	20	CPT 20	BH 4
9	CPT 9	BH 72	21	CPT 21	BH 27
10	CPT 10	BH 57	22	CPT 22	BH 9
11	CPT 11	BH 58	23	CPT 23	BH 63
12	CPT 12	BH 19	24	CPT 24	BH 43

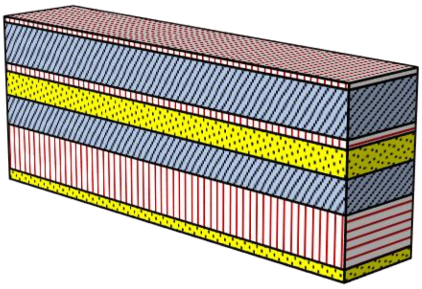
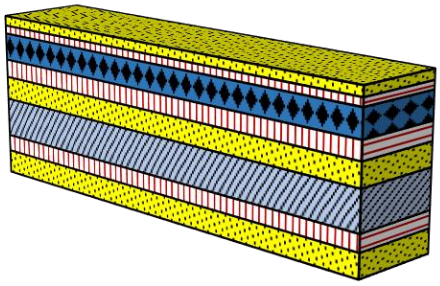
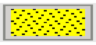
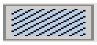
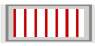
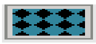
			
(a) CPT soil profile		(b) SPT soil profile	
Legend:			
Sand		Clay	
Silt		Organic	

Fig. B.1: CPT and SPT soil profies (CPT 01 and Proximity SPT BH-02)

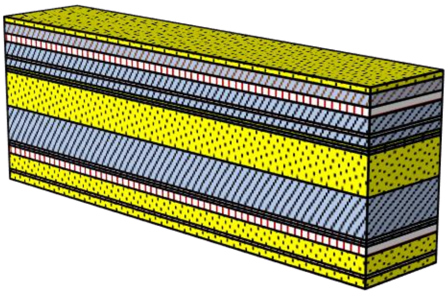
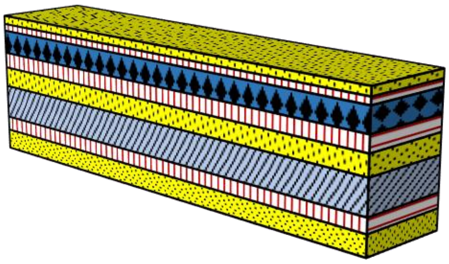
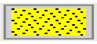
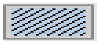
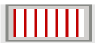
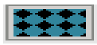
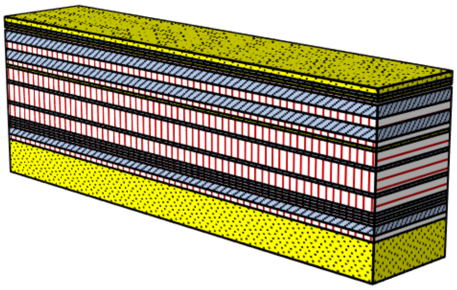
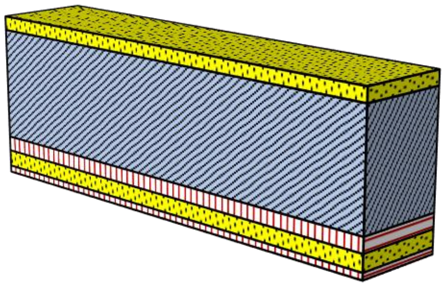
			
(a) CPT soil profile		(b) SPT soil profile	
Legend:			
Sand		Clay	
Silt		Organic	

Fig. B.2: CPT and SPT Soil Profies (CPT 02 and Proximity SPT BH-02)

	
(a) CPT soil profile	(b) SPT soil profile

Legend:

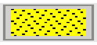
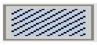
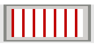
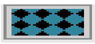
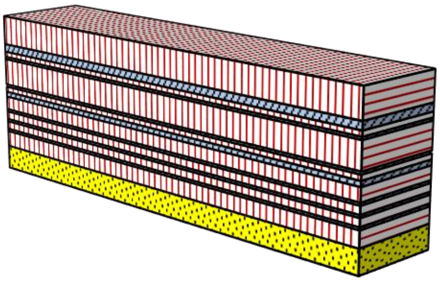
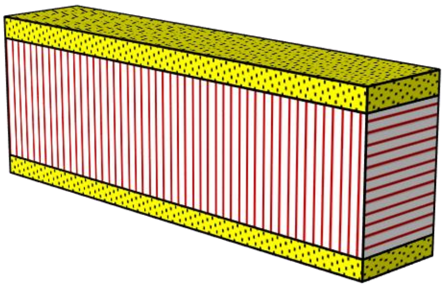
Sand		Clay	
Silt		Organic	

Fig. B.3: CPT and SPT Soil Profies (CPT 03 and proximity SPT BH-26)

	
(a) CPT soil profile	(b) SPT soil profile

Legend:

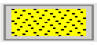
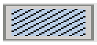
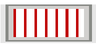
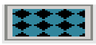
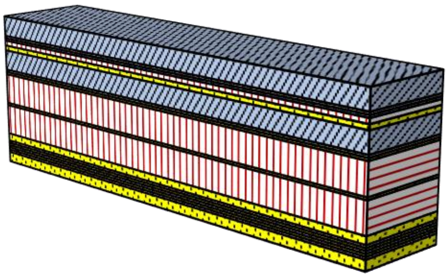
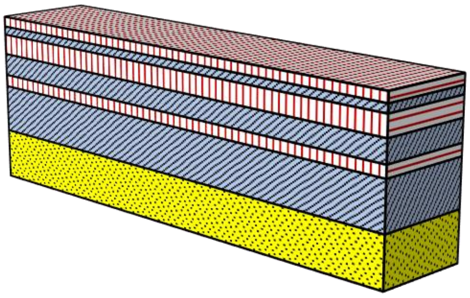
Sand		Clay	
Silt		Organic	

Fig. B.4: CPT and SPT Soil Profies (CPT 04 and proximity SPT BH-70).



(a) CPT soil profile



(b) SPT soil profile

Legend:

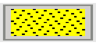
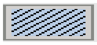
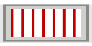
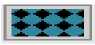
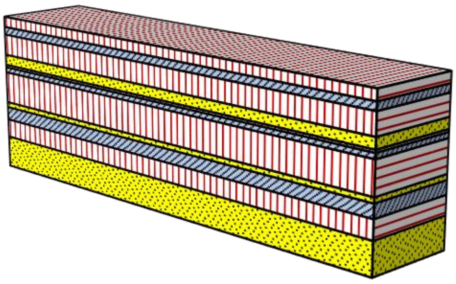
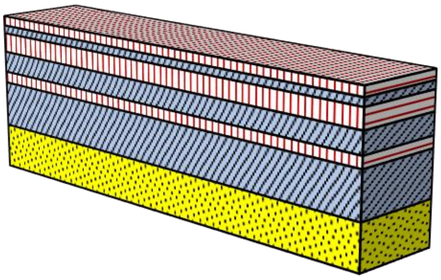
Sand		Clay	
Silt		Organic	

Fig. B.5: CPT and SPT soil profies (CPT 05 and proximity SPT BH-12)



(a) CPT soil profile



(b) SPT soil profile

Legend:

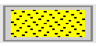
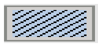
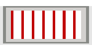
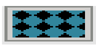
Sand		Clay	
Silt		Organic	

Fig. B.6: CPT and SPT soil profies (CPT 06 and proximity SPT BH-12)

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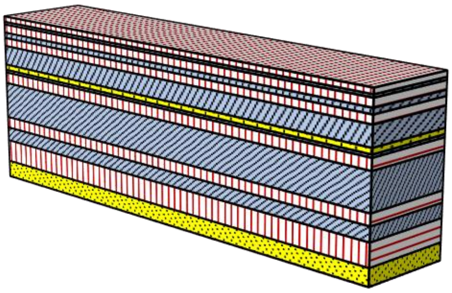
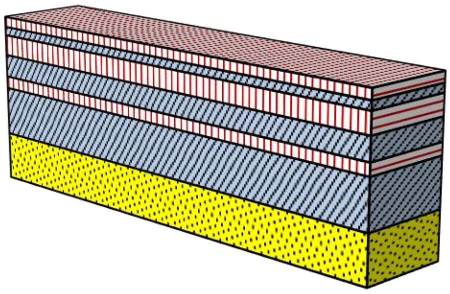
<tr><td colspan="2"></td><td colspan="2"></td></tr>
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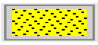
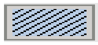
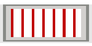
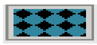
<tr><td colspan="4">Legend:</td></tr>
<tr><td>Sand</td><td></td><td>Clay</td><td></td></tr>
<tr><td>Silt</td><td></td><td>Organic</td><td></td></tr>
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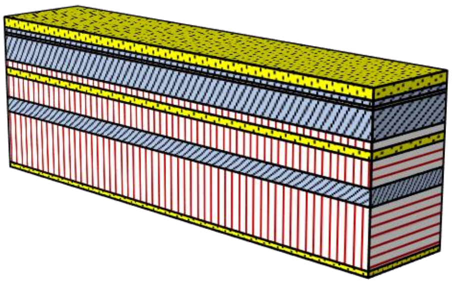
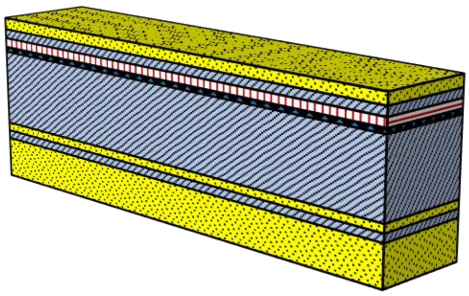
<tr><td colspan="2"></td><td colspan="2"></td></tr>
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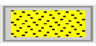
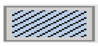
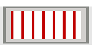
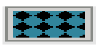
<tr><td colspan="4">Legend:</td></tr>
<tr><td>Sand</td><td></td><td>Clay</td><td></td></tr>
<tr><td>Silt</td><td></td><td>Organic</td><td></td></tr>
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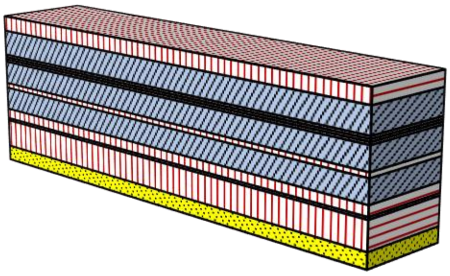		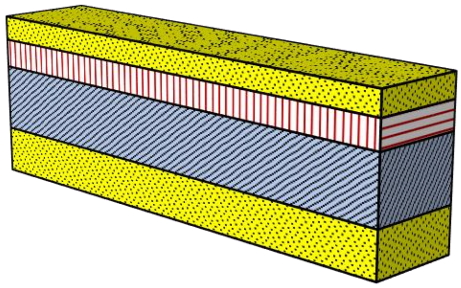	
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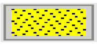
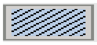
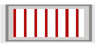
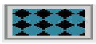
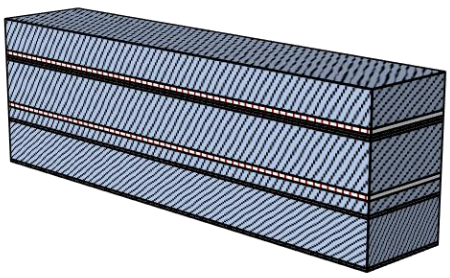
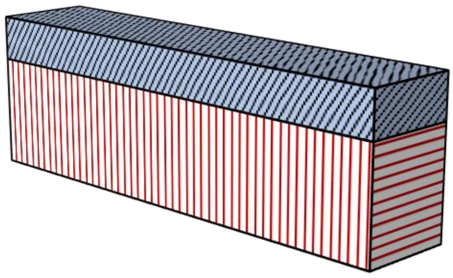
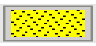
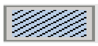
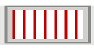
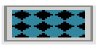
Legend:			
Sand		Clay	
Silt		Organic	
Fig. B.9: CPT and SPT soil profies (CPT 09 and proximity SPT BH-72)			

			
(a) CPT soil profile		(b) SPT soil profile	
Legend:			
Sand		Clay	
Silt		Organic	
Fig. B.10: CPT and SPT soil profies (CPT 10 and proximity SPT BH-57)			

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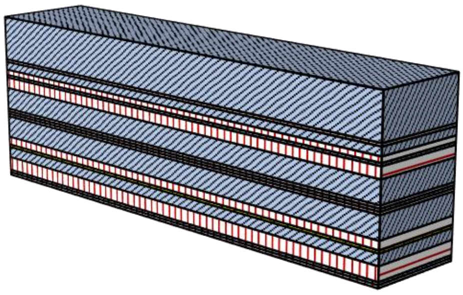
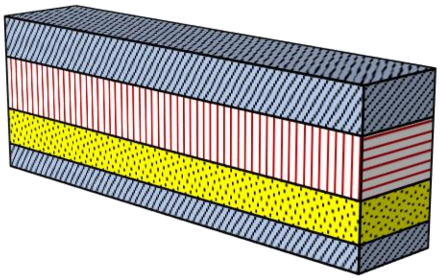
<tr><td colspan="2"></td><td colspan="2"></td></tr>
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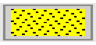
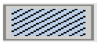
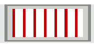
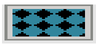
<tr><td>Sand</td><td></td><td>Clay</td><td></td></tr>
<tr><td>Silt</td><td></td><td>Organic</td><td></td></tr>
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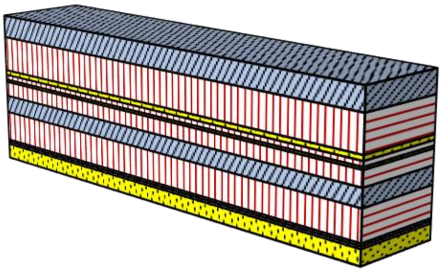
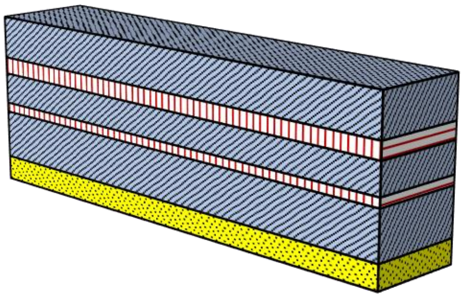
<tr><td colspan="2"></td><td colspan="2"></td></tr>
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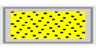
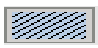
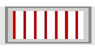
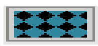
<tr><td>Sand</td><td></td><td>Clay</td><td></td></tr>
<tr><td>Silt</td><td></td><td>Organic</td><td></td></tr>
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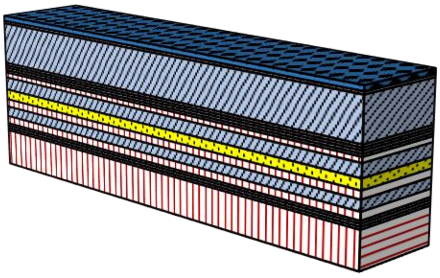
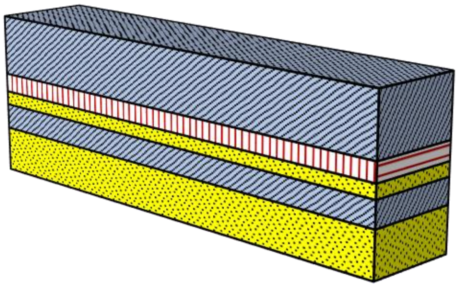
	
(a) CPT soil profile	(b) SPT soil profile

Legend:

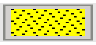
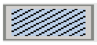
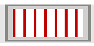
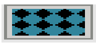
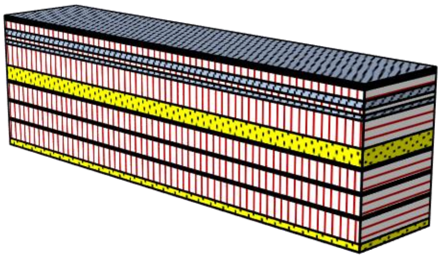
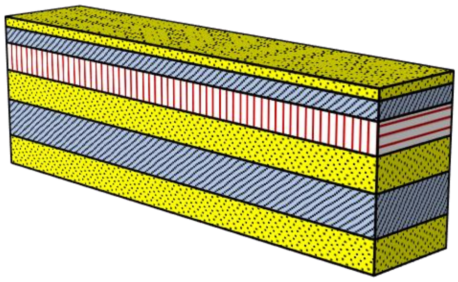
Sand		Clay	
Silt		Organic	

Fig. B.13: CPT and SPT soil profies (CPT 13 and proximity SPT BH-18)

	
(a) CPT soil profile	(b) SPT soil profile

Legend:

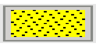
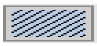
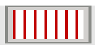
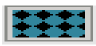
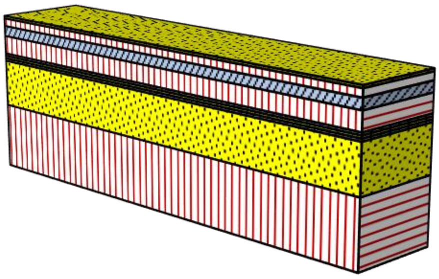
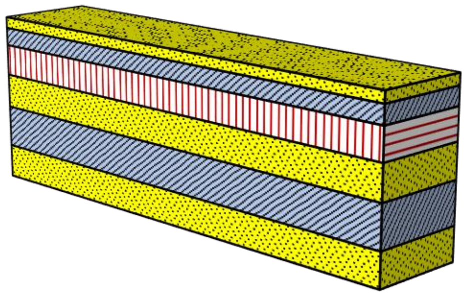
Sand		Clay	
Silt		Organic	

Fig. B.14: CPT and SPT soil profies (CPT 14 and proximity SPT BH-36)



(a) CPT soil profile

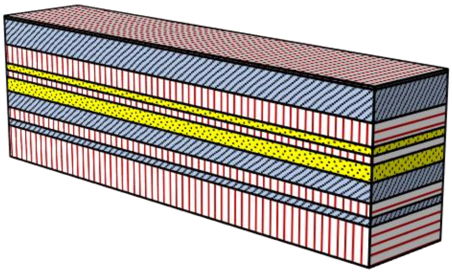


(b) SPT soil profile

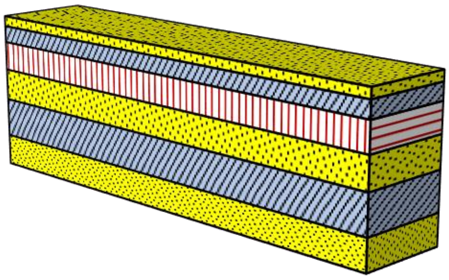
Legend:

Sand		Clay	
Silt		Organic	

Fig. B.15: CPT and SPT soil profies (CPT 15 and proximity SPT BH-36)



(a) CPT Soil Profile

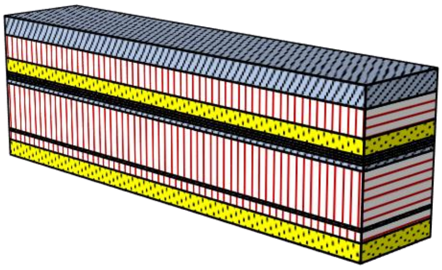


(b) SPT Soil Profile

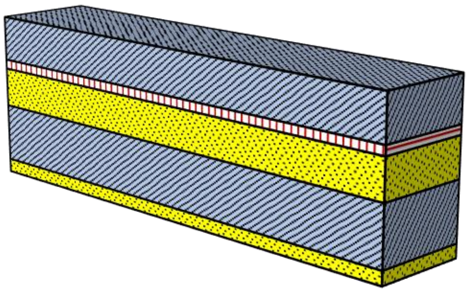
Legend:

Sand		Clay	
Silt		Organic	

Fig. B.16: CPT and SPT soil profies (CPT 16 and proximity SPT BH-36)



(a) CPT soil profile



(b) SPT soil profile

Legend:

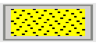
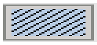
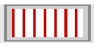
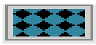
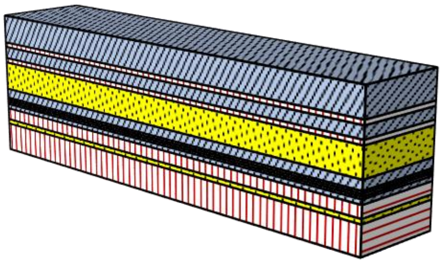
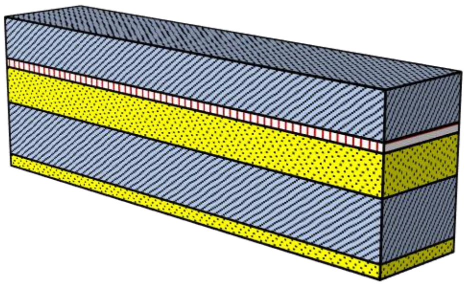
Sand		Clay	
Silt		Organic	

Fig. B.17: CPT and SPT soil profies (CPT 17 and proximity SPT BH-37)



(a) CPT soil profile



(b) SPT soil profile

Legend:

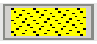
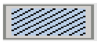
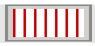
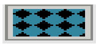
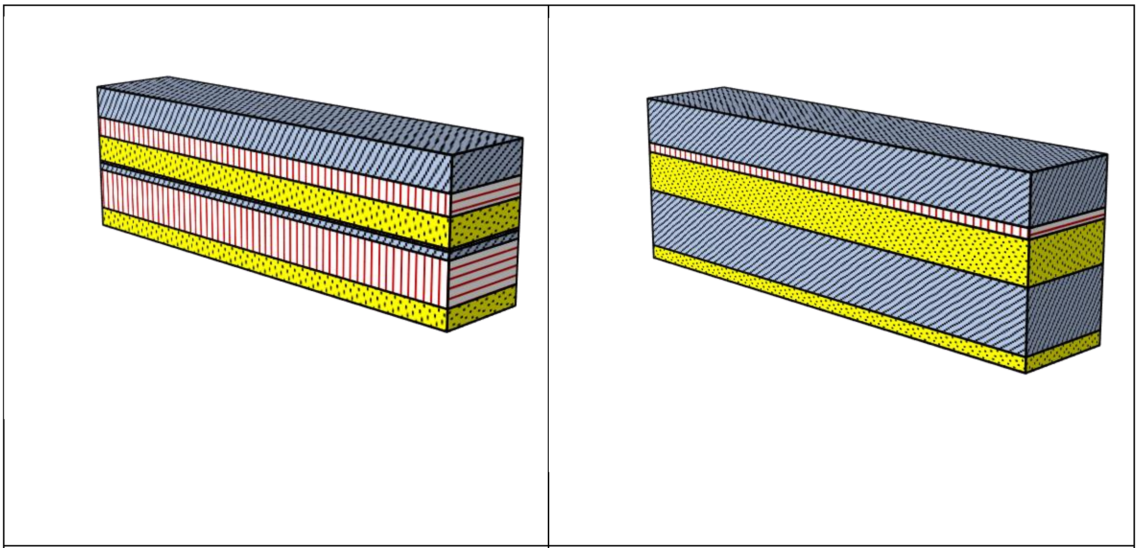
Sand		Clay	
Silt		Organic	

Fig. B.18: CPT and SPT soil profies (CPT 18 and proximity SPT BH-37)

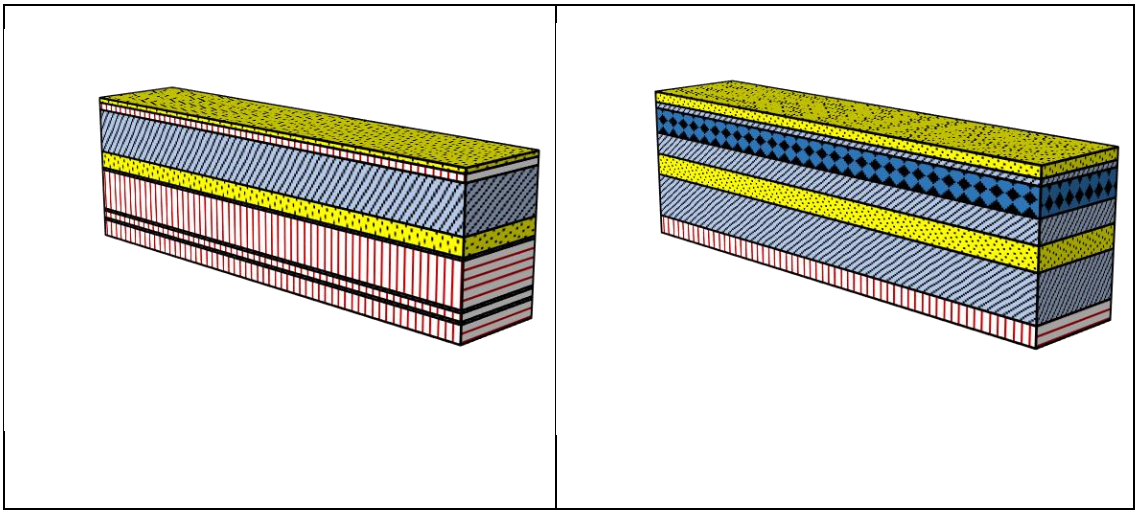


(a) CPT soil profile	(b) SPT soil profile

Legend:

Sand		Clay	
Silt		Organic	

Fig. B.19: CPT and SPT soil profies (CPT 19 and proximity SPT BH-37)

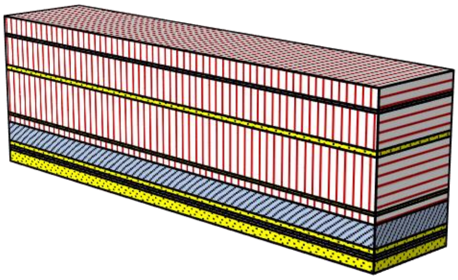
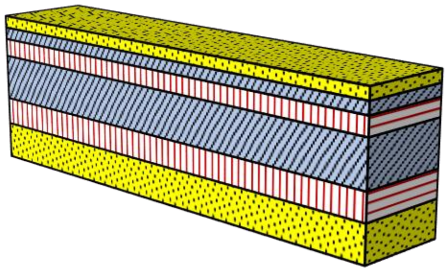


(a) CPT soil profile	(b) SPT soil profile

Legend:

Sand		Clay	
Silt		Organic	

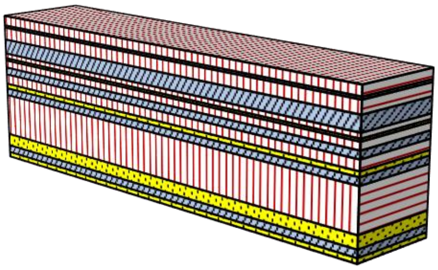
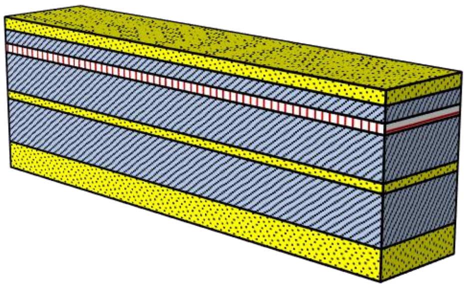
Fig. B.20: CPT and SPT soil profies (CPT 20 and proximity SPT BH-04)

	
(a) CPT soil profile	(b) SPT soil profile

Legend:

Sand		Clay	
Silt		Organic	

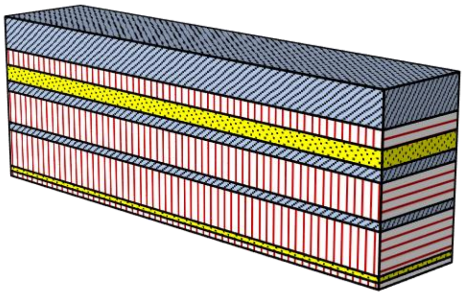
Fig. B.21: CPT and SPT soil profies (CPT 21 and proximity SPT BH-27)

	
(a) CPT soil profile	(b) SPT soil profile

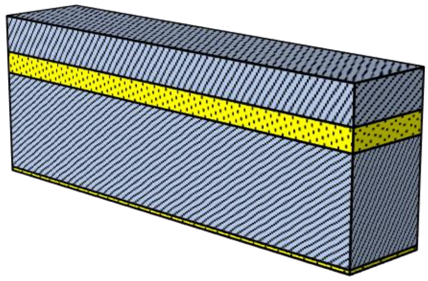
Legend:

Sand		Clay	
Silt		Organic	

Fig. B.22: CPT and SPT soil profies (CPT 22 and proximity SPT BH-09)



(a) CPT soil profile

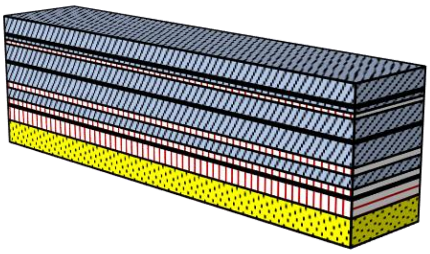


(b) SPT soil profile

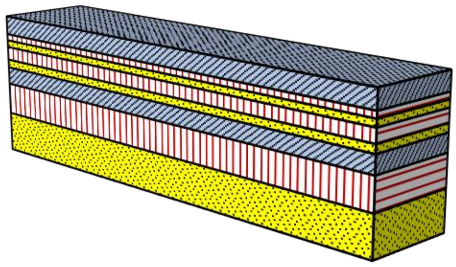
Legend:

Sand		Clay	
Silt		Organic	

Fig. B.23: CPT and SPT soil profies (CPT 23 and proximity SPT BH-63)



(a) CPT Soil Profile



(b) SPT Soil Profile

Legend:

Sand		Clay	
Silt		Organic	

Fig. B.24: CPT and SPT soil profies (CPT 24 and proximity SPT BH-43)

APPENDIX- C

CPT AND SPT PENETRATION DATA AND SOIL PROPERTIES

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N - value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 1	18.0	40	18763	395.2	2.106	Silty sand (SM)					
	19.63	36	21359	260.8	1.221						
	21.0	47	3197	141.6	4.429						
	22.63	52	3731	198.4	5.318						
	27.5	48	3096	41.3	1.334					56	44
	29.0	50	1830	27.5	1.503					51	49
	30.5	60	3197	97.9	3.062					71	29
CPT 2	1.60	4	1634	16.6	1.016	Silty sand (SM)				80	20
	12.42	37	20107	254	1.263					71	29
	13.80	40	21110	292.7	1.387					73	27
	15.31	60	23795	247.8	1.041					71	29
	27.50	48	17882	237.3	1.327					56	44
	29.00	54	16111	256.7	1.593					67	33
	30.55	66	14543	250.4	1.722					69	31
CPT 3	1.77	8	4296	27.8	0.647	Silty sand (SM)				82	18
	10.23	26	5990	144.3	2.409						
	11.78	24	12547	314.1	2.503						
	13.23	24	7095	159.9	2.254						
	23.78	48	11712	248	2.117						
	25.23	32	13530	161.8	1.196						

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N - value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 3	26.78	43	18541	248.8	1.342	Silty sand (SM)					
	28.23	42	23055	143.3	0.622						
CPT 4	1.78	8	2553	12.8	0.501	Silty sand (SM)					
	10.23	26	7518	179.5	2.388						
	11.78	24	3688	62	1.681						
	13.23	24	3121	68.4	2.192						
	23.78	48	9291	273.5	2.944						
	25.23	32	11560	286.3	2.477						
	26.78	43	13546	190.2	1.404						
	28.23	42	14678	183.9	1.253						
	29.78	49	16769	192.1	1.146						
CPT 5	24.23	31	12282	296.8	2.417	Silty sand (SM)				54	46
	25.75	33	13976	241.1	1.725					58	42
	27.23	34	13828	262.5	1.898					59	41
	28.73	41	14916	291.7	1.956					66	34
	30.23	44	17737	231.1	1.303					60	40
CPT 6	0.725	4	4021	27	0.671	Silty sand (SM)					
	11.73	15	1800	21.5	1.194						
	13.23	17	1669	7.3	0.437						
	22.23	28	11071	307	2.773						
	23.73	30	10805	353.3	3.270					76	24
	25.23	38	16155	187	1.158						
	26.73	35	18562	204.8	1.103						
	29.00	49	14421	176.3	1.223						

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N - value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 7	22.93	30	9626	225	2.337	Silty sand (SM)					
	24.46	37	10802	340	3.148					62	38
	26.00	35	10588	221.4	2.091						
	27.50	47	16471	285.2	1.732					58	42
	29.00	49	18307	362.9	1.982						
	30.55	75	18596	262.6	1.412					60	40
CPT 8	0.45	17	16770	97.2	0.580	Silty sand (SM)					
	1.225	10	9278	62.5	0.674					97	3
	23.73	36	8574	386.1	4.503						
	25.23	42	10646	283.65	2.664						
	26.73	46	12935	367.05	2.838						
	28.23	48	11931	305.8	2.563						
	29.73	69	16886	343.8	2.036						
CPT 9	0.725	4	2548	21.2	0.832	Silty sand (SM)					
	2.725	0	701	11.5	1.641						
	11.73	15	1656	55.8	3.369						
	13.23	17	3185	138.5	4.349						
	22.23	28	6752	326.9	4.842						
	23.73	30	10255	421.2	4.107					76	24
	25.23	38	11529	430.8	3.737						
	26.73	35	12293	398.1	3.238						
	28.23	44	17295	397.6	2.299					59	41
	29.73	49	17751	242.5	1.366						

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 11	19.23	33	2081	46	2.211	Silty sand (SM)					
	20.73	51	3760	161.3	4.290						
	22.23	57	8210	331.6	4.039					53	47
	23.73	62	8210	331.6	4.039						
	25.23	19	10870	287	2.640						
CPT 12	10.23	17	10510	252.5	2.403	Silty sand (SM)					
	11.73	28	10955	273.4	2.496					52	48
	13.23	31	5223	163.6	3.132						
	14.23	31	1975	28.8	1.459						
	16.23	48	2675	72.8	2.721						
	28.23	37	15841	308.9	1.950						
	29.73	38	16860	214.2	1.270						
CPT 13	15.31	11	5463	160.9	2.945	Silty sand (SM)				60	40
	16.84	14	10674	118.2	1.107					58	42
	22.93	28	3530	96.9	2.745					55	45
	24.64	50	2648	32.9	1.242					54	46
	26.00	41	2973	32.9	1.107						
	27.50	43	3170	32.9	1.038					60	40
	29.00	57	4077	28.2	0.692					64	36
	30.50	60	3768	23.1	0.613						
CPT 14	1.225	2	4359	30.6	0.702	Silty sand (SM)					
	11.73	26	8269	136.8	1.654						
	13.23	31	10449	152	1.455					83	17
	14.73	37	15769	149.9	0.951						

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 14	25.23	43	9679	358.1	3.700	Silty sand (SM)					
	26.73	38	9423	392.5	4.165						
	28.23	36	14710	314.1	2.135						
	29.73	44	15011	240.6	1.603						
CPT 15	1.225	2	2913	22.4	0.769	Silty sand (SM)					
	5.725	14	2174	57.6	2.650						
	10.23	20	10346	227.7	2.201						
	11.73	26	17622	152	0.863						
	13.23	31	16368	119.5	0.730					83	17
	14.73	37	16119	144.4	0.896						
	16.23	28	26572	272.5	1.026						
	17.73	22	16977	179.5	1.057						
CPT 16	11.73	26	9238	62	0.671	Silty sand (SM)					
	13.23	31	7328	68.4	0.933					83	17
	14.73	37	12081	121.8	1.008						
	16.23	28	5237	83.3	1.591						
	25.23	43	10559	286.3	2.711						
	26.73	38	11693	190.2	1.627						
CPT 17	10.23	17	12770	115.9	0.908	Silty sand (SM)					
	11.73	28	16876	234.4	1.389					52	48
	16.23	48	6427	193.2	3.006						
	28.23	37	14700	267.5	1.820						
	29.73	38	15914	176.7	1.110						

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 18	11.73	28	15038	223.3	1.485	Silty sand (SM)				52	48
	13.23	31	20918	236	1.128						
	14.73	31	20376	215.7	1.059						
	16.23	48	18418	324.3	1.761						
	31.23	37	13985	241.7	1.728						
CPT 19	10.23	17	6798	211.1	3.105	Silty sand (SM)					
	11.73	28	15618	278.4	1.783					52	48
	13.23	31	15730	308.5	1.961						
	14.73	31	23235	207.2	0.892						
	16.23	48	20382	254.2	1.247						
	28.23	37	3367	20	0.594						
	29.73	38	9335	151.7	1.625						
CPT 20	1.60	5	4321	60.4	1.398	Silty sand (SM)					
	13.8	35	17824	132.5	0.743					57	43
	15.31	38	6944	74	1.066					68	32
CPT 21	1.60	4	1957	10.2	0.521	Silty sand (SM)				89	11
	26.0	43	11166	194.5	1.742					61	39
	27.5	54	17037	187.4	1.100					62	38
	29.0	54	13066	310	2.373						
	30.5	60	16224	173	1.066						
CPT 22	15.3	40	11343	111	0.979	Silty sand (SM)				52	48
	26.0	39	12535	241.8	1.929						
	27.5	60	13482	202.5	1.502					66	34

Table C.1: SPT, CPT test results and index properties of non-plastic silty sand (SM)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 22	29.00	42	8728	377.8	4.329	Silty sand (SM)					
	30.55	66	17184	208	1.210						
CPT 23	10.23	21	12802	242.9	1.897	Silty sand (SM)					
	11.73	29	13821	438.1	3.170						
CPT 24	23.73	36	8645	405	4.685	Silty sand (SM)					
	25.23	38	9729	238.3	2.449					78	22
	26.73	54	11183	389.7	3.485						
	27.50	48	12589	344.7	2.738					62	38
	29.00	54	21667	402.6	1.858						
	30.50	66	19380	176.8	0.912						

Table C.2: SPT, CPT test results and index properties of low plastic silt and non-plastic sandy silt (ML)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 1	0.8	10	4949	49.2	0.994	Low plastic silt (ML)					
	1.5	3	789	22.5	2.851		43	27	16	10	90
	3.0	6	750	42.0	5.598						
	9.0	18	7255	154.6	2.131		40	27	13	9	91
	10.7	26	10663	284.6	2.668						
	12.0	24	20075	221.8	1.105						

Table C.2: SPT, CPT test results and index properties of low plastic silt and non-plastic sandy silt (ML)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 1	13.6	47	17106	213.9	1.250	NP sandy silt (ML)					
	24.5	37	3197	97.9	3.062					19	81
	26	39	7384	440.2	5.962					24	76
CPT 2	3.125	4	668	7.0	1.048	NP sandy silt (ML)				19	81
	10.75	13	9246	120.0	1.297						
	24.5	37	8638	400.3	4.634					19	81
	25.98	39	14873	219.5	1.476					24	76
CPT 3	7.2	18	710	13.3	1.869	Low plastic silt (ML)	38	28	10	11	89
	8.8	13	3706	91.4	2.466						
	14.8	13	2675	59.0	2.207		45	28	17	9	91
	16.2	15	2085	43.9	2.107						
	17.8	27	4959	142.7	2.878						
	20.775	18	6850	180.5	2.636	NP sandy silt (ML)					
	22.225	26	7439	359.2	4.829						
CPT 4	7.2	18	851	10.7	1.255	Low plastic silt (ML)	38	28	10	11	89
	8.8	13	2908	64.1	2.205						
	14.8	13	3759	121.8	3.240						
	16.2	15	3333	83.3	2.500						
	17.8	27	3262	96.2	2.947						
	20.775	18	4823	132.5	2.747	NP sandy silt (ML)					
	22.225	26	9291	346.2	3.726						
CPT 5	1.2	2	486	22.1	4.540	Low plastic silt (ML)					

Table C.2: SPT, CPT test results and index properties of low plastic silt and non-plastic sandy silt (ML)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 6	20.725	17	10281	396.5	3.857	NP sandy silt (ML)					
CPT 7	1.6	0	428	10.5	2.446	NP sandy silt (ML)					
	4.7	9	588	8.4	1.432	Low plastic silt (ML)	34	25	9		
	6.2	20	963	17.8	1.849					4	96
	12.415	22	2139	47.3	2.212	NP sandy silt (ML)				45	56
CPT 8	2.7	6	260	9.4	3.616	Low plastic silt (ML)					
	4.2	7	1154	22.6	1.959		34	24	10	9	91
	5.7	6	1430	23.7	1.654						
	7.2	9	783	9.1	1.156						
	8.7	3	1086	11.5	1.059						
	10.2	8	8309	130.1	1.566						
	11.7	22	11968	202.0	1.688						
	13.2	25	4035	107.6	2.667						
	14.7	28	2794	38.4	1.374		35	28	7	9	91
	16.2	23	3726	116.2	3.117						
	17.7	22	3931	159.7	4.061						
	19.2	29	2858	81.8	2.860						
	20.7	30	2221	29.6	1.332						
	22.2	33	5223	213.5	4.087		44	31	13	40	60

Table C.2: SPT, CPT test results and index properties of low plastic silt and non-plastic sandy silt (ML)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 10	10.2	14	3017	87.1	2.885	Low plastic silt (ML)					
	11.7	16	4337	223.4	5.151		43	31	12	13	87
CPT 11	8.7	20	3246	88.9	2.738	Low plastic silt (ML)					
	10.2	30	3636	106.3	2.922						
	11.7	24	3760	116.8	3.106						
	13.2	18	3634	94.7	2.606		47	28	19	11	89
	14.7	18	2630	101.7	3.867						
	16.2	13	2984	108.2	3.627						
	17.7	22	2335	57.5	2.460						
CPT 13	12.4	8	7036	292.6	4.159	Low plastic silt (ML)	34	25	9		
	13.8	7	2981	114.3	3.835						
CPT 14	5.725	14	3654	93.4	2.557	NP sandy silt (ML)					
CPT 15	25.225	43	2737	48.2	1.761	NP sandy silt (ML)					
	26.725	38	2917	44.3	1.517						
	28.225	36	3789	99.5	2.626						
	29.725	44	4707	76.9	1.633						
CPT 17	13.225	31	2859	58.8	2.057	NP sandy silt (ML)					
	14.725	31	2925	77.8	2.660						
CPT 18	10.225	17	7596	163.1	2.146	NP sandy silt (ML)					
	28.225	37	2767	38.6	1.395						
	29.725	38	3623	75.8	2.092						

Table C.2: SPT, CPT test results and index properties of low plastic silt and non-plastic sandy silt (ML)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 20	27.5	47	5093	132.5	2.601	NP sandy silt (ML)				32	68
	29	54	2444	25.8	1.056						
	30.5	60	3111	64.5	2.074					24	76
CPT 21	6.17	12	518	7.9	1.525	NP sandy silt (ML)				8	92
	7.7	14	921	9.4	1.026						
CPT 22	7.7	9	810	17.7	2.180	Low plastic silt (ML)	28	22	6.09		
	9.2	8	5340	73.1	1.368					10	90
	21.41	36	3123	73.1	2.339						
	24.5	46	3044	67.3	2.209		28	22	6.2		
CPT 23	1.2	1	4249	50.4	1.187	Low plastic silt (ML)					
	2.7	3	733	20.6	2.806						
	4.2	8	1490	37.8	2.541		45	31	14	9	91
	5.7	16	1288	39.4	3.060						
CPT 24	4.2	8	2241	55.8	2.490	Low plastic silt (ML)					
	5.7	15	5517	128.2	2.323						
	20.725	16	2595	34.2	1.316	NP sandy silt (ML)					
	22.225	26	9044	408.8	4.520						

Table C.3: SPT, CPT test results and index properties of high plastic silt (MH)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Testing Parameter				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 3	3.77	6	833	9.6	1.153	Silt of high plasticity (MH)	55	31	24	10	90
	5.77	11	3755	77.2	2.056						
	19.23	53	3092	59.6	1.927						
CPT 4	3.775	6	709	10.7	1.509	Silt of high plasticity (MH)	55	31	24	10	90
	5.775	11	993	8.5	0.856						
	19.23	53	2340	47	2.008						
CPT 5	2.725	1	1117	34.6	3.099	Silt of high plasticity (MH)	67	36	31	31	69
	5.725	4	5181	111.3	2.148						
	7.60	7	808	-1.2	-0.149		60	31	29	15	85
CPT 6	2.725	0	544	21.6	3.974	Silt of high plasticity (MH)	58	32	26	8	92
	4.60	4	4041	59.5	1.472						
CPT 9	4.60	4	764	23.1	3.022	Silt of high plasticity (MH)	58	32	26	8	92
CPT 12	1.225	8	1338	42.1	3.147	Silt of high plasticity (MH)					
	2.725	9	1529	59.3	3.879						
	4.225	8	1783	43.7	2.450		57	30	27	14	86
	5.725	9	2229	41.5	1.862						
	7.225	10	3057	79.8	2.610						

Table C.3: SPT, CPT test results and index properties of high plastic silt (MH)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Testing Parameter				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 13	1.6	10	2039	31	1.521	Silt of high plasticity (MH)					
	3.125	9	1348	54.3	4.030						
	4.65	16	1418	46.5	3.280		50	32	18		
	6.17	14	1423	40.7	2.859						
	18.34	15	3764	95	2.524		51	32	19		
	19.9	17	3644	127.9	3.510						
	21.41	13	2762	48.4	1.752						
CPT 17	1.225	8	1343	29.7	2.211	Silt of high plasticity (MH)					
	2.725	9	1753	54.4	3.103						
	4.225	8	1819	39.3	2.160		57	30	27		
	5.725	9	2724	57.4	2.107						
	7.225	10	2538	67.1	2.644						
	8.725	13	2478	58.2	2.349						
CPT 18	1.225	8	1454	25.6	1.760	Silt of high plasticity (MH)					
	2.725	9	1432	40.5	2.828						
	4.225	8	1734	55.6	3.207		57	30	27		
	5.725	9	1237	26.5	2.143						
	7.225	10	4581	168	3.668						
CPT 19	1.225	8	674	8.3	1.231	Silt of high plasticity (MH)					
	2.725	9	1348	53.6	3.975						
	4.225	8	1517	55.1	3.633		57	30	27		
	5.725	9	1404	28	1.994						
	7.225	10	1910	31.1	1.628						

Table C.3: SPT, CPT test results and index properties of high plastic silt (MH)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Testing Parameter				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 21	18.4	18	2533	39.4	1.556	High plastic silt (MH)	53	34	20		
	19.9	21	2763	47.8	1.730						
	21.41	21	2705	47.7	1.763						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 1	5.00	5	1523.2	65.3	4.287	Clay of low plasticity; silty clay (CL)					
	7.00	6	1742.6	65.0	3.730						
	15.00	38	4692.2	128.1	2.730						
	16.63	18	3185.4	130.1	4.084		44	26	18		
CPT 2	4.65	11	370.8	8.6	2.320	Clay of low plasticity; silty clay (CL)	50	28	22		
	6.17	8	1081.2	19.2	1.771						
	7.70	2	2310.0	29.2	1.264						
	9.23	4	6335.9	100.4	1.584		41	24	17		
	16.84	8	11408.2	273.5	2.397		44	26	18		
	18.37	16	3119.4	113.6	3.642						
	19.90	18	3486.3	120.8	3.465						
	21.41	12	2412.9	46.9	1.944		40	24	16		
	22.93	11	4196.8	143.0	3.407						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 5	10.10	6	971.0	0.4	0.041	Clay of low plasticity; silty clay (CL)					
	12.60	21	2840.3	104.7	3.686						
	13.78	17	3263.5	49.0	1.501						
	15.23	22	2139.6	19.7	0.921						
	16.73	26	2811.7	21.8	0.775						
	18.23	21	5169.2	88.1	1.704						
	19.73	14	3187.8	8.6	0.270		45	27	18		
	21.23	14	8865.5	227.6	2.567						
	22.73	27	11296.1	335.2	2.967						
CPT 6	6.60	6	1009.4	1.4	0.139	Clay of low plasticity; silty clay (CL)					
	8.6	15	14738	110.3	0.748		58	28	30	9	91
	10.75	17	2525.5	67.5	2.673						
	14.73	13	3954.2	109.7	2.774						
	16.23	20	2768.1	67.9	2.453						
	17.73	21	7762.6	112.6	1.451						
	19.23	17	7038.6	387.5	5.505						
CPT 7	3.13	7	641.7	13.4	2.088	Clay of low plasticity; silty clay (CL)					
	7.70	5	3101.6	121.6	3.921						
	9.23	10	5133.7	71.8	1.399						
	10.75	17	2727.3	164.4	6.028						
	13.80	17	1978.6	45.5	2.300						
	15.30	17	3422.5	75.7	2.212						
	16.84	20	3475.9	118.7	3.415						
	18.40	14	2834.2	116.9	4.125						
	19.90	15	2246.0	30.2	1.345		45	27	18		

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 7	21.41	17	4973.3	262.1	5.270	Clay of low plasticity; silty clay (CL)					
CPT 9	6.60	6	764.3	17.3	2.263	Clay of low plasticity; silty clay (CL)					
	14.73	13	2101.9	36.5	1.737		46	27	19	15	85
	16.23	20	2993.6	98.1	3.277						
	17.73	21	3121.0	123.1	3.944						
	19.23	17	2738.9	101.9	3.721		39	24	15	8	92
	20.73	12	1910.8	36.5	1.910						
CPT 10	13.23	10	2640.0	69.3	2.625	Clay of low plasticity; silty clay (CL)	36	20	16	21	79
	14.73	17	3142.9	132.6	4.219						
	16.23	15	1948.6	74.7	3.834						
	17.73	10	2640.0	70.6	2.674						
	19.23	17	1697.1	85.8	5.056						
	20.73	14	3080.0	158.7	5.153						
	22.23	17	2577.1	54.6	2.119						
	23.73	18	4965.7	283.3	5.705						
	25.23	24	2891.4	60.0	2.075						
	26.73	18	2891.4	92.5	3.199						
	28.23	21	2957.1	126.4	4.274						
	29.73	24	3471.4	125.6	3.618						
	31.23	26	2957.1	79.8	2.699						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 11	26.73	26	2999.1	91.1	3.038	Clay of low plasticity; silty clay (CL)					
	28.23	28	3063.1	50.2	1.639		47	25	22	28	72
	29.73	41	3228.1	94.0	2.912						
	31.23	31	3073.1	38.8	1.263						
CPT 12	8.73	13	4140.1	71.9	1.737	Clay of low plasticity; silty clay (CL)					
	17.73	14	3566.9	126.4	3.544						
	19.23	16	4331.2	143.5	3.313						
	20.73	11	3375.8	79.9	2.367						
	22.23	6	2356.7	33.5	1.421						
	23.73	10	3312.1	62.1	1.875						
	25.23	13	11210.2	306.2	2.731						
	26.73	12	12293.0	294.4	2.395						
CPT 13	7.70	9	2383.2	71.7	3.009	Clay of low plasticity; silty clay (CL)					
	9.23	8	1692.3	38.8	2.293						
	10.75	6	1381.5	17.4	1.260						
CPT 14	2.73	1	1346.2	15.0	1.114	Clay of low plasticity; silty clay (CL)					
	4.23	7	1153.9	24.4	2.115						
	7.23	13	1794.9	10.5	0.585						
	8.73	14	6025.6	166.1	2.757						
	10.23	20	8397.4	148.6	1.770						
	16.23	28	4423.1	93.9	2.123						
	17.73	22	3205.1	41.8	1.304						
	19.23	14	2179.5	20.4	0.936						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 14	20.73	12	7051.3	237.5	3.368	Clay of low plasticity; silty clay (CL)					
	22.23	12	3782.1	87.3	2.308						
	23.73	17	3910.3	50.6	1.294						
CPT 15	2.73	1	1315.8	28.4	2.158	Clay of low plasticity; silty clay (CL)					
	4.23	7	2173.8	57.6	2.650						
	7.23	13	1401.2	11.2	0.799						
	8.73	14	3981.0	124.8	3.135						
	19.23	14	3818.9	89.1	2.333						
	20.73	12	2053.4	31.4	1.529						
	22.23	12	4144.1	93.2	2.249						
	23.73	17	2286.4	32.3	1.413						
CPT 16	1.23	2	1055.2	10.7	1.014	Clay of low plasticity; silty clay (CL)					
	2.73	1	1201.4	6.4	0.533						
	4.23	7	1841.9	8.5	0.461						
	5.73	14	3469.6	8.5	0.245						
	7.23	13	2135.3	10.7	0.501						
	8.73	14	2282.3	64.1	2.809						
	10.23	20	6705.7	179.5	2.677						
	17.73	22	3492.8	96.2	2.754						
	19.23	14	2652.7	47.0	1.772						
	20.73	12	3128.3	132.5	4.236						
	22.23	12	2042.6	346.2	16.949						
	23.73	17	6218.1	273.5	4.398						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 17	17.73	14	3142.1	87.9	2.797	Clay of low plasticity; silty clay (CL)					
	19.23	16	2868.3	53.4	1.862						
	20.73	11	2495.3	32.9	1.319						
	22.23	6	2275.8	9.0	0.395						
	23.73	10	2499.2	21.9	0.876						
	25.23	13	7081.5	246.8	3.485						
	26.73	12	10455.7	350.4	3.351						
CPT 18	8.73	13	3409.6	94.7	2.777	Clay of low plasticity; silty clay (CL)					
	17.73	14	2425.1	85.9	3.542						
	19.23	16	3271.8	129.6	3.961						
	20.73	11	2139.7	69.2	3.234						
	22.23	6	2052.3	28.4	1.384						
	23.73	10	6194.3	92.7	1.497						
	25.23	13	3036.9	58.0	1.910						
	26.73	12	2511.1	34.5	1.374						
CPT 19	8.73	13	2471.9	68.0	2.751	Clay of low plasticity; silty clay (CL)					
	17.73	14	3146.1	110.8	3.522						
	19.23	16	2359.6	60.0	2.543						
	20.73	11	2303.4	16.0	0.695						
	22.23	6	1573.0	4.0	0.254						
	23.73	10	1966.3	8.9	0.453						
	25.23	13	3539.3	101.5	2.868						
	26.73	12	2977.5	6.9	0.232						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 20	3.13	3	1388.9	25.3	1.822	Clay of low plasticity; silty clay (CL)					
	9.23	7	848.8	15.6	1.838		50	24	26		
	10.75	8	925.9	15.6	1.685						
	12.42	6	9413.6	52.6	0.559						
	16.83	33	3395.1	99.4	2.928						
	18.36	15	3163.6	58.4	1.846		46	27	19		
	19.90	17	2623.5	37.0	1.410						
	21.41	15	2932.1	50.6	1.726						
	22.93	19	4861.1	120.8	2.485						
	24.46	18	5555.6	214.3	3.857						
	26.00	25	3703.7	81.8	2.209						
CPT 21	3.13	5	1439.0	10.0	0.695	Clay of low plasticity; silty clay (CL)					
	4.65	6	518.0	9.8	1.892		43	26	17		
	9.23	4	1208.7	9.3	0.769		46	25	22		
	10.75	5	5928.5	52.4	0.884						
	12.42	5	1266.3	8.9	0.703						
	13.84	11	2187.2	22.6	1.033						
	15.31	13	3453.5	38.0	1.100		38	22	16		
	16.84	16	3280.8	91.6	2.792						
	22.93	15	4777.3	139.4	2.918						
	24.46	17	7079.7	361.2	5.102						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 22	1.60	4	1353.3	4.5	0.333	Clay of low plasticity; silty clay (CL)					
	3.13	5	1889.0	7.3	0.386						
	10.75	5	4767.8	135.3	2.838						
	12.05	13	3993.3	185.3	4.640						
	13.84	24	3798.2	92.8	2.443						
	16.84	6	2844.1	88.1	3.098		41	23	18		
	18.37	9	3845.7	93.5	2.431						
	19.90	11	3668.1	59.7	1.628						
	22.93	40	3092.5	85.1	2.752		35	24	11		
CPT 23	7.23	8	3963.8	70.6	1.781	Clay of low plasticity; silty clay (CL)					
	8.73	13	4021.6	115.8	2.879						
	13.23	14	5594.4	221.6	3.961						
	14.73	14	12455.9	303.4	2.436						
	16.23	11	2138.5	57.3	2.679		31	20	11	35	65
	17.73	23	3678.9	72.8	1.979						
	19.23	36	3739.3	109.2	2.920						
	20.73	11	14524.6	442.2	3.044						
	22.23	12	2111.5	42.6	2.018						
	23.73	10	3916.2	73.8	1.885		45	22	23	17	83
	25.23	12	2580.6	56.2	2.178						
	26.73	16	2551.3	28.1	1.101						
	28.23	16	3647.8	73.2	2.007						
	29.73	18	3419.2	150.0	4.387						

Table C.4: SPT, CPT test results and index properties of low plastic silty clay (CL)

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 24	1.23	1	723.1	46.1	6.376	Clay of low plasticity; silty clay (CL)					
	2.73	6	1169.5	62.8	5.370		45	25	20	7	93
	7.23	9	2471.1	69.8	2.825						
	8.73	13	1702.4	55.9	3.284						
	10.23	34	2879.7	205.1	7.122						
	11.73	20	3921.1	165.5	4.221						
	13.23	14	5745.8	220.0	3.829		35	23	12	6	94
	14.73	17	1935.3	64.0	3.307						
	16.23	25	4700.5	131.9	2.806						
	17.73	25	5328.5	166.6	3.127						
	19.23	24	3342.7	110.2	3.297						

Table C.5: SPT, CPT test results and index properties of high plasticity clay (CH) soil

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
CPT 9	8.6	13	3185	123.1	3.865	Clay of high plasticity (CH)	58	28	30	9	91
	10.225	22	2166	61.5	2.840						
CPT 10	1.225	6	440	34.4	7.818	Clay of high plasticity (CH)					
	2.725	7	1446	103.5	7.159						

Table C.5: SPT, CPT test results and index properties of high plasticity clay (CH) soil

CPT ID	Depth (m)	Field SPT N-value	Cone resistance (q_c) kPa	Sleeve friction (f_s) kPa	Friction ratio (R_f) %	Soil classification (BNBC, 2020)	Consistency limits and grain size				
							LL (%)	PL (%)	PI (%)	Sand (%)	Fines (%)
	4.225	8	1760	89.8	5.102		55	25	30	12	88
	5.725	5	1257	66.5	5.290						
	7.225	14	6160	170.2	2.763						
	8.725	12	4777	256.5	5.369						
CPT 11	0.45	3	703	61.6	8.766	Clay of high plasticity (CH)					
	1.225	7	1271	76.4	6.009		60	28	32	13	87
	2.725	7	1615	74.1	4.588						
	4.225	9	1710	68.8	4.023						
	5.725	9	1303	50.2	3.854						
	7.225	13	1813	1095.2	60.406						
