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Deriving Sensitivity and Rapidity from the Clay Cutter Test

An Assessment of Remoulding Capacity and Rapidity Parameter Development

Master's thesis in Infrastructure and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover: A picture of the Clay Cutter and its components

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Abstract

Landslides are among the most destructive natural hazards affecting Sweden and other Nordic countries, which makes their prevention an important geotechnical challenge. In Sweden, landslide risk assessments commonly involve laboratory and in situ investigations of soil conditions, where soil sensitivity is often estimated using the fall cone test (FC). However, this method is associated with known limitations, and the resulting parameters require empirical correction factors. This has motivated the development of alternative approaches for characterizing sensitive clays, which may also provide insight into the rate of strength degradation during disturbance.

The Clay Cutter Test (CCT) is a recently developed laboratory device intended for measuring the undrained shear strength of clay and is currently undergoing further development and evaluation. This study explores the potential of the CCT for estimating remoulded shear strength, sensitivity and rapidity and compares its behaviour with that of the conventional FC test, using previously obtained data for validation. The results suggest that full remoulding, needed for assessing sensitivity, is not consistently achieved within the tested CCT procedures. However, the obtained results appear to align best with more homogeneous clay conditions, similar to those for which the FC test is developed. Due to the lack of full remoulding for several soil samples, the rapidity analysis was only performed on homogeneous clay samples. The results indicated that there are promising results, however because of the uncertainty in the remoulding process and shortage of clay test samples, a sufficient conclusion could not be drawn. This suggests that further investigation of the remoulding behaviour using the CCT is needed to better understand its potential use.

Keywords: Soil sensitivity, remoulded shear strength, fall cone test, clay cutter test, rapidity

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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CCT	Clay Cutter Test
CPT	Cone Penetration Test
CPTu	Piezocone Penetration Test
FC	Fall Cone
FVT	Field Vane Test
OCR	Overconsolidation Ratio
SGI	Swedish Geotechnical Institute

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

i	Loop index
n	Number of loops
x	Selected remoulding level
a, b	Selected adjacent interpolation points on the remoulding index - work curve

Parameters

St	Sensitivity [-]
d	Vane width [mm]
h	Vane height [mm]
a	Net area ratio (typically 0.7–0.85) [-]
σ_v	Overburden pressure [kPa]
σ'_p	Preconsolidation pressure [kPa]
N_{kt}	Cone correction factor (typically 10–18) [-]
K	Cone factor [-]
m	Cone mass [g]
g	Gravitational acceleration (9.82) [m/s ²]
F_{cc}	Wire force [kN]
A_w	Lateral cross-sectional area of the wire [m ²]
N_{cc}	Correction factor (15.7) [-]
I_R	Remoulding index [%]

Variables

$T_{\max}$	Maximum torque before failure [Nm]
q_{in}	Initial penetration resistance [kPa]
q_{ext}	Initial extraction resistance [kPa]
q_r	Remolded resistance [kPa]
q_t	Corrected cone resistance [kPa]
q_c	Cone tip resistance [kPa]
u	Pore pressure [kPa]
c_u	Undisturbed undrained shear strength [kPa]
c_{ur}	Fully remolded undrained shear strength [kPa]
c_{ux}	Remolded shear strength at given drop height/loop [kPa]
$c_{ur,CCT}$	Shear strength from CCT test [kPa]
W	Energy per unit volume [J]
W_i	Work for each loop [J]
W_N	Cumulative work for all loops [J]
W_x	Cumulative work at point x [J]
W_a	Cumulative work at point a [J]
W_b	Cumulative work at point b [J]
IR	Remoulding index [%]
IR_x	Remoulding index at point x [%]
IR_a	Remoulding index at point a [%]
IR_b	Remoulding index at point b [%]
RE	Rapidity index [-]
W_{85}	Cumulative work for 85% remoulding [J]
W_{95}	Cumulative work for 95% remoulding [J]
F	Force [N]
s	Displacement [mm]
i	Fall cone indent [mm]

Contents

List of Acronyms	viii
Nomenclature	x
List of Figures	xv
List of Tables	xvii
1 Introduction	1
1.1 Aim	2
1.2 Research Questions	2
1.3 Limitations	2
2 Soil Sensitivity and Rapidity	4
2.1 Soil sensitivity	4
2.2 In-situ Methods for Determining Soil Sensitivity	6
2.2.1 Field Vane Shear Test	6
2.2.2 Full-Flow Penetrometer Test	7
2.2.3 Cone Penetration Test	9
2.3 Laboratory Methods for Determining Soil Sensitivity	10
2.3.1 Fall Cone Test	10
2.3.2 Flaws and Limitations Regarding the Fall Cone Test	12
2.3.3 Sample Quality	13
2.3.4 Method Validation Using Reference Clay	14
2.4 Rapidity	15
2.5 Rapidity Throughout the Decades	15
2.5.1 Söderblom's Rapidity	16
2.5.2 Remoulding Energy	16
2.5.3 In-Situ Methods for Determining Rapidity & Remoulding Energy	18
3 The Clay Cutter Test	21
3.1 Deriving Sensitivity from CCT	22
3.2 Deriving Rapidity from CCT	24
3.2.1 Energy and Rapidity	25

3.2.2	Assumptions and Limitations	27
4	Method	29
4.1	Provided Material	29
4.2	Development of the CCT Remoulding Method	30
4.2.1	Laboratory Procedure 1	31
4.2.2	Laboratory Procedure 2	31
4.2.3	Laboratory Procedure 3	32
4.3	Selection and Preparation of Reference Clay	33
5	Geotechnical Properties of the Samples	37
5.1	Test sample A1	37
5.2	Test sample A2	37
5.3	Test sample B1	38
5.4	Test sample B2	38
5.5	Test sample C1	39
5.6	Test sample C2	39
5.7	Test sample C3	40
5.8	Test sample D	40
5.9	Test sample E	41
5.10	Test sample F	41
5.11	Test sample G	42
5.12	Test sample H	42
5.13	Test sample J	42
5.14	Test sample K	43
5.15	Test sample L	43
6	Results	44
6.1	Analysis of CCT Remoduling Capacity and Corresponding Sensitivity	44
6.1.1	Comparison Against Index Parameter	47
6.2	Cumulative Work and Rapidity Index Results	51
6.2.1	Comparison Between Cumulative Work at 95% Remoulding W_{95} Against Geotechnical Parameters	52
6.2.2	Comparison Between Rapidity Index Against Geotechnical Parameters	54
6.3	Results for Kaolin Clay of the Remoulding Processes	56
7	Discussion	59
7.1	The Possibility of Deriving Sensitivity from the CCT	59
7.2	Interpretation of W_{95} and The Rapidity Index R_E	61
7.3	Kaolin response to remoulding process	63
8	Conclusion	65
8.1	Further Work	66
	Bibliography	68
A	Appendices	I

A.1	Incremental Loading (IL) Results - Axial Strain Over Time for Kaolin Clay	I
A.2	Sensitivity Plot Divided by Soil Classification	III

List of Figures

2.1	Fall cone test set up for reading of a remoulded sample equipped with a manual ruler with 1 mm measurement resolution	11
2.2	Kaolin structure and behavior under consolidation, figure inspired from Yu et al. (2016).	15
2.3	A reworked $W_N - I_R$ graph for different clay samples from Tavenas et al. (1983).	17
2.4	Example of a remoulded vane shear test inspired from Berghel and Hagrydh (2023), where A describes the area under the graph	19
2.5	Example of a T-bar cyclic test inspired from Jannuzzi et al. (2012)	20
3.1	Picture of the Clay Cutter machine	21
3.2	Shear strength - displacement curve of a CCT test, the upper red line is an average value of shear strength and the lower orange line is the minimum remoulded shear strength	23
3.3	The simple shear strength curve, illustrating the remoduling process over the recorded data points during a test. The upper red line is an average value of shear strength and the lower orange line is the minimum remoduled shear strength	24
3.4	Example of four different soil samples and their respective Remoulding Index - Cumulative work curve	26
4.1	Overview of the experimental workflow, including method development and laboratory testing	29
4.2	Conceptual illustration of the first remoulding procedure applied to an intact sample.	31
4.3	Conceptual illustration of the control test for wire movement in an open channel.	32
4.4	Conceptual illustration of the control test for wire movement against displaced material.	32
4.5	3D model of the support sleeve	33
4.6	Finalized laboratory procedure used for the remoulded CCT	33
4.7	Sedimentation analysis of kaolin 2025, interpreted as a clayey kaolin, and kaolin 2026, interpreted as a silty kaolin, compared with a typical clay sample, LE.	34
4.8	95% slurry placed into cell using a syringe	35
4.9	55% paste packed into cell	35

6.1	Comparison of c_u derived from CCT and FC	45
6.2	Comparison of c_{ur} derived CCT and FC	45
6.3	Comparison of c_{ur} derived from CCT and FC, for soil classification clay	45
6.4	Comparison c_{ur} derived from CCT and FC, for soil classification having mixed soil content	45
6.5	Comparison of sensitivity derived from CCT and FC, divided by 60g cone marked in dots or 10g cone marked in triangles	46
6.6	Closeup of sensitivity derived from CCT and FC for samples classified as clay	47
6.7	Closeup of sensitivity derived from CCT and FC for sample classified as having mixed content	47
6.8	Sensitivity derived from CCT against quasi index w_n/w_l	48
6.9	Sensitivity derived from FC against quasi index w_n/w_l	48
6.10	Sensitivity derived from CCT against density	49
6.11	Sensitivity derived from FC against density	49
6.12	Sensitivity derived from CCT against water content w_n	50
6.13	Sensitivity derived from FC against water content w_n	50
6.14	Sensitivity derived from CCT against liquid limit w_l	50
6.15	Sensitivity derived from FC against liquid limit w_l	50
6.16	Comparison between W_{95} and C_{ur} derived from CCT	52
6.17	Comparison between W_{95} and C_{ur} derived from FC	52
6.18	Comparison between W_{95} and sensitivity derived from CCT	53
6.19	Comparison between W_{95} and sensitivity derived from fall cone	53
6.20	Comparison between W_{95} and density	53
6.21	Comparison between W_{95} and quasi-index, W_n/W_l	54
6.22	Comparison between RE and remoulded shear strength for CCT	55
6.23	Comparison between RE and remoulded shear strength for FC	55
6.24	Comparison between RE and sensitivity derived from CCT	55
6.25	Comparison between RE and sensitivity derived from FC	55
6.26	Comparison between RE and density	56
6.27	Comparison between RE and quasi-index, W_n/W_l	56
6.28	Remoulded CCT process for silty kaolin with 70% water content	58
6.29	Remoulded CCT for clayey kaolin with 70% water content	58
7.1	Potential trend forming for c_{ur} in clay	60
A.1	Axial Strain from incremental loading under 3 days for Silty Kaolin clay with 95% mixed W_n	I
A.2	Axial Strain from incremental loading under 7 days for Silty Kaolin clay with 55% mixed W_n	II
A.3	Axial Strain from incremental loading under 5 days for Clayey Kaolin 2025, unknown W_n	II
A.4	Axial Strain from incremental loading for Silty Kaolin clay with 55% mixed W_n	III
A.5	Axial Strain from incremental loading for Silty Kaolin clay with 55% mixed W_n	III

List of Tables

2.1	Sensitivity classification according to Swedish Geotechnical Institute (SGI) (Rankka et al., 2004)	5
2.2	Approximate relative error in calculated shear strength due to reading uncertainties in penetration depth of FC.	13
4.1	Number of samples based of their soil characterization	30
5.1	Soil properties for sample A1	37
5.2	Soil properties for sample A2	38
5.3	Soil properties for sample B1	38
5.4	Soil properties for sample B2	39
5.5	Soil properties for sample C1	39
5.6	Soil properties for sample C2	40
5.7	Soil properties for sample C3	40
5.8	Soil properties for sample D	40
5.9	Soil properties for sample E	41
5.10	Soil properties for sample F	41
5.11	Soil properties for sample G	42
5.12	Soil properties for sample H	42
5.13	Soil properties for sample J	43
5.14	Soil properties for sample K	43
5.15	Soil properties for sample L	43
6.1	Calculated values of W_{85} , W_{95} and rapidity index R_E	51
6.2	Results summary of CCT and FC for the kaolin tests.	57

1

Introduction

Soil sensitivity is part of standard geotechnical testing and is an essential design parameter in stability problems and deformation behavior. Sensitivity describes the maximum loss of undrained shear strength that a soil exhibits upon being disturbed (Åhnberg & Larsson, 2012). It dictates how a seemingly stable deposit can fail under natural or man-made conditions, such as changes in pore water, erosion, external loading or vibrations. This can be caused by heavy rainfall or changes in groundwater, extensive loading causing internal remoulding, or vibration due to construction work or traffic. In practice, both the undisturbed and disturbed shear strengths are used to evaluate different stages of failure, and to estimate the potential for failures.

As urbanization expands into areas with sensitive geological profiles, it becomes increasingly important to design the built environment accordingly. This requires a high level of reliability in the design parameters. Special caution is required for highly sensitive soil profiles, where remoulding can lead to a significant loss of strength and potentially result in liquefaction, where the soil exhibits fluid-like behavior (Rankka et al., 2004). This type of soil type is known as quick clay and has historically been a major cause of highly destructive landslides in Sweden, Norway and Canada.

Although sensitivity is an informative parameter, it only quantifies the magnitude of strength loss and does not account for the energy required or how quickly the soil reaches this state (Åhnberg & Larsson, 2012). These aspects can instead be described in terms of soil rapidity, the required energy to reach full remoulding. Soil rapidity could serve an important design parameter for highly sensitive profiles. Despite having been continuously investigated since the mid-20th century, no established method exists for determining this parameter, nor is there a standardized approach for its implementation. However, the intended use is to further be able to forecast potential stability issues and properly assess guidelines and dimensioning parameters by quantifying the degree of sensitivity by means of rapidity in order to avoid landslides and other stability issues.

The CCT is an emerging geotechnical laboratory method which with precision derives shear strength in a piston sample by cutting it with a wire connecting to load cells which record the forces acting on the wire and translating it to shear strength (Hedborg, 2026). The test is quicker than conventional advanced laboratory methods, and yields high resolution data throughout the sample. Hence, the CCT

provides insight in natural weaker zones and soil anisotropy giving a more precise shear strength for the profile. The further development of the CCT method aims to investigate whether it is possible to derive the disturbed, i.e. remoulded, shear strength by allowing the wire to move up and down at short intervals. Since the CCT records the forces acting on the wire, it is further investigated whether these forces can be translated to rapidity for these intervals by the terms of the work required to disturb the sample.

1.1 Aim

The aim of this project is to conduct a benchmark study on the developing CCT method to evaluate its ability to retrieve remoulded shear strength and potentially the corresponding rapidity. As part of the laboratory method development for remoulding procedure, a support sleeve is incorporated and evaluated as an alternative testing arrangement for the CCT. The CCT will be compared with the established Swedish FC test and with scales used for assessing soil sensitivity. A kaolin-based reference clay will be prepared for validation against both the fall cone test and the CCT, as kaolin has well-documented geotechnical properties.

1.2 Research Questions

To determine whether it is possible to derive sensitivity and rapidity with the CCT, the following research questions are investigated

- How effective is the CCT in remoulding clay samples, and to what extent do sensitivity values obtained from the CCT correspond with those determined using established standardized testing methods?
- Can rapidity be quantified using CCT measurements, for instance through assessment of the energy required to achieve complete remoulding of the sample?
- Can a reference clay be produced to enable comparison of the remoulding process between the CCT and the FC?

1.3 Limitations

This study builds upon previous findings related to the CCT, where parameters within an designated range, such as testing speed and wire thickness, have already been evaluated and shown not to influence the determination of shear strength by CCT. The CCT will only be compared to common Swedish method of laboratory deriving sensitivity. The laboratory process and material to compare against are limited to the equipment, previous data and remaining or available sampling material after routine investigations at AFRY geotechnical laboratory. Since some of the material is under confidentiality, as it stands for geotechnical investigations for ongoing projects, all samples will be anonymized. Hence, the material can be

from upper, middle or lower tube and have been stored for at least six months. A supplementary part of this project is producing a reference clay. As this is an addition to the evaluation of CCT against FC, this part of the project is not the main priority as there is a limited time for production.

2

Soil Sensitivity and Rapidity

Sensitive clay landslides are considered a major geotechnical hazard due to their rapid development and their ability to affect large areas. Thereby posing serious risks to human life, infrastructure, and ecosystems. In Scandinavia and other regions with sensitive clay deposits, including Sweden, Norway, and Canada, such landslides have resulted in evacuations, significant economic losses, and extensive infrastructure damage and fatalities. This highlights the importance of making proper assessment for safe geotechnical design (Urmi et al., 2023).

2.1 Soil sensitivity

The soil sensitivity is defined as the ratio between undisturbed shear strength and remoulded shear strength. Sensitivity essentially describes the loss of shear strength the soil exhibit when being disturbed without changing the water content (Abuhajar et al., 2010). Sensitivity is generally quantified with the following equation (2.1).

$$S_t = \frac{c_u}{c_{ur}} \quad (2.1)$$

- S_t – Sensitivity [-]
- c_u – Undisturbed shear strength [kPa]
- c_{ur} – Remoulded shear strength [kPa]

Sensitivity is primarily associated with cohesive soils, such as clay, where shear strength is governed by interparticle bonding forces that contribute to the soil structure (Åhnberg & Larsson, 2012). When the soil is remoulded, these interparticle bonds and structures are disrupted. The particle structure collapses and the pore water begins to have a greater influence on the soil behavior. This leads to a reduction in shear strength, and depending on the soil type, the degree of strength loss varies, as some soils are more easily disturbed than others. As a result, the soil becomes more dispersed and, in some cases, may even behave more as a liquid. This behavior is classified using a sensitivity scale, which is adapted to the methods used

for deriving sensitivity (Abuhajar et al., 2010). In Sweden, the sensitivity scale has three classes ranging from low to high sensitivity, as shown in the following table 2.1

Table 2.1: Sensitivity classification according to Swedish Geotechnical Institute (SGI) (Rankka et al., 2004)

Definition	Sensitivity
Low sensitivity	< 8
Medium sensitivity	$8 - 30$
High sensitivity	> 30

The soil's undisturbed shear strength and its response to remoulding are dependent on geological history, e.g. structural characteristics, deposition environment, and past and present loading conditions (Knappett & Craig, 2012). Clay minerals are flat and negatively charged and interact with positively charged ions in the pore water. This creates a particle structure where the bonding between particles is influenced by the ion composition (Rankka et al., 2004). Depending on the mineral composition, different bonding forces act between the particles, resulting in structural arrangements of varying stability.

If the clay is deposited in fresh water, repulsive forces between particles allow them to arrange in a more layered and dense structure with a low void ratio (Rankka et al., 2004). This results in a relatively stable structure with low sensitivity. When this type of clay is remoulded, the soil retains a significant part of its shear strength. If the clay is deposited in sea water, the particles tend to form a flocculated structure, resulting in a higher void ratio during sedimentation. Leaching of the salt reduces the ion concentration in the pore water, weakening the interparticle bonds that hold the structure together. The degradation of these bonds can also be caused by contact with organic content. When these types of soils are remoulded, the low ion concentration and ion composition hinder reflocculation. This causes the particles to disperse and the soil to lose strength dramatically, potentially behaving like a fluid. If the clay measures a sensitivity higher than 50 and a remoulded shear strength below 0,4 kPa, the clay falls under the classification quick clay (Rankka et al., 2004). As these processes are not uniform with depth, the sensitivity varies within a soil profile depending on the degree of leaching, ion composition, stress history, and stratigraphy.

The current stress state relative to the preconsolidation stress is also linked to soil sensitivity, as it reflects the maximum effective stress previously experienced by the soil and thereby influences its stiffness, strength, and deformation characteristics (Laloui & Rotta Loria, 2020). The mechanical behaviour of clay is governed by effective stress, where only the stress carried by the soil skeleton contributes to shear strength, while pore water pressure counteracts particle contact stresses (Rankka et al., 2004).

In a Swedish context, soil sensitivity is primarily determined using the laboratory fall cone test, and in some cases complemented by the field vane test (Abuhajar et al., 2010). Internationally, Swedish clays are seen as highly sensitive due to the geological history. The methods used to determine sensitivity, which will be further discussed in the chapter, vary between countries and for example Norway relies more on field testing compared to Sweden (Abuhajar et al., 2010). As different sensitivity methods involve varying approaches to remoulding, such as manual remoulding in the laboratory or in situ remoulding in the field, it is not always possible to ensure complete or equivalent remoulding of the soil. This means that the resulting sensitivity values can vary depending on the method used. Hence, classification and grading systems are typically developed to align with the standard test methods and the prevailing geological conditions within each country, sensitivity should be seen as a method-dependent index rather than a fundamental soil property.

2.2 In-situ Methods for Determining Soil Sensitivity

Field testing to determine shear strength and soil sensitivity can provide valuable insight into the behaviour of soft soils, particularly in highly sensitive deposits where sampling may cause significant disturbance (Knappett & Craig, 2012). Preferably, these tests are to be combined with laboratory testing to gain a comprehensive understanding of the soil.

2.2.1 Field Vane Shear Test

The field vane shear test (FVT) is used to evaluate shear strength and remoulded shear strength in soft soils (SGI, 2013). It consist of a four bladed vane, arranged in a cross shape, which is connected to a friction coupling. The friction coupling allows for slip to compensate for rod friction, which increases with penetration depth. The vane is carefully pushed into the ground to a desired depth and held still for 2-5 minutes, while attaching the rotation measurement, and allowing the soil to stabilize before starting the test.

The test is performed by rotating the vane and measuring the corresponding torque as the soil resists this motion (Knappett & Craig, 2012). The maximum torque recorded before the point of soil failure T_{max} , which is assumed to happen cylindrically around the vane, is used to derive the undrained shear strength using the equation (2.2.1).

$$T_{max} = \pi c_u \left(\frac{d^2 h}{2} + \frac{d^3}{6} \right) \quad (2.2)$$

- T_{max} – Maximum torque before failure [Nm]
- c_u – Shear strength [kPa]
- d – Vane width [mm]
- h – Vane height [mm]

The recorded values are corrected using an empirically derived correction factor μ (Knappett & Craig, 2012). To find the remoduled shear strength the vane is quickly rotated 20 times, disturbing the soil (SGI, 2013). Then the corresponding torque T_{rem} is measured after remoduling, and is quantified by following equation (2.3).

$$T_{rem} = \pi c_{ur} \left(\frac{d^2 h}{2} + \frac{d^3}{6} \right) \quad (2.3)$$

- T_{max} – Torque at remoduled state [Nm]
- c_{ur} – Remoduled shear strength [kPa]
- d – Vane width [mm]
- h – Vane height [mm]

The test is developed for soft cohesive soils and assuming isotropic conditions (Knappett & Craig, 2012). If the soil exhibit high anisotropy it can disturb the results of the vane test since it mobilizes soil in multiple directions. As FVT records a point value, several tests are needed along the profile to get a comprehensive picture of the soil. For deeper testing exceeding 20 meters, there is a risk that the friction coupling does not properly compensate for the rod friction (SGI, 2017). This can to some extent be corrected by using a protecting sleeve as the vane is pushed into the ground.

2.2.2 Full-Flow Penetrometer Test

The T-bar test is an in-situ full flow penetretation test often used in soft clays for determining the undrained shear strength and when performed cyclically, e.g. up and down, the remoulded undrained shear strength and sensitivty can also be derived (Yafrate et al., 2009). The T-bar consists of a cylindrical horizontal bar (T-shaped) that pushes into the soil downwards and upwards in a predetermined depth interval. During the test, the penetration and extraction resistance is continuously recorded. The ball penetration test is comparable to the T-bar test, but the horizontal bar is replaced with a ball and consequently having the same procedure and function as the T-bar test. The initial penetration resistance represents the undrained shear strength of the soil, whilst the remoulded resistance q_{rem} after a successive of cycles correlates to the disturbed shear strength.

To evaluate the remoulded process, the cyclic resistance data points are plotted as a degradation curve against number of cycles. As the soil gets more disturbed, the penetration resistance decreases until it reaches a stabilized value. According to Yafrate et al. (2009), the initial penetration q_{in} and the initial extraction resistance q_{ext} , as well as the aforementioned remoulded resistance q_{rem} can be used to evaluate the soil sensitivity.

For full flow penetrometer, the soil sensitivity can either be assessed from the initial values, quantified by equation (2.4).

$$S_t = \left(\frac{q_{in}}{q_{ext}} \right)^{3.7} \quad (2.4)$$

- S_t – Sensitivity [-]
- q_{in} – Initial penetration resistance [kPa]
- q_{ext} – Initial extraction resistance [kPa]

Or the soil sensitivity can be quantified using the remoulded resistance (2.5)

$$S_t = \left(\frac{q_{in}}{q_{rem}} \right)^{1.4} \quad (2.5)$$

- S_t – Sensitivity [-]
- q_{in} – Initial penetration resistance [kPa]
- q_r – Remoulded resistance [kPa]

An important advantage of the cyclic full flow penetrometer test is that it allows for in situ testing for estimating the remoulded and undrained shear strength, as well as the soil sensitivity without having the need for laboratory procedures. Nonetheless, there are several disadvantages with a cyclic test. For instance, soil profile near the ground surface is not always fully homogeneous and can contain organic layers that could affect the results negatively (Jannuzzi et al., 2012). In addition, the penetrometer test requires a full flow around the instrument when entering the soil to be fully viable (Han et al., 2024). As the measuring probe penetrates the soil, the soil should fully flow around the probe rather than separate from it or leave a cavity behind. The full flow mechanism is essential for the measured resistance to reflect the actual remoulding behavior of the soil.

2.2.3 Cone Penetration Test

The cone penetration test (CPT) is an in situ testing method performed to determine the soil profile and evaluate a range of geotechnical soil parameters, including unit weight, overconsolidation ratio OCR, preconsolidation pressure, friction angle, shear strength, sensitivity, among others (Robertson & Cabal, 2022). A commonly applied variation of this method in Sweden is the piezocone penetration test CPTu. In addition to the standard CPT measurements the CPTu records pore water pressure, thereby enhancing the reliability of soil classification and interpretation (SGI, 2013). The CPTu apparatus comprises a cone tip, a pore pressure filter, and a friction sleeve equipped with integrated sensors measuring resistance from the soil. Cone tip resistance q_c is the ratio between the acting force through the area of the cone, sleeve friction f_s is the surface area of the friction sleeve, pore water pressure u is measured directly behind the tip. Following equation explains the corrected cone resistance, see equation (2.6)

$$q_t = q_c + u(1 - a) \quad (2.6)$$

- q_t – Corrected cone resistance [kPa]
- q_c – Cone tip resistance [kPa]
- u – Pore pressure [kPa]
- a – Net area ratio (typically 0.7–0.85) [-]

The soil parameters are assessed with empirical correlations and adjustments or correction factors depending on pore water and affected area. They are normalized for effective overburden pressure, which increases with depth, in order to increase the comparability between data. The undrained shear strength of the soil c_u is calculated using the corrected cone resistance q_t , the overburden pressure σ_v and a cone factor N_{kt} (Robertson & Cabal, 2022), according to equation (2.7). N_{kt} can be computed using friction ratio (F_r) which is suitable for most soil types, or using pore pressure (B_q) suitable for fine graind, saturated soils.

$$c_u = \frac{q_t - \sigma_v}{N_{kt}} \quad (2.7)$$

- c_u – Shear strength [kPa]
- q_t – Corrected cone resistance [kPa]
- σ_v – Overburden pressure [kPa]
- N_{kt} – Cone correction factor, (typically ranging between 10–18) [-]

As the cone is pushed into the ground un undrained conditios, the sleeve resistance f_s can be set equal to the remoulded shear strength $c_{u,rem}$. Sensitivity can be computed as the ratio between peak shear strength and sleeve friciton using equation (2.8). However this is an approximative method, as it relies on the soils not being too sensitive (Robertson & Cabal, 2022) and it is certain that the soil will be fully remoulded along the sleeve. Hence, the soil sensitivity S_u from CPTu is not reliable for all soil profiles and sensitivity can only be used as a guide and not a design parameter.

$$S_t = \frac{q_t - \sigma_v}{N_{kt}f_s} \quad (2.8)$$

It is essential that the CPT or CPTu test is performed in accordance with established standards, ensuring that the equipment remains undamaged and that the system is regularly calibrated. When properly maintained and operated, the method provides high-quality soil property data. To obtain a representative assessment of subsurface conditions, the test should preferably be performed at multiple locations across the site (Robertson & Cabal, 2022). Nevertheless, derived parameters and particularly soil sensitivity, should be validated and supplemented with laboratory testing.

2.3 Laboratory Methods for Determining Soil Sensitivity

The fall cone test is a Swedish standard method used to determine the undisturbed and remoulded undrained shear strength, sensitivity, and liquid limit of soft soils (Hov & Holmén, 2018). It is used to varying extents across Scandinavia and Canada, since soft soils occur in these locations as a result of the geological history.

2.3.1 Fall Cone Test

FC test has been continuously developed since the beginning of the 20th century, and the current standards are SS 027125 or SS EN 17892-6 (Hov & Holmén, 2018). The equipment consists of a cone with a designated weight and apex angle, which is placed in a holder that can be equipped with either a visual ruler or a digital reader. The mass and apex angle of the cone depends on the soil properties, where samples with higher shear strength require a greater cone mass. There are the 400g - 30°, 100g - 30°, 60g - 60° and 10g - 60°. However, the more common are the 100 gram with 30° for undisturbed samples and 60 gram with 60° cone for remoulded samples. According to SS 027125 the shear strength and undisturbed shear strength should be tested on the middle tube of piston samples, where a total of three piston samples are extracted for each level. To avoid potential disturbance effects, the outermost part should be trimmed prior to testing.



Figure 2.1: Fall cone test set up for reading of a remoulded sample equipped with a manual ruler with 1 mm measurement resolution

The test is performed by placing the cone so that the tip just touches the sample, see figure 2.1. The cone is then released into the soil. The depth of the indentation is immediately read on the apparatus ruler which should be done with a precision of 0,1 mm, whereas indentation between 7-19,9 mm are valid (Hov & Holmén, 2018). Same procedure goes for the remoulded shear strength, where the same sample is extracted and mixed by hand. Due to thixotropic effects, e.g. the soil regaining strength over time, the time between mixing and conducting FC should be minimal. The FC test should be repeated three times calculating a medium indent between the three to account for soil heterogeneity. The undrained shear strength is defined according to following equation (2.9).

$$c_u = K \frac{mg}{i^2} \quad (2.9)$$

- c_u – undrained shear strength [kPa]
- K – Cone factor [-]
- i – Cone indent [mm]
- m – Cone Mass [g]
- g – gravitational acceleration of 9,82 [m/s^2]

The fall cone test has the empirically derived cone factor (K) based of Swedish clay extracted at depths between 5 - 20 m (Hov & Holmén, 2018). The K factor has been slightly allterd between the two standards. The SS 027125 has been calibrated against field vane test where as the newer SS EN 17892-6 standard is calibrated against laboratory vane test. The SS 027125 K factor for the test with an apex angle of 30° is 1,0 and 0,25 for 60° . For the SS EN 17892-6 the values are 0,8 and 0,27 respectively. Hence, the new method underestimate the shear strength, and subsequently the sensitivity. The derived shear strength is not intended for dimensioning and another correction factor μ , based of liquid limit of the sample, is applied.

2.3.2 Flaws and Limitations Regarding the Fall Cone Test

The FC method itself has identified flaws that could affect the results such as initial placement of the cone, reading of the indentation, sample quality, and soil composition (Hov & Holmén, 2018). The consequences of the flaws could lead to an under- or overestimation of the shear strength, sensitivity, and liquid limit of the undrained soil, yielding an unrepresentative result.

As the method used in Sweden is empirically derived for a Swedish clay between 5–20 meters depth, the results derived outside of this domain might become less reliable even with usage of correction factor μ (Hov & Holmén, 2018). Organic clay and silty clay are usually included in the soft soil evaluation. Organic clay with silty content differs in mechanical behavior compared to inorganic clay, with a more open pore structure prone to larger deformations before failure (Westerberg et al., 2015). Soils containing both organic material and elevated silt content exhibit a more complex undrained response. The fall cone test is to simplified to capture the large strains occurring prior to failure in these type of soils. Further, soils containing sulphides suggest that the empirical correction factors become increasingly dependent on the stress level at higher shear strengths, introducing additional uncertainty in the interpretation of fall cone results for stiffer or more consolidated organic and silty clays.

Measurement uncertainties also influence the FC results and it can be caused by equipment imperfections or operator bias (Knuuti & Länsivaara, 2021). To ensure accurate assessment of soil properties, the equipment must comply with established standards (Hov & Holmén, 2018). Wear and tear on the equipment can alter the apex angle and surface friction, which can affect the test results. Hence, regular inspection and maintenance of the equipment are necessary to minimize uncertainty in the testing process. The results may also differ between operators, since both laboratory procedures and prior experience can influence the measurements (Knuuti & Länsivaara, 2021). As the indent of the cone is calculated in an exponential manner, small misreading can affect the accuracy of the results. The following table 2.2 illustrates how a small misreadings of the FC indentation within a narrow margin

can influence the derived shear strength or remoulded shear strength, resulting in percentage differences in the calculated results.

Table 2.2: Approximate relative error in calculated shear strength due to reading uncertainties in penetration depth of FC.

FC indent	± 0.1 mm	± 0.2 mm	± 0.3 mm	± 0.4 mm
7 mm	± 2.9 %	± 5.7 %	± 8.6 %	± 11.4 %
10 mm	± 2.0 %	± 4.0 %	± 6.0 %	± 8.0 %
15 mm	± 1.3 %	± 2.7 %	± 4.0 %	± 5.3 %

Due to the nature of the equation, small misreadings at lower penetration depths, such as 7 mm, result in greater relative errors compared to larger penetrations such as 15 mm.

2.3.3 Sample Quality

When conducting laboratory tests the results reflects on the quality of the provided sample and several standard laboratory processes are dependent on this (L’Heureux & Kim, 2014). Causes of disturbances of the piston sample can be due to extraction from the ground, handling in field or in laboratory or during transport. During extraction the soil is exposed to disturbances, such as from drilling, stress release, friction between soil tube and suction effects during withdrawal (Chung et al., 2014). These effects are most prominent at the ends of each individual tube as well as in the ends of the tube sequence of the three tubes together. Hence, the sample quality is the best in the middle tube and each sample should be prepared by removing the outermost part of each tube before testing.

Another source of disturbance is sample storage which can cause both mechanical and chemical aging in the sample. Hence, laboratory procedures should be done within 14 days and preferably as soon as possible after extraction (Karlsson et al., 2015). As the soil is extracted, it is released from the surrounding in-situ stresses, which can cause the clay to swell in the tube (L’Heureux & Kim, 2014). The swelling effect is especially critical when studying quick clay. The swelling causes deformation in the soil, which in turn causes a change in pore water, yielding lokal variation of effective stresses within the sample. In varved clays, consisting of alternating silt and clay layers, differences in suction drive water transfer between layers and causes swelling and further structural disturbance.

Exposure to oxygen may occur during sampling, handling, and storage, even in properly sealed piston samples. Small amounts of oxygen can still initiate oxidation reactions in the pore water, leading to chemical aging of the soil (L’Heureux & Kim, 2014). In soils containing materials such as organic matter or iron sulfides, these reactions may generate acids that dissolve carbonates and alter the ionic composition of the pore water. This process weakens interparticle bonds and contributes to the

progressive breakdown of the soil's mineral and structural framework. As a result of these combined processes, the original soil structure is progressively degraded, which in turn affects the measured geotechnical properties. Properties such as preconsolidation stress, soil stiffness, compression index, maximum shear strength, remoulded shear strength and subsequently sensitivity, deteriorates with time.

2.3.4 Method Validation Using Reference Clay

A reference clay is used to provide a material with reproducible and defined properties for method comparison and experimental evaluation. Purified kaolin clay is widely used as a reference material in geotechnical engineering, both in laboratory studies and in offshore modelling (Bi et al., 2026). Its well-documented properties and high reproducibility makes it particularly suitable for method comparison and model development, as it does not have natural variability of soil samples influencing test results. Several types of kaolin exist, with examples including Malaysian kaolin and kaolin from the University of Western Australia (UWA kaolin) (Bi et al., 2026).

Natural deposits of kaolin clay are fine-grained and mainly composed of the mineral kaolinite, together with varying amounts of other minerals such as quartz, feldspar, or mica, depending on the deposition environment. Kaolin is used in a range of industries, including paper, ceramics, and paint. Industrial kaolin is refined according to its intended application, with impurities and coarser particles removed to the required extent (Bloodworth et al., 1993). Reconstituted kaolin is typically homogeneous and exhibits relatively high compressibility and permeability. Depending on its composition, kaolin may range from more clay rich to more silty material. Examples include UWA kaolin, which generally has a higher clay content, and Malaysian kaolin, which contains a greater proportion of silt and is therefore often classified as a silty clay (Bi et al., 2026). This leads to differences in key geotechnical properties such as stiffness, permeability, and cyclic resistance.

Kaolinite particles are plate-shaped (Knappett & Craig, 2012), which tend to form aggregates (Yu et al., 2016). During sedimentation and consolidation, the particles partially align as the open edge-to-face structure. During 1D consolidation, this aggregate structure collapses, creating a face-to-face structure, see figure 2.2, which aligns horizontally along the principal stress direction. However, this alignment does not fully replicate the structural features of natural clays, as cementation, aging, and geological history are not reproduced (Bi et al., 2026).

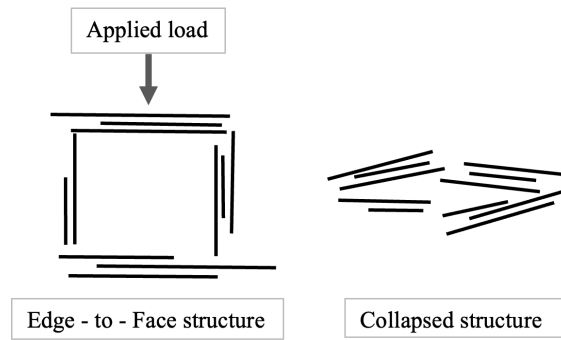


Figure 2.2: Kaolin structure and behavior under consolidation, figure inspired from Yu et al. (2016).

Despite extensive research on kaolin clay there is no standard procedure for producing and refining kaolin specifically for geotechnical experiments and modelling (Bi et al., 2026). Consequently, different types of kaolin are used in the production of reference clays, where they are typically referred to be uniform and homogeneous soils.

2.4 Rapidity

Soil sensitivity describes the reduction in undrained shear strength between undisturbed and remoulded states. However, it only quantifies the magnitude of strength loss and does not account for the rate of degradation. This limitation motivates the introduction of soil rapidity, which aims to describe how quickly the clay structure breaks down once being remoulded (Soderblom, 1974). Söderblom's work showed that highly sensitive clay may display very different remoulding behaviour, where some clays lose their structure immediately, whereas other clays required a greater amount of work for their soil structure to reach a fully remoulded state. Therefore, Soderblom (1974) proposed that quick clay behaviour should not be described by sensitivity alone, but also by a rapidity number. Currently there is no standardized method for determining the rapidity (Dehlbom & Lundström, 2020). The addition of a rapidity parameter should not be a replacement for sensitivity, instead a complementary parameter that may better describe the loss of shear strength in sensitive soils.

2.5 Rapidity Throughout the Decades

There are several interpretation of rapidity and the term was initially coined by Soderblom (1974), to visually determine how quick the undrained shear strength of quick clay decreases when being disturbed. However, the definition was quickly reinterpreted some years after because the method's results found to be highly dependent on the testing procedure and user. In 1983, a new method was developed

to be able to quantify rapidity by calculating the the required energy to fully break down the natural structure of clay. The new approach made it possible to objectively measure the remoulding energy and the rate of how quick clay structure deteriorates, offering a quantitative interpretation of the phenomenon that was previously described as rapidity. Over the past decades, numerous studies and research has been conducted to develop reliable methods quantifying the remoulding energy. Although, several approaches has been presented, such as cyclic loading in T-bar test and remoulded vane shear tests, no standardized or universal method currently exists.

2.5.1 Söderblom's Rapidity

The term rapidity was first introduced 1974 by Söderblom (Soderblom, 1974) to determine how quickly the undrained shear strength of quick clay reduces during repeated disturbances. To be able to differentiate the quick clay, a cylindrical specimen of 40x50mm was dropped 250 times from a 10 mm height using a Casagrande apparatus. Based on the magnitude of deformation, the specimen is assigned to a rapidity number between 1-10, 1 being not visually affected and 10 indicating the whole specimen is a liquid mass.

2.5.2 Remoulding Energy

Söderblom's method is considered subjective and too unreliable when tested on non-sensitive clay, making it difficult to use to determine rapidity. Therefore, a new concept was introduced, by calculating the required energy to remould a specimen fully (Tavenas et al., 1983). The paper proposed that rapidity should be governed by the total mechanical energy required to break down a soil completely and how fast the structure collapses as energy is applied. This could be defined as a relationship between the normalized remoulding energy W_n and remolding index I_R , as shown in figure 2.3.

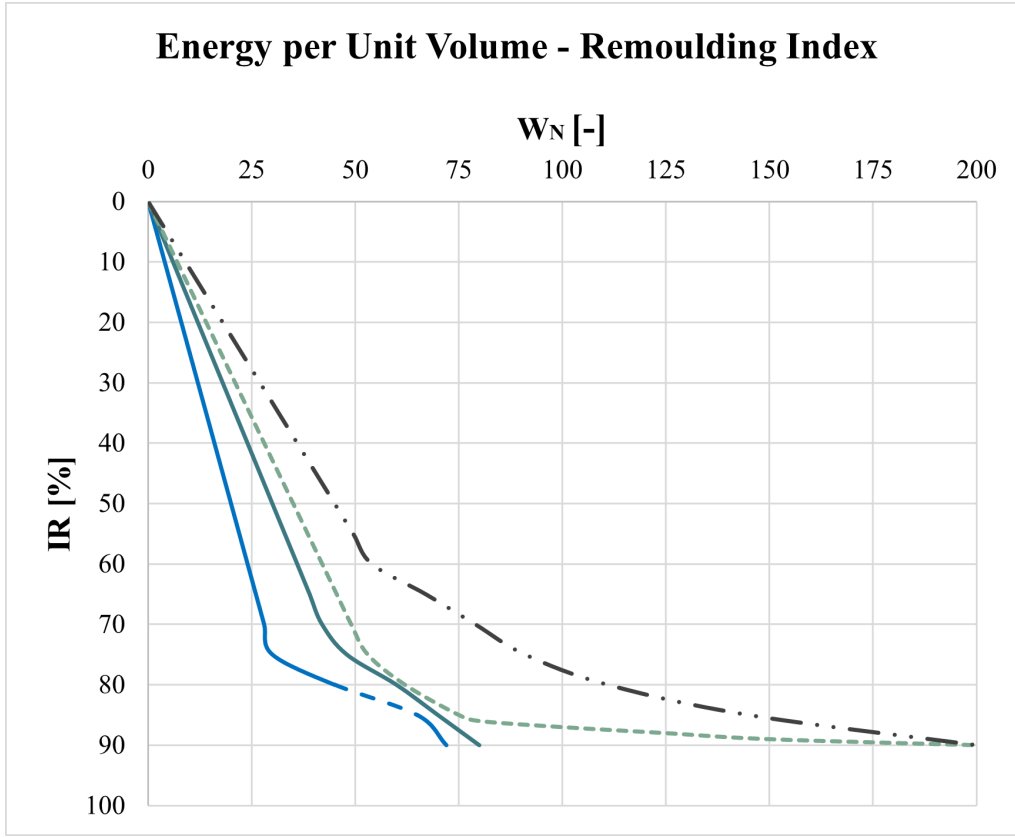


Figure 2.3: A reworked $W_N - I_R$ graph for different clay samples from Tavenas et al. (1983).

Normalized remoulding energy W_N is expressed as the ratio between energy per unit volume $W = \frac{E}{V}$ and the reference energy $W_{LS} = 0.013 \sigma'_p$, see equation (3.4). W_N measures the required mechanical work to destroy the soil's structure, adjusted for the soil's strength level. Values near 1 indicates minimal degradation and larger values indicates more complete remoulding.

$$W_N = \frac{W}{0.013 \sigma'_p} \quad (2.10)$$

- W_N – Normalized remoulding energy [-]
- W – Energy per unit volume [J]
- σ'_p – Preconsolidation pressure [kPa]

The remoulding index I_R indicates how rapidly the undrained shear strength c_u decreases as the soil is affected by remoulding, calculated using (2.11). In this

case, the specimen is dropped between a height of 0,2 - 2 meters. After each drop, the disturbed shear strength C_{ur} is measured through a fall cone apparatus and the experiment is done until the shear strength no longer decreases with further specimen disturbances.

$$I_R = \frac{c_u - c_{ux}}{c_u - c_{ur}} * 100 \quad (2.11)$$

- I_R – Remoulding index [%]
- c_u – Undrained shear strenght [kPa]
- c_{ur} remolded shear strength [kPa]
- c_{ux} – remolded shear strength at given drop height [kPa]

The remoulding index I_r ranges between 0% -100%, where 0% represents an undisturbed clay specimen and 100% represents a completely remolded specimen.

2.5.3 In-Situ Methods for Deteremining Rapidity & Remoulding Energy

The previously mentioned methods used to quantify remoulding energy are primarily based on laboratory testing. In addition to these controlled approaches, several in-situ field methods have been developed to evaluate remoulding behavior under cyclic loading conditions. Among these, the T-bar test and the vane shear test are the most widely applied techniques, allowing for the assessment of soil strength degradation and energy dissipation during cyclic loading (Larsson & Åhnberg, 2011).

The vane shear test can be applied to estimate the remoulding energy of sensitive clays (Berghel & Hagrydh, 2023). This approach is based on interpreting the stress strain behavior during vane rotation, where progressive degradation of shear strength is captured. During the test, the vane is 7,4-8,5 meters below ground surface, rotating 360°. The applied torque is continously recorded and translated to shear stress, while the rotation angle is converted to shear strain. From the measured data, a stress-strain curve is able to be plotted, where the reduction from peak to residual shear strength represents the remoulding process. The remoulding energy is defined as the work required to fully degrade a soil's structure and is estimated to be the area under the stress-strain curve after beyond peak strength. Figure 2.4 showcases an example of a stress-strain curve.

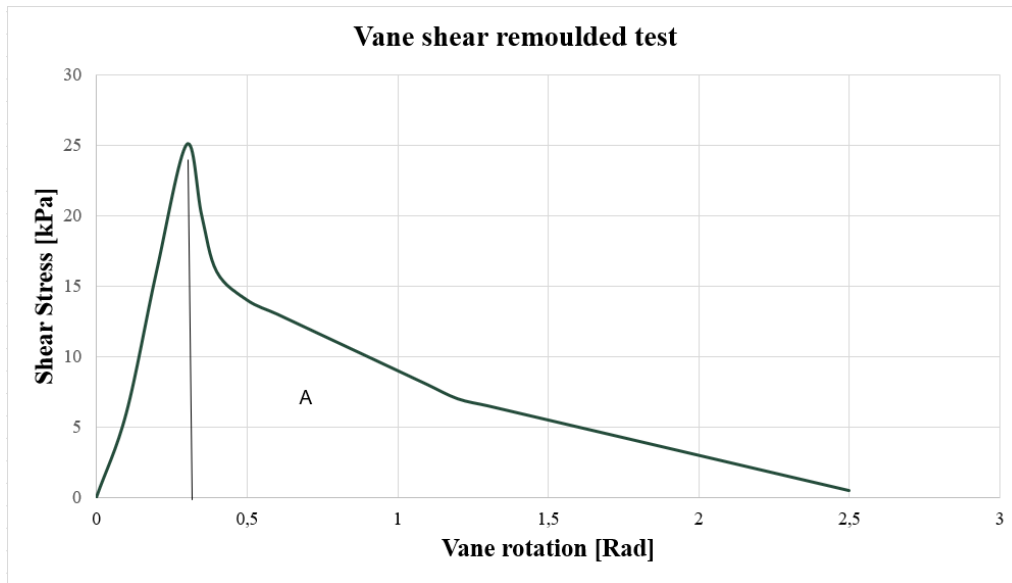


Figure 2.4: Example of a remoulded vane shear test inspired from Berghel and Hagrydh (2023), where A describes the area under the graph

The T-bar test is another in-situ method for evaluating both the intact and remolded undrained shear strength, as well as sensitivity. To assess the remoulding, cyclic T-bar tests are performed by repeatedly penetrating and extracting the bar at a specific depth between an interval. During the test, the forces is penetrating and extracting forces are continuously monitored and translated into penetration resistances (Jannuzzi et al., 2012). By plotting the resistance force against cycle number, a degradation curve can be obtained, showing how the undrained shear strength decreases after each cycle.

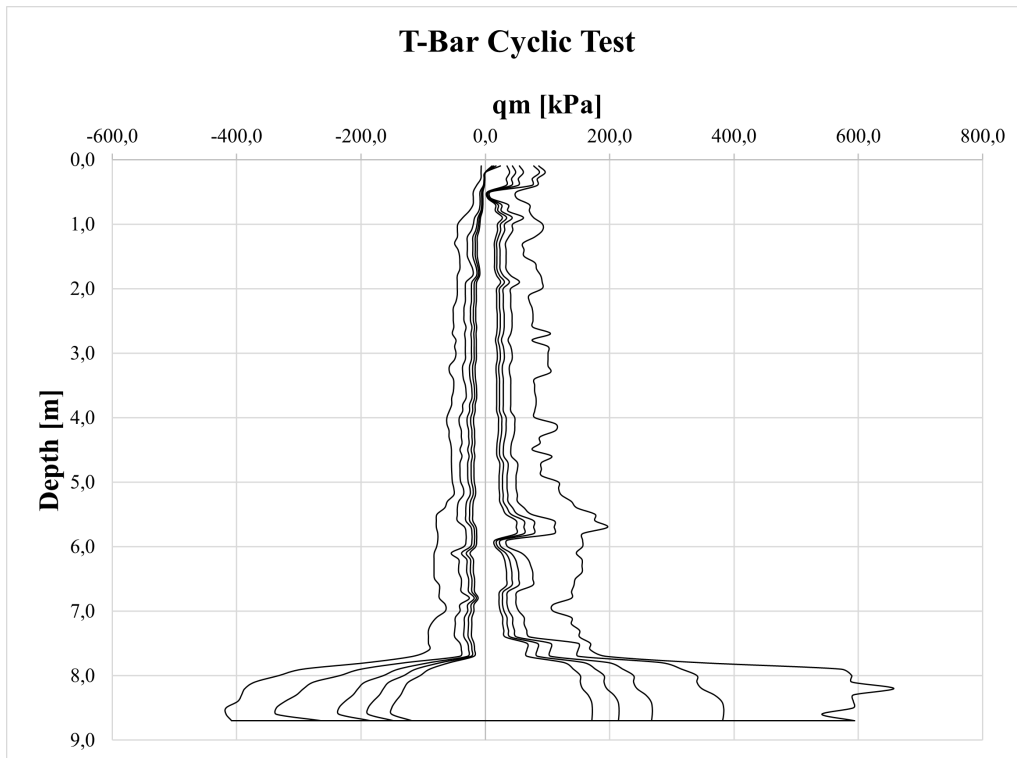


Figure 2.5: Example of a T-bar cyclic test inspired from Jannuzzi et al. (2012)

Figure 2.5 show a conceptual graph of a cyclic T-bar test. The initial resistance represents the intact state of a soil, whereas the stabilized resistance corresponds to the remoulded state. An important difference between the T-bar and Vane shear remoulding test is that the T-bar does not define the remolding energy as the area under the graph. Instead, it describes the progressive degradation of penetration resistance over successive cycles, rather in terms of energy.

3

The Clay Cutter Test

The CCT is a developing method used to derive shear strength in an undisturbed sample (Hedborg, 2025). The clay cutter consists of a fork that stretches a metal wire which is driven vertically through a soil sample at a constant rate. These are connected to 100 N load cells which record the forces acting on the wire from the soil, providing high resolution data with an error below 0,06%. Internal sensors record the position of the wire as it cuts through the soil sample. The resistance force mobilized from the soil is continuously measured during the test and translated into undrained shear strength along with the position of the wire which is plotted into a graph. Figure, 3.1, provides an overview of the machine.



Figure 3.1: Picture of the Clay Cutter machine

The CCT is preformed directly on piston samples. A desired height is cut out of the sample and placed onto the machine. It is possible to perform the test on the whole sample height, which is not possible in conventional laboratory testing methods. Conventional methods commonly uses a smaller part of the sample whereas the result is dependent on said part. The CCT can be repeated multiple times in one sample, using 4 cuts it is possible to catch anisotropic behavior. The standard procedure consists of cutting a sample at a rate of 40 mm/min using a 0,25 mm wire diameter (Hedborg, 2025). The CCT has previously been compared against Direct Simple Shear test (DSS), fall cone test and triaxial test. Around a total of 2000 data points indicates how CCT values correspond with the conventional methods of deriving shear strength.

Diameter between ranges 0,2-0,3 mm can be used with no significant impact on test results (Bergroth, 2025). The cutting rate between 40 - 80 mm/min has shown no effect of the results of deriving shear strength. The undrained shear strength of a sample can be quantified according to equation (3.1).

$$C_{u,CCT} = \frac{F_{cc}}{N_{cc} A_w} \quad (3.1)$$

- $C_{u,CCT}$ – Shear strength [kPa]
- F_{cc} – Wire force [kN]
- A_w – Lateral cross section area of the wire [m^2]
- N_{cc} – Correction factor of 15,7 [-]

The test is based on the assumption that the wire will cut the soil sample where half the area of the wire is in contact with the soil, where the contact area is based of the cutting rate. The N_{cc} factor has been empirically developed to take the acting area as well as taking SI units into account (Hedborg, 2026). The wire should be secured using the wire installation process and be regularly re-tensioned to avoid deflection exceeding 2 mm, as this affect the results.

3.1 Deriving Sensitivity from CCT

The sensitivity, i.e. shear strength and remoulded shear strength, is tested by letting the wire cut into a sample, then repeatedly moving the thread up and down in a set interval which defines a loop, this process will be further explained in the methodology chapter. The corresponding graph then illustrates the remoulding of shear strength which happen by each loop, see figure 3.2. Depending on the sample, the curve will start to converge indicating that the soil has reached a presumed remolded state.

When reading the shear strength - displacement curve it should be done in the stabilized part, after the first 2-5 mm . If large peaks occur in the graph, it is likely that there is a fault in the sample which skews the results, such as gravel or shells. In standard testing with the CCT the shear strength is evaluated as the average value along the cut. The remodeled shear strength is derived by picking the lowest recorded value as this would represent maximum disturbance of the sample. An example is presented in the following figure 3.2 where the wire interval is set between 16 - 20 mm for 20 loops. The graph has a symmetry of the value of the presumed remoulded shear strength over the x-axis, which resembles a cyclic T-bar graph.

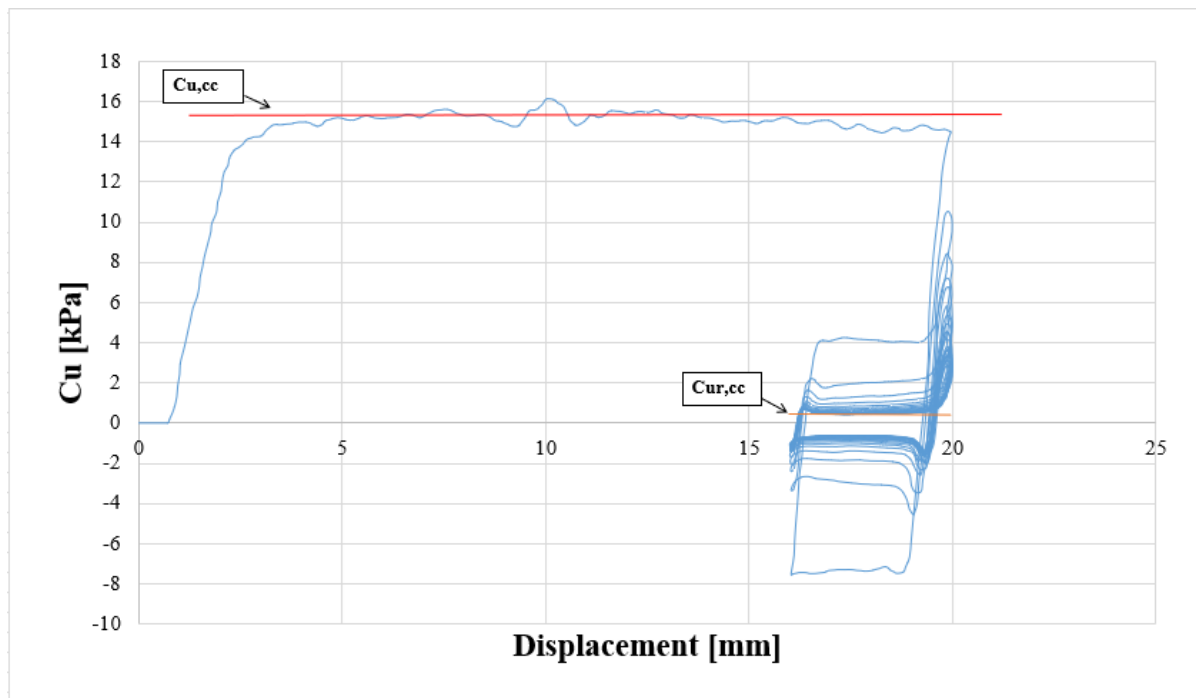


Figure 3.2: Shear strength - displacement curve of a CCT test, the upper red line is an average value of shear strength and the lower orange line is the minimum remoulded shear strength

However, as the CCT yields a set of different graphs it does not mean that this is the only way of evaluating the sample. The simple shear strength curve, shows shear strength & remoulded shear strength degradation over the sample testing, see figure 3.3. It illustrates the degradation for each passing of the wire and give insight to how quickly the soil loses it's strength for each pass. This ease in the evaluation weather a stable value is reached and in extraction of a representative value of the remoulded shear strength.

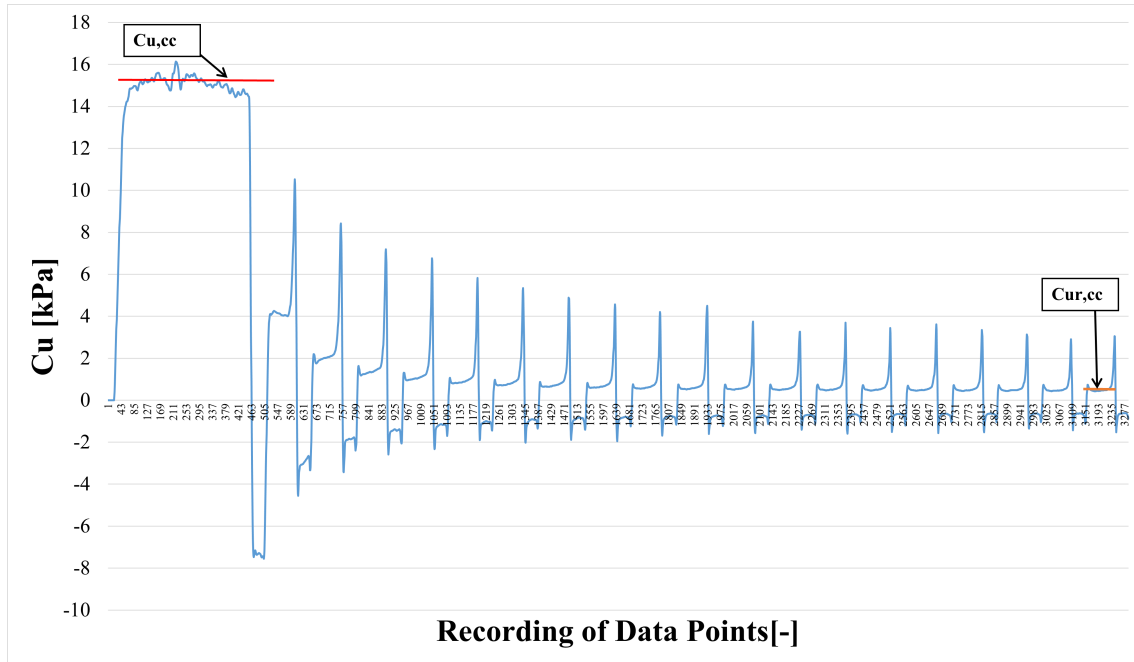


Figure 3.3: The simple shear strength curve, illustrating the remoduling process over the recorded data points during a test. The upper red line is an average value of shear strength and the lower orange line is the minimum remoulded shear strength

The way the thread is attached is assumed to contribute to the slight asymmetry of the peak value for both graphs as the wire changes direction. This is because the wire is being slightly supported when being pushed down into the soil. As the wire is moving up it does so more freely as there is no support on the way up. Hence, the recorded peak values in the graphs are assumed to not be representative for the material. Instead the peak value in the negative side, representing the standard downward motion of the wire, is assumed to be a representative for the material. Nevertheless, the value derived from the data is the lowest recorded point for remoulded shear strength, and the mean value for the shear strength.

3.2 Deriving Rapidity from CCT

A remoulding laboratory method was developed for the CCT within the scope of this thesis for determining the remoulded shear strength and corresponding rapidity. The purpose of the method is to be able to quantify the rapidity and remoulded energy from the measured values obtained from a Clay Cutter machine test and to allow comparisons between existing methods.

The method was established by combining the remoulding index, I_R , with the cumulative work W_n derived from CCT for each selected sample. In this thesis, W_{95} was used to represent near fully remoulding state. In addition, the rapidity

index I_R , was defined as the ratio between W_{85} and W_{95} . This ratio was used to describe how rapidly the remoulding process develops between 85% and 95%.

3.2.1 Energy and Rapidity

The method used to determine remolding rapidity from the Clay Cutter test is largely based on the approach proposed by Tavenas et al. (1983). As the undrained shear strength, c_u decreases with each successive loop, the disturbed shear strength corresponding to each loop is recorded as c_{ux} . After a number of loops were carried out, the shear strength reaches a remoulded state c_{ur} . The progressive reduction in shear strength is then used to express the remoulding process in terms of a remoulding index, I_R by following equation (3.2).

$$I_R = \frac{c_u - c_{ux}}{c_u - c_{ur}} * 100 \quad (3.2)$$

- I_R – Remoulding index [%]
- c_u – Undrained shear strength [kPa]
- c_{ur} – Fully remolded shear strength [kPa]
- c_{ux} – Remolded shear strength at given loop [kPa]

Furthermore, each loop produces an input work W_i which is expressed in joules. In the CCT, the work is derived from the shear strength - displacement graph, by converting shear strength to force using equation (3.1). For each remoulding loop, the cutting force varies continuously as the wire moves through the soil, and the work is determined as the area under the force - displacement curve. For one *loop* i , the work can be expressed by equation (3.3).

$$W_i = \int F ds \quad (3.3)$$

- W_i – Work for each loop [J]
- F – Force [N]
- s – Displacement [mm]

Where F is the measured cutting force (N) and s is the displacement (m). Therefore, W_i represents the mechanical energy supplied to the soil during one loop. The cumulative work after N loops is then defined as the sum of all loop work W_N according to equation (3.4).

$$W_N = \sum_{i=1}^n W_i \quad (3.4)$$

- W_N – Cumulative work for all loops [J]
- W_i – Cumulative work for one loop [J]

By combining the cumulative work W_N with the remoulding index I_R for each corresponding loop, the remoulding index - work curve can be expressed, as illustrated in figure 3.4. This curve describes how the the shear strength decreases as additional mechanical work is applied to the soil.

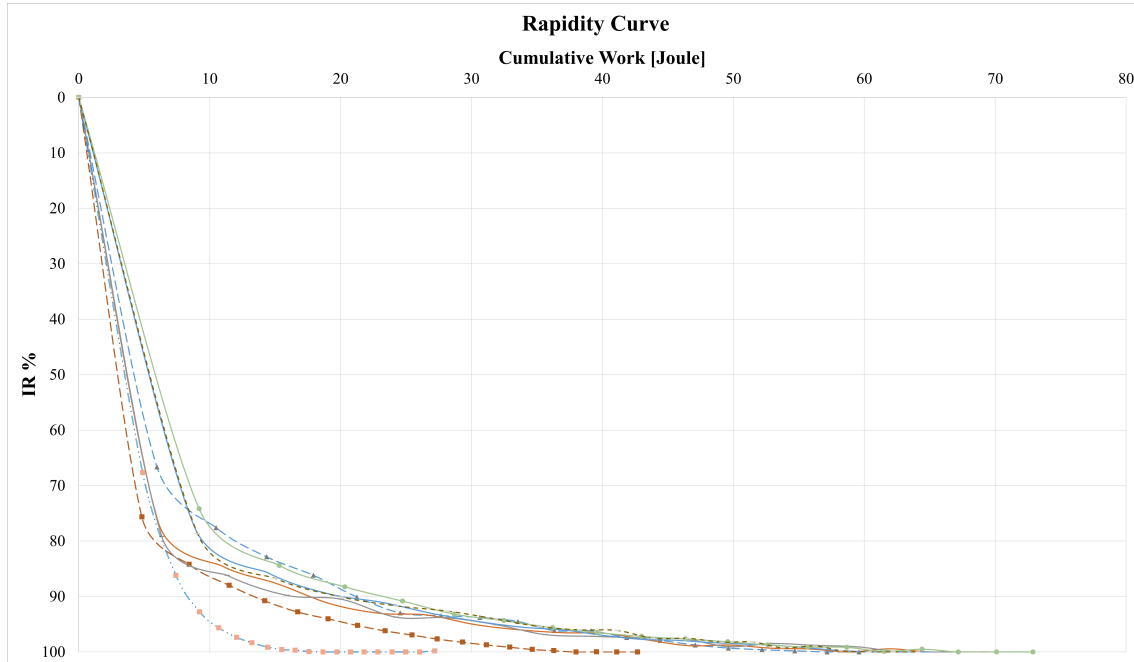


Figure 3.4: Example of four different soil samples and their respective Remoulding Index - Cumulative work curve

Once the cumulative work W_N had been established for each loop, reference work values were defined at selected remoulding levels. In this thesis, W_{95} and W_{85} were chosen to represent the cumulative work required to reach 85% and 95% remoulding in a soil sample. These values is derived from the remoulding index - work curve. Since not every remoulding level coincide exactly with a measured loop, the corresponding work values are determined by linear interpolation between two adjacent values, denoted a and b , on the remoulding index - work curve, see equation (3.5).

$$W_x = W_a + \frac{I_{Rx} - I_{Ra}}{I_{Rb} - I_{Ra}}(W_b - W_a) \quad (3.5)$$

- W_x – Cumulative work at point x [J]
- W_a – Cumulative work at point a [J]
- W_b – Cumulative work at point b [J]
- I_{Rx} – Remoulding index at point x [%]
- I_{Ra} – Remoulding index at point a [%]
- I_{Rb} – Remoulding index at point b [%]

I_{Rx} is the chosen remoulding level and W_x is the cumulative work corresponding to that level. In this thesis, interpolation was applied for I_{R95} and I_{R85} , yielding the reference work values W_{95} and W_{85} respectively.

The ratio between W_{95} and W_{85} was then defined as a unitless rapidity index R_E , by equation (3.6). The index describes how much additional work is required to reach 95% remoulding after the soil has already reached 85%, relative to the work already required to reach 85%.

$$R_E = \frac{W_{95}}{W_{85}} \quad (3.6)$$

- R_E – Rapidity index [-]
- W_{85} – Cumulative work for 85% remoulding [J]
- W_{95} – Cumulative work for 95% remoulding [J]

A low R_E indicates that only a small increase in work is needed in the later stage of remoulding, corresponding to a more rapid degradation process. A higher R_E value indicates that a greater amount of work is needed after 85% remoulding to reach 95%, which reflects a more gradual remoulding behaviour.

3.2.2 Assumptions and Limitations

The reference work levels W_{95} and W_{85} were selected as the most suitable points for describing remoulding development in this thesis. The selection is based on the assumption that the remoulding index - work curve provides a representative representation of the remoulding process in the CCT. A lower threshold, such as 50%, was considered unsuitable, since most tested samples had already exceeded this level after the first loop. Furthermore, it is assumed that W_{50} would largely reflect first loop response, including initial structural breakdown and possible start up effects, rather than the developed remoulding process. It is further assumed that linear interpolation between two adjacent points on the remoulding index - work curve provides a reasonable estimate of the cumulative work at selected remoulding levels. In the present study, W_{85} was assumed to represent a sufficiently developed

remoulding stage, while W_{95} was assumed to represent a near fully remoulding state.

The proposed rapidity method is based on the present dataset and should therefore be regarded as a Clay Cutter specific approach rather than a universal soil parameter. The choice of 85% and 95% remoulding is empirical and was made from the observed shape of the remoulding index - work curves in this study. The method is considered most applicable to clay and clay-dominated samples, since mixed soils containing shells, sand or organic material showed less consistent behaviour and were therefore excluded from the main rapidity evaluation. In addition, the calculated work values depend on the available remoulding data samples with insufficient loop records could not be evaluated reliably because interpolation of W_{95} and W_{85} was not possible. The rapidity index R_E should therefore be interpreted as an index describing remoulding behaviour within a specific Clay Cutter framework, i.e. specific remoulding interval, thread speed and number of loops, rather than as a general soil parameter independent of the test setup and procedure.

4

Method

This study builds on a foundation of theory and background knowledge which forms the basis for two main development areas, the laboratory method comparing CCT to FC, and the preparation of kaolin test samples. The theoretical study consists of a review of academic sources, providing background knowledge and context for the work. The practical part consists of laboratory experiments carried out through a series of tests and is complemented by archived data used to support the experimental results. The scheme of the study is illustrated in following figure 4.1.

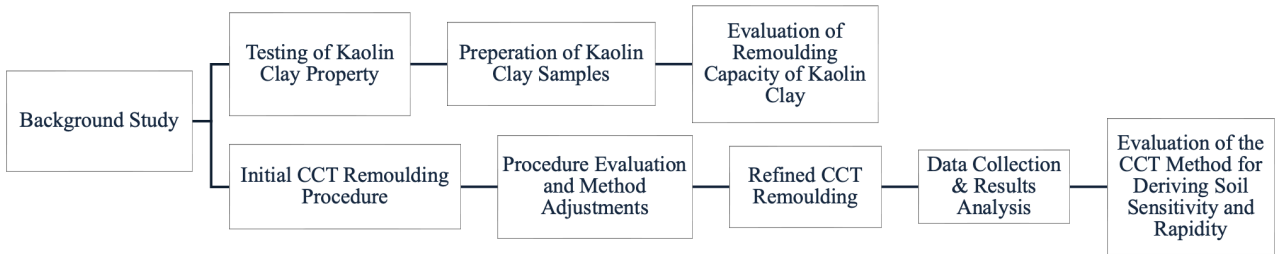


Figure 4.1: Overview of the experimental workflow, including method development and laboratory testing

4.1 Provided Material

AFRY geotechnical laboratory provides samples from different project. All samples used in the testing, has been stored in a climate controlled chamber keeping a temperature of 7° and constant humidity, sealed in piston samples. However, laboratory testing are performed on residual or remaining samples which have been stored for 6 months or more. The piston tubes used can be upper, middle or lower tube depending on what was available. For all laboratory testing, samples were cut to a height of 40 mm, but firstly removing the upper 20-30mm to avoid potential disturbances, making it possible to obtain two or three soil pucks from each piston. The soil classification and number of samples tested for the finalized version of the

laboratory is stated in following table.

Soil Characterization	Number of samples
CLAY	34
sandy CLAY	1
slightly sandy CLAY	2
silty CLAY	2
gyttja-bearing silty CLAY	27
gyttja-bearing silty CLAY shells	3
gyttja-bearing silty CLAY sandy layer	4
gyttja-bearing sandy CLAY	1
gyttja-bearing sandy silty CLAY	1
silty CLAY	2
slightly gyttja-bearing CLAY	5
gyttja-bearing CLAY	1
clayey GYTTJA	1
silty clayey GYTTJA	3
sandy GYTTJA	1
GYTTJA shells	2
gyttja-bearing clayey SAND	3

Table 4.1: Number of samples based of their soil characterization

The complementary data is collected from previous fall cone test and standard soil identification. Soil classification is conducted through visual assessment and considers the particle and organic content of the sample (Sällfors, 2013). Parameters such as density φ , water content w_n , liquid limit w_L as well as shear strength $c_{u,fc}$, remoulded shear strength $c_{ur,fc}$ and sensitivity $S_{t,fc}$ has been evaluated using the Swedish standard.

4.2 Development of the CCT Remoulding Method

To assess the capability of the CCT to derive remoulded shear strength, a laboratory method was used and progressively refined during the project. The third procedure was established through an iterative development process involving several experimental stages. The initial tests (laboratory procedure 1) produced inconsistent results indicating that the procedure required refinement. Modifications were introduced (laboratory procedure 2) to investigate whether the results are inconsistent due to faults in the testing process. These adjustments formed the basis for the final method (laboratory procedure 3).

4.2.1 Laboratory Procedure 1

The first laboratory procedure was based on the standard CCT speed of 40 mm/min and wire dimensions of 0,27 mm. Initially the FC test were performed on the sample, following the SS-EN ISO 17892-6 and SGF Notat 2:2018 standard. After the FC test, the remodeling procedure by CCT is carried out. This is done by cutting into the sample until the wire reaches a given depth of 25 mm, based of a staring point at 0 mm, then reversing the wire up 10 mm, see conceptual figure 4.2.

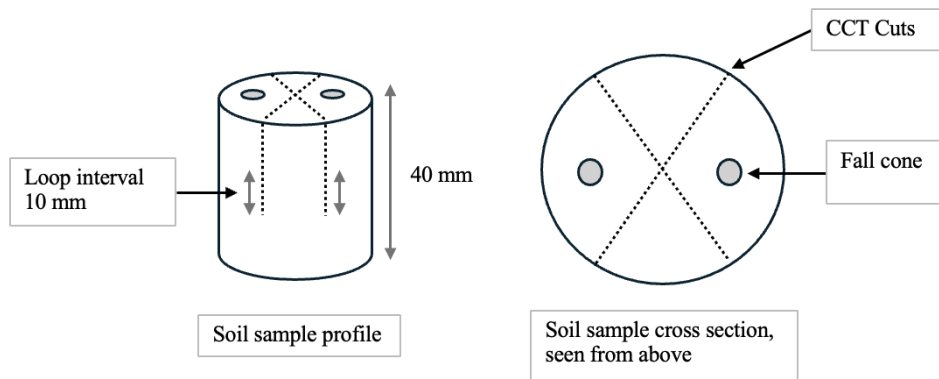


Figure 4.2: Conceptual illustration of the first remoulding procedure applied to an intact sample.

This is looped for 10 intervals, ensuring the cuts are at least 1 cm from the to the FC indents. After the CCT is completed, the sample is removed and manually remoduled and FC test is performed on the sample.

4.2.2 Laboratory Procedure 2

Controlling the result from the laboratory 1 procedure by investigating the possibility if the test process affects the results. This was done in several steps, firstly controlling a channel created by the wire and affecting the results. By allowing lab 1 to run, 30 seconds is added at the end of the last interval. This allows for manually turning the sample 45° into an undisturbed area and running the lab 1 procedure again, see conceptual figure 4.3.

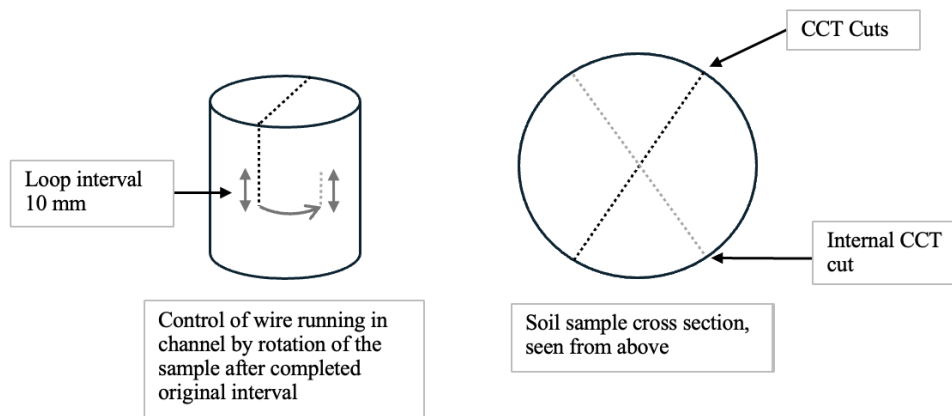


Figure 4.3: Conceptual illustration of the control test for wire movement in an open channel.

As no differences are observed between the two cuts, this is disregarded and another check is performed. The aim is to investigate whether the wire interacts with the clay that is displaced sideways during the loops. This is done by reducing the interval length for each pass, see conceptual figure 4.4.

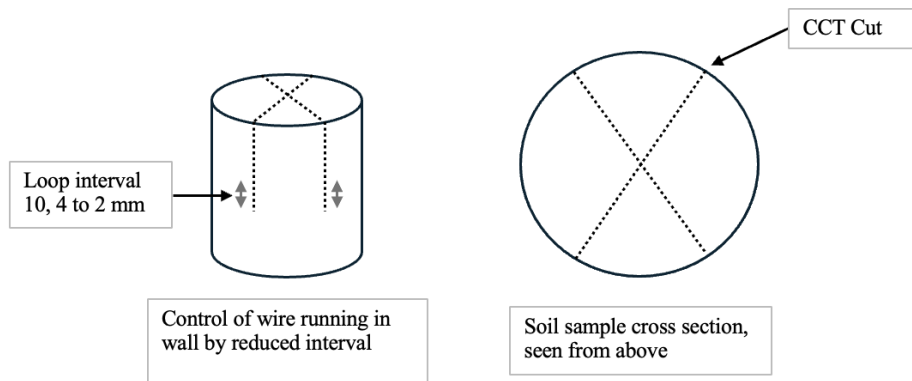


Figure 4.4: Conceptual illustration of the control test for wire movement against displaced material.

As none of these adjustments had no impact on the observed results. Consequently, these are disregarded as potential faults in further tests for this project.

4.2.3 Laboratory Procedure 3

As samples with higher shear strength visibly lifted with the wire, a supporting sleeve was developed which clamped the sample in place. The sleeve was developed using a 3D CAD program and was 3D printed. The sleeve was securing around the sample with bolts and screws, to keep the sample in place.

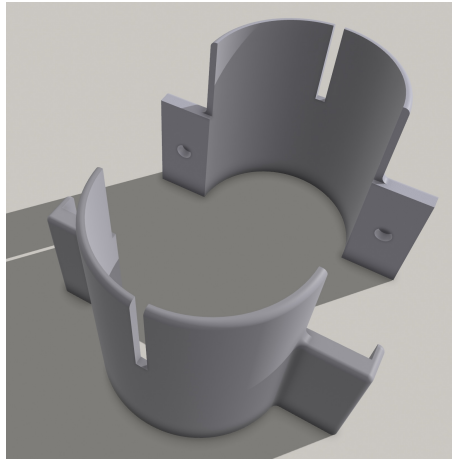


Figure 4.5: 3D model of the support sleeve

The interval was shortened to 4 mm and run for 20 loops to reach a converged value and the speed was increased to 80 mm/min. This allowed the wire to pass a point at a quicker pace, the finalized laboratory method is conceptualized in figure 4.6.

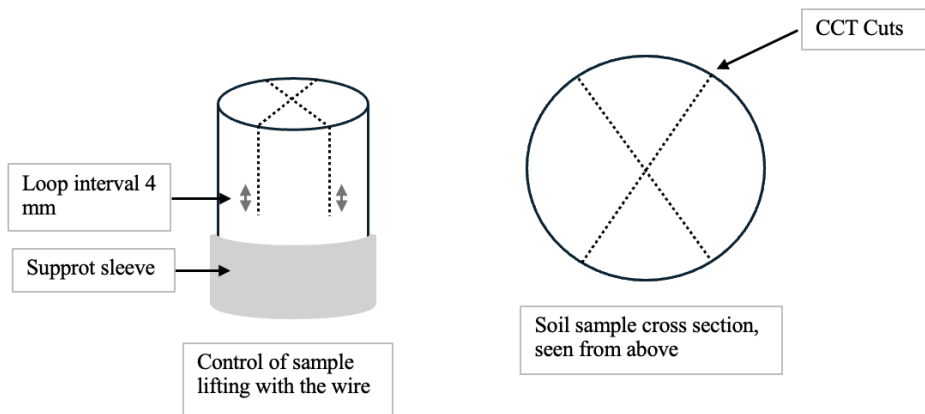


Figure 4.6: Finalized laboratory procedure used for the remoulded CCT

The finalized version of the laboratory procedure is implemented and are presented in the results. In addition, a few tests were made with a wire of 2 mm in diameter following this scheme. However, these results stalled at one remodeled shear strength and were disregarded in further parts of the project.

4.3 Selection and Preparation of Reference Clay

The reference clay is of type Kaolin E, ordered as powder in 2 kg bags from cebex.se, a ceramics retailer. The initial step in constructing the reference clay was to evaluate the kaolin powder quality through a sedimentation analysis. The sedimentation

analysis was performed to determine the grain size distribution of the powder clay. Hence, 50 grams of the powder was dried for 24 h. A 13.3 g dispersant agent, sodium hexametaphosphate, was mixed with distilled water in a 1 litre beaker. The dried kaolin powder was then added, ensuring full dispersion of particles. Measurements were taken using a hydrometer, recording the sedimentation process over 24 h. Additionally, another kaolin material, referred to as Kaolin 2025 which was previously evaluated by Bergroth, 2025, was also compared to the Cebex kaolin, referred to as Kaolin 2026. From the sedimentation analysis, presented in figure 4.7, the results indicate that Kaolin 2026 is a fined-grained material classified as a silty kaolin with some clay fractions. Meanwhile, Kaolin 2025 is classified as a clayey kaolin with silt fractions. A sedimentation analysis on a typical clay sample is also presented, marked as LE.

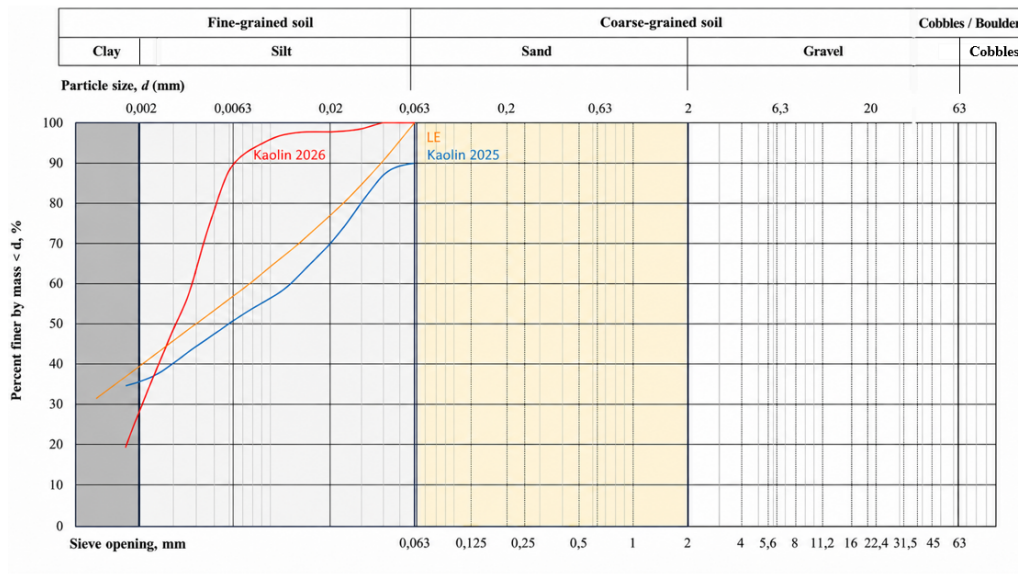


Figure 4.7: Sedimentation analysis of kaolin 2025, interpreted as a clayey kaolin, and kaolin 2026, interpreted as a silty kaolin, compared with a typical clay sample, LE.

To create samples, Kaolin 2026 powder was mixed with water to prepare specimens for testing shear strength and remoulded shear strength. Initially, several small batches with different water contents (w_n) were prepared in order to find a workable mixture. Two representative batches were selected for further testing, one slurry with w_n 95% and one paste with w_n 55%. The goal was to obtain a consolidated shear strength of approximately 15–20 kPa with homogeneous behavior. The samples were placed in cells with filter stones above and below the clay mixture, allowing for double drainage, see figure 4.8 and 4.9. After ensuring that both the samples and filter stones were fully submerged in water, they were loaded with 4 kg (approximately 20 kPa) and allowed to consolidate for 1 week.



Figure 4.8: 95% slurry placed into cell using a syringe



Figure 4.9: 55% paste packed into cell

After consolidation, the Kaolin 2026 samples were tested using the CCT with four cuts. Closely located cuts showed minor differences in shear strength, while cuts oriented 90° apart showed slightly larger variations. The slurry exhibited lower variability in shear strength (3.4–3.8 kPa) compared to the paste (10.5–11.75 kPa) and was therefore considered more homogeneous. The paste showed more variability, possibly due to compaction during sample preparation. Based on this, two additional slurry batches were consolidated for another week and loaded with 20 and 40 kPa, respectively. The increased load resulted in only a minor increase in shear strength. An incremental loading (IL) test up to 160 kPa over four days and the slurry again resulted in being too soft to achieve a manageable strength within the project time frame. The slurry sample was compressed just over 30% in the IL test, see appendix A.1.

Hence, another trial was performed using the paste with w_n 55%, applying incremental loading up to 160 kPa over 10 days. The results shows a compression of around 15%, see appendix A.2. This resulted in a manageable shear strength of approximately 22 kPa. A second batch of the paste mixture showed similar results, indicating good repeatability. Two additional batches were then loaded with 80 and 120 kPa to evaluate the linearity of the kaolin behaviour, to be able to roughly estimate the consolidated shear strength after approximately 10 days of loading. Two new batches were made with the intent of testing remoulding capacity between FC and CCT. The paste was packed into cells where the bottom filter stone was replaced with a double layer of filter paper to produce larger samples. To achieve a

shear strength of approximately 25 kPa, the mixture was loaded with 155 kPa.

Although the mixed w_n 55% paste reached a sufficient shear strength after consolidation, further adjustments to the material composition were made to improve overall behaviour. A higher water content mixture $w_n = 70\%$ was therefore prepared, along with an alternative kaolin (Kaolin 2025) with higher clay content. Kaolin 2025 was prepared by drying and grinding the material into a powder, followed by mixing with water and consolidation under incremental loading for 4 days, reaching a total compression of approximately 20% see appendix A.3. After a process of trial and refinement in the development of a reference clay, final batches consisting of 70% silty kaolin and Kaolin 2025 were prepared and used in the subsequent validation tests of the CCT and FC methods.

5

Geotechnical Properties of the Samples

The geotechnical properties of the investigated samples are presented in this chapter. The precise site where the sample has been extracted from is anonymised due to confidentiality, but all samples are collected from the west coast in Sweden. Each site has been assigned a letter representing the general location. In addition, when a sample originates from the same location, a number is added to distinguish between them. The presented properties include soil type, density, water content w_n , liquid limit w_l , undrained shear strength and remoulded shear strength from FC and CCT, as well as the sensitivity S_t for each respective method. These properties are used to characterise the tested material and form the basis for the comparison between FC test and CCT presented in the subsequent results chapter.

5.1 Test sample A1

A1 consists mainly of brown clay between 4 and 9 m depth with slightly sandy clay observed at the deepest tested level. The water content and liquid limit generally decreases with depth and an increase in density and undrained shear strength from the FC and CCT. A part from the slightly sandy clay, the sample A1 is relatively consistent and the properties are shown in table 5.1

Table 5.1: Soil properties for sample A1

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_l [%]	$c_{u,fc}$ [kPa]	$c_{u,cct}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{u,ccc}$ [kPa]	$S_{t,cc}$
4	Upper	Brown CLAY	1,57	80	73	10	0,75 (60g)	13	7	1,75	4,00
5	Upper	Brown CLAY	1,55	80	75	11	1,02 (60g)	11	8	1,73	4,62
8	Upper	Brown CLAY	1,61	70	69	19	1,41 (60g)	14	14	2,16	6,48
9	Upper	Brown slightly sandy CLAY	1,65	63	64	20	1,63 (60g)	12	16	2,45	6,53

5.2 Test sample A2

Sample A2 is tested between an interval of 4 and 10 m depth. The soil description is uniform throughout the depths, consisting of brown clay, with no major change

in soil type noted in the table. The water content is relatively stable with depth, while both FC and CCT undrained shear strength generally increase. The detailed properties are presented in table 5.2

Table 5.2: Soil properties for sample A2

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
4	Lower	Brown CLAY	1,62	74	73	12	1,39 (60g)	9	11	2,14	5,14
5	Lower	Brown CLAY	1,64	69	73	16	2,04 (60g)	8	13	2,51	5,18
6	Lower	Brown CLAY	1,63	69	75	18	1,78 (60g)	10	13	2,24	5,80
8	Lower	Brown CLAY	1,63	71	73	19	1,86 (60g)	10	16	2,42	6,61
10	Lower	Brown CLAY	1,65	69	77	24	2,62 (60g)	9	18	2,99	6,02

5.3 Test sample B1

Sample B1 consists mainly of grey and mottled grey clay between 4 and 20 m depth and grey sulphide-mottled clay can be observed at the deeper levels. The water content and liquid limits vary with depth, mean while the undrained shear strength from both the FC and CCT increases with depth. The soil properties are presented in table 5.3.

Table 5.3: Soil properties for sample B1

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
4	Upper	Grey CLAY	1,66	70	68	20	0,75 (60g)	26,7	22,0	2,10	10,48
5	Upper	Grey mottled CLAY	1,58	66	61	22	1,02 (60g)	21,6	20,0	2,40	8,33
6	Upper	Grey mottled CLAY	1,52	80	78	20	0,87 (60g)	23,0	18,0	2,30	7,83
8	Upper	Grey mottled CLAY	1,51	83	79	20	0,87 (60g)	23,0	18,0	2,40	7,50
10	Upper	Grey mottled CLAY	1,50	90	79	21	0,87 (60g)	24,1	22,0	2,40	9,17
12	Upper	Grey sulphide-mottled CLAY	1,48	86	79	25	0,94 (60g)	26,6	24,5	2,00	12,25
14	Upper	Grey sulphide-mottled CLAY	1,58	78	76	27	0,94 (60g)	28,7	28,0	1,70	16,47
16	Upper	Grey mottled CLAY	1,67	62	51	33	0,94 (60g)	35,1	30,0	1,90	15,79
18	Upper	Grey sulphide-mottled CLAY	1,60	74	78	38	1,53 (60g)	24,8	33,0	2,00	16,50
20	Upper	Grey sulphide-mottled CLAY	1,62	69	74	37	2,30 (60g)	16,1	32,0	2,80	11,43

In addition, the sensitivity for the sample can be considered medium throughout the profile. The presence of different soil types and the variation in index parameters should be considered when evaluating the results.

5.4 Test sample B2

Sample B1 shows a large variation in soil types, varying between clay to slightly gyttja bearing clay and grey mottled clay, in the intervals of 4 to 20 m depth. There is no consistent trend in density, water content and liquid limit, as the three fluctuate between levels, which is shown in table 5.4.

Table 5.4: Soil properties for sample B2

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
4	Upper	Grey CLAY	1,62	73	72	20	1,02 (60g)	20,0	17,2385	1,77	9,74
6	Upper	Grey mottled CLAY	1,59	79	74	20	0,70 (60g)	28,0	17,8	1,60	11,12
8	Upper	Grey slightly gyttja-bearing CLAY	1,56	90	81	22	1,11 (60g)	20,0	19,7	2,41	8,17
10	Upper	Grey mottled CLAY	1,55	86	80	21	1,02 (60g)	21,0	22,1	2,55	8,67
12	Upper	Bluish grey CLAY	1,56	82	77	23	1,02 (60g)	25,5	24,0	1,61	14,91
14	Upper	Grey mottled CLAY	1,55	83	81	27	1,02 (60g)	30,0	28,1	1,19	23,61
18	Upper	Grey mottled gyttja-bearing sandy CLAY	1,73	52	56	38	3,00 (60g)	36,5	33,0	1,19	27,73
20	Upper	Grey mottled CLAY	1,6	71	73	32	1,63 (60g)	30,0	32,3825	2,43	13,33

The undrained shear strength obtained from both the FC and CCT shows a general increase with depth. However, the remoulded undrained shear strength from both methods displays greater variation and does not follow the same trend. As a result, the calculated sensitivity is strongly affected by variations in the remoulded strength.

5.5 Test sample C1

Sample C1 consists mainly of greenish grey gyttja-bearing silty clay and grey mottled slightly gyttja-bearing clay, where the latter soil type appears in the deeper levels. The soil profile extends from 6 to 20 m depth. The density decreases with depth, whereas the water content, liquid limit and undrained shear strength generally increases with depth. The soil properties are detailed in table 5.5.

Table 5.5: Soil properties for sample C1

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
6	Upper	Greenish grey gyttja-bearing silty CLAY	1,76	50	48	39	0,94 (60g)	41,5	44	1,23	35,77
8	Upper	Greenish grey gyttja-bearing silty CLAY	1,70	58	49	40	0,87 (60g)	46,0	40	1,29	31,01
10	Upper	Greenish grey gyttja-bearing silty CLAY	1,68	58	53	38	0,75 (60g)	50,7	38	1,37	27,74
12	Upper	Greenish grey gyttja-bearing silty CLAY	1,68	62	52	41	0,94 (60g)	43,6	44	1,57	28,03
15	Upper	Greenish grey slightly gyttja-bearing CLAY	1,65	64	61	51	1,63 (60g)	31,3	49	1,17	41,88
20	Upper	Grey mottled slightly gyttja-bearing CLAY	1,63	67	69	60	2,04 (60g)	29,4	58	1,07	54,21

The remoulded undrained shear strength is low for both the FC. The FC sensitivity varies with depth, mainly due to changes in remoulded strength. The CCT sensitivity also varies due to the influence of variation in remoulded undrained shear strength for the CCT.

5.6 Test sample C2

Even though C2 and C1 are sampled from the same location, the soil composition differs. Sample C2 consists of silty clay, clay and mottled clay at the deeper parts. No definite trend in density or water content can be established, but there is an increase in undrained shear strength for FC and CCT as the level increases. The soil properties for sample C2 are shown in table 5.6.

Table 5.6: Soil properties for sample C2

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
2	Lower	Grey silty CLAY	1,74	54	57	36	2,04 (60g)	17,6	41	3,08	13,31
3	Lower	Grey CLAY	1,52	82	58	36	0,81 (60g)	44,4	38	1,49	25,50
4	Middle	Grey mottled CLAY	1,63	70	60	32	0,75 (60g)	42,7	36	1,45	24,83
6	Middle	Grey mottled CLAY	1,61	67	67	35	0,70 (60g)	50,0	37	1,13	32,74
6	Lower	Grey mottled CLAY	1,61	67	67	38	0,16 (60g)	237,5	45	1,25	36,00

Furthermore, a notable decrease in remoulded shear strength for respective method can be noted as depth increases, which is also reflected in the calculated sensitivities. For test sample C2, both lower and middle tube sections were used because a complete set of five sample from only one position was not available.

5.7 Test sample C3

Test sample C3 was tested between 4 and 18m depth. The soil type is predominantly greenish grey gyttja-bearing silty clay, changing to grey gyttja bearing silty clay in the deeper parts of the profile. Organic material were noted at the shallowest levels which could have affected the results. The soil properties are presented in table 5.7.

Table 5.7: Soil properties for sample C3

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
4	Upper	Greenish grey gyttja-bearing silty CLAY	1,64	51	60	29	0,99 (60g)	29,3	31	0,39	79,49
5	Upper	Greenish grey gyttja-bearing silty CLAY	1,60	64	50	35	1,26 (60g)	27,8	33	0,29	113,79
6	Upper	Greenish grey gyttja-bearing silty CLAY	1,64	60	50	30	1,17 (60g)	25,6	32	0,15	213,33
8	Upper	Greenish grey gyttja-bearing silty CLAY	1,69	51	52	35	0,91 (60g)	38,5	34	0,54	62,96
10	Upper	Greenish grey gyttja-bearing silty CLAY	1,73	48	44	38	0,94 (60g)	40,4	37	0,81	45,68
12	Upper	Greenish grey gyttja-bearing silty CLAY	1,75	50	44	41	0,67 (60g)	61,2	37	0,98	37,76
15	Upper	Grey gyttja-bearing silty CLAY	1,66	58	44	47	0,41 (60g)	114,6	46	1,32	34,85
18	Upper	Grey gyttja-bearing silty CLAY	1,64	65	48	41	0,45 (60g)	91,1	42	1,99	21,11

Both FC and CCT undrained shear strength generally increases with depth. The remoulded undrained shear strength is markedly lower than in several of the previous samples, particularly in the upper and middle part of the profile, resulting in relatively high CCT sensitivity values.

5.8 Test sample D

Test sample D covers the interval from 5 to 8 m depth and is dominated by silty clayey gyttja. This makes the sample different from the previous clay dominated profiles, since the organic and silty content may influence both the FC and CCT. The soil properties is presented in table 5.8.

Table 5.8: Soil properties for sample D

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
5	Lower	Clayey GYTTJA	1,5	93	67	13	0,15 (10g)	91	13	1,84	7,07
6	Upper	Silty clayey GYTTJA	1,57	80	51	8	0,08 (10g)	95	8	1,08	7,41
7	Upper	Silty clayey GYTTJA	1,61	71	50	9	0,13 (10g)	76	7	1,24	5,65
8	Middle	Silty clayey GYTTJA	1,63	68	50	9	0,11 (10g)	82	7	0,61	11,48

The FC results indicate a very high sensitivity, mainly due to the very low remoulded FC strength measured with the 10 g cone. In contrast, the CCT remoulded strength is considerably higher, which in turn yields a lower sensitivity. This difference indicates that the two methods may not capture the remoulded behaviour in the same way for this specific soil type. The values for sample D should therefore be treated with caution in the later comparison.

5.9 Test sample E

Test sample E is tested between an interval of 5 to 12 m depth and differs from the previous sample by containing sandy material. The upper level is classified as gyttja-bearing clayey sand, while deeper levels contains grey sandy clay and sulphide-mottled slightly sandy clay. The soil properties is presented in table 5.9

Table 5.9: Soil properties for sample E

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
5	Middle	Gyttja-bearing clayey SAND	1,82	34,5	38	26	1,11 (60g)	23	29	2,37	12,24
10	Middle	Grey sandy CLAY	1,77	53	54	36	1,50 (60g)	24	35	2,67	13,11
12	Middle	Sulphide-mottled slightly sandy CLAY	1,66	62	66	27	0,94 (60g)	28	27	1,63	16,56

The undrained shear strength from both the FC and CCT is the highest at 10 m, but overall does not show a consistent trend. The water limit and water content can be considered low considering where the sample was taken from. The remoulded shear strength remains relatively low for both methods, resulting in a moderate sensitivitiy. The sample in the tube at 12 m depth was noted to have cracks during testing, which should be considered when interpreting the results.

5.10 Test sample F

The sample F covers the interval from 2 to 19 m depth and is characterized by gyttja-bearing silty clay, with sulphide-mottled and sand layers occurring in parts of the profile. This makes the sample relatively heterogenous compared to the more unifrom clay samples. The soil properties is presented in table 5.10

Table 5.10: Soil properties for sample F

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
2	Middle	Gyttja-bearing silty CLAY	1,62	80	76	11	1,02 (60g)	11	12	2,07	5,80
4	Middle	Gyttja-bearing silty CLAY	1,55	80	58	11	0,11 (10g)	104	10	0,73	13,70
6	Upper	Gyttja-bearing silty CLAY	1,49	36	39	14	0,06 (10g)	232	12	0,27	44,44
12	Middle	Sulphide-mottled gyttja-bearing silty CLAY with sand layer	1,61	71	48	22	0,06 (10g)	336	22	0,56	39,29
15	Middle	Sulphide-mottled gyttja-bearing silty CLAY	1,6	76,1	51	23	0,06 (10g)	373	19	0,80	23,75
19	Middle	Gyttja-bearing silty CLAY with sand layer	1,68	69,4	63	32	0,06 (10g)	526	32	1,19	26,89

The undrained shear strength generally increases with depth for respective method. The majority of the FC values were obtained by using the 10 g cone, indicating very low remoulded shear strength. This results in high sensitivity, espically at greater depths. Overall, the CCT records higher remoulded values with greater variability compared to the FC.

5.11 Test sample G

The tested levels in sample G ranges from 2 to 6 m depth. The material consists of gyttja and gyttja-bearing silty clay with shell bits observed throughout the soil profile. The soil properties is shown in table 5.11

Table 5.11: Soil properties for sample G

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
2	Middle	GYTTJA with shells	1,43	120,4	88	6	0,37 (60g)	17	20	0,89	22,47
3	Middle	GYTTJA with shells	1,42	126	79	9	0,17 (10g)	52	5	0,37	13,51
4	Upper	Gyttja-bearing silty CLAY with shells	1,61	81	62	10	0,11 (10g)	95	11	0,83	13,25
5	Upper	Gyttja-bearing silty CLAY with shells	1,58	79	57	10	0,08 (10g)	119	10	1,28	7,81
6	Middle	Gyttja-bearing silty CLAY with shells	1,56	81	58	10	0,05 (10g)	206	12	0,71	16,90

The relatively low FC strength in the upper levels of the profile are consistent with the high water content and organic content. In addition, shell fragments could be observed during testing and may have influenced the CCT resistance if the thread interacted with shells. The results from sample G should be treated with caution, since the tubes were reportedly disturbed before CCT.

5.12 Test sample H

Test sample H includes material from 3 to 12 m depth and mainly consists of gyttja-bearing clay. Sulphide-spotted and sulphide-mottled clay occur in the deeper part of the profile, which indiciates some variation in the soil composition. The soil properties are presented in table 5.12

Table 5.12: Soil properties for sample H

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
3	Middle	Gyttja-bearing silty CLAY	1,53	89	70	14	0,45 (60g)	30,0	15,7	0,78	20,13
4	Upper	Gyttja-bearing silty CLAY	1,5	93	69	13	2,04 (60g)	6,0	11,20	0,76	14,74
5	Middle	Gyttja-bearing silty CLAY	1,54	90	68	12	0,30 (10g)	51,0	16,5	0,78	21,15
6	Middle	Gyttja-bearing silty CLAY	1,53	91	70	14	0,44 (10g)	33,0	16,6	0,89	18,65
7	Middle	Sulphide-spotted gyttja-bearing silty CLAY	1,53	87	67	18	0,41 (60g)	44,0	21,8	0,96	22,71
8	Middle	Sulphide-spotted gyttja-bearing silty CLAY	1,54	86	67	18	0,54 (60g)	33,0	20,8	1,11	18,74
10	Middle	Sulphide-mottled slightly gyttja-bearing CLAY	1,56	84	70	20	0,67 (60g)	31,0	4,4	0,17	25,88
12	Middle	Sulphide-mottled CLAY	1,57	75	67	20	0,68 (60g)	30,0	4,74	0,25	18,95

The FC results show moderate sensitivity for most depths, mainly due to the low remoulded fall cone strength and relatively moderate shear strength. The CCT results, however, do not follow the same trend throughout the profile. In particular, the undisturbed and remoulded shear strength at 10 and 12 m depths are unusually low compared to the previous depths, indicating some kind of disturbance before CCT.

5.13 Test sample J

Test sample J includes material from 3 to 8 m depth and is characterized mostly by gyttja-bearing silty clay and at the shallowest depth, gyttja-bearing sandy silty clay.

The soil profile is therefore somewhat homogeneous. The soil properties is shown in table 5.13.

Table 5.13: Soil properties for sample J

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
3	Middle	Gyttja-bearing sandy silty CLAY	1,61	70	58	14	0,39 (60g)	36,0	12,4	0,76	16,32
4	Middle	Gyttja-bearing silty CLAY	1,57	81	63	11	0,19 (10g)	61,0	14,8	1,15	12,87
5	Middle	Gyttja-bearing silty CLAY	1,58	78	58	14	0,19 (10g)	73,0	14,6	1,38	10,58
6	Middle	Gyttja-bearing silty CLAY	1,51	94	63	11	0,11 (10g)	102,0	15,8	0,96	16,46
7	Middle	Gyttja-bearing silty CLAY	1,55	85	58	13	0,08 (10g)	158,0	14,9	0,46	32,39
8	Middle	Gyttja-bearing silty CLAY	1,56	81	57	14	0,08 (10g)	187	16,9	0,69	24,52

The FC sensitivity is high throughout the profile due to the low remoulded FC strength, where the 10 g cone was used. The CCT undrained shear strength shows no apparent trend. The same analysis could be said regarding the remoulded CCT strength.

5.14 Test sample K

Test sample K mainly consists of brownish grey clay and brown sandy gyttja with brown clay at the shallowest depths. The difference in soil type is also reflected in the CCT results, where remoulded shear strength at 4 m is extremely low and therefore gives a high sensitivity. This value should therefore be treated with caution in later comparison. The detailed properties are shown in table 5.14.

Table 5.14: Soil properties for sample K

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
4	Upper	Brown sandy GYTTJA	1,64	66	61	23	1,47 (60g)	15,0	27,2	0,06	453,07
6	Upper	Brown CLAY	1,54	75	53	20	1,33 (60g)	15,0	13,2	0,57	23,09
7	Upper	Brownish grey CLAY	1,51	84	74	23	1,63 (60g)	14,0	12,9	1,47	8,81
8	Upper	Brownish grey CLAY	1,51	81	85	23	1,86 (60g)	13,0	14,0	1,32	10,63
9	Upper	Brownish grey CLAY	1,53	82	83	25	1,47 (60g)	17,0	15,2	2,02	7,51
10	Upper	Brownish grey CLAY	1,53	80	87	25	2,04 (60g)	12,0	16,8	2,39	7,04

5.15 Test sample L

Sample L consists of grey-gyttja bearing clay, slightly gyttja-bearing clay and silty clay, where the soil extends from 12 to 20 m depth. Compared to the previous shallower with higher organic content, sample L shows a clearer transition towards more clay dominated material with depth. The soil properties is presented in table 5.15.

Table 5.15: Soil properties for sample L

Depth [m]	Tube	Soil Type	Density [g/cm ³]	w_n [%]	w_L [%]	$c_{u,fc}$ [kPa]	$c_{ur,fc}$ [kPa]	$S_{t,fc}$	$c_{u,cc}$ [kPa]	$c_{ur,cc}$ [kPa]	$S_{t,cc}$
12	Upper	Grey gyttja-bearing CLAY	1,49	99	77	20	0,57 (60g)	35,1	22	1,24	17,74
15	Upper	Grey slightly gyttja-bearing CLAY	1,52	94	73	21	0,57 (60g)	36,8	23	1,68	13,69
20	Upper	Grey silty CLAY	1,61	68	66	30	1,11 (60g)	27,0	29	3,10	9,34

6

Results

The following text will present the results derived for the finalized laboratory procedure regarding both remoduling capability and corresponding sensitivity, as well as the evaluation of the method for deriving rapidity.

6.1 Analysis of CCT Remoduling Capacity and Corresponding Sensitivity

The results from the finalized version of the laboratory scheme is presented below this chapter. All recorded points are included in the c_u plot, ssee figure 6.1 where soil containing sand or shells are removed from all other plots. When conducting the CCT on samples with this content, the results are often compromised. Either the wire caught and sheared larger debree during the test, causing excessive resistance, or the sandy clay which cracks throughout the test, resulting in the wire passing only through air after a few loops.

Plot 6.1 indicates that the c_u values obtained with the CCT compared to FC shows good agreement with the 1:1 line, marked in yellow showing where an ideal relationship between the tests. The R^2 value indicates how well the data points fit their respective trendline. In the c_u plot, the $R^2 \approx 0.87$ indicating a good correlation between the CCT and FC. In the c_{ur} in plot 6.2, the data is divided by FC made with the the 60°-60g cone, illustrated as dots in the plot, and the 30°-10g cone, illustrated as triangles in the plot. This division provides insight into how the CCT captures both softer and stiffer soils compared to FC. The results indicates that the CCT genreally records higher c_{ur} compared to FC where the majority of the points are found below the 1:1 line. For the 60°-60g cone the $R^2 \approx 0.1$, and for the 30°-10g cone $R^2 \approx 0.02$ indicating a low correspondence between the CCT and FC.

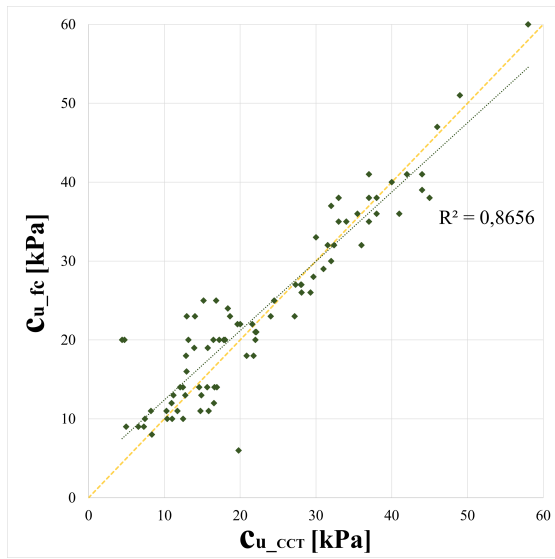


Figure 6.1: Comparison of c_u derived from CCT and FC

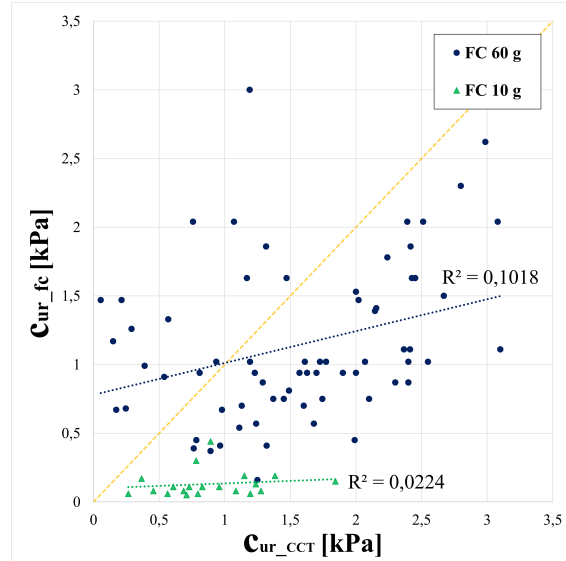


Figure 6.2: Comparison of c_{ur} derived CCT and FC

By backtracking to the theory of the FC and how it was developed and empirically calibrated to a clay. The values were filtered by soil classified as clay, see plot 6.3 and in mixed soil containing one or more of clay, gyttja or silt, see plot 6.4.

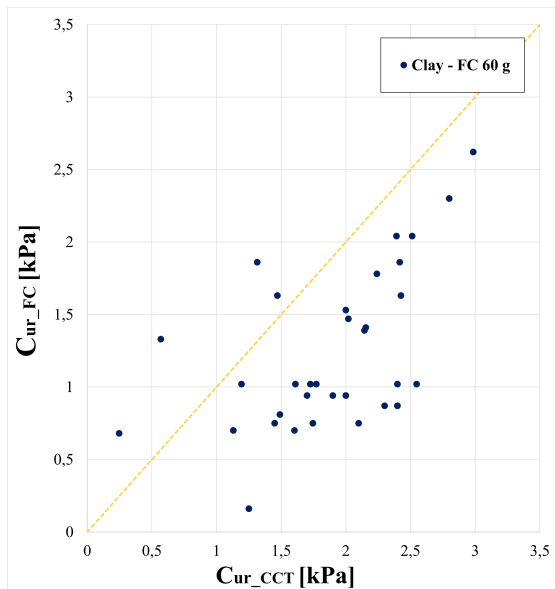


Figure 6.3: Comparison of c_{ur} derived from CCT and FC, for soil classification clay

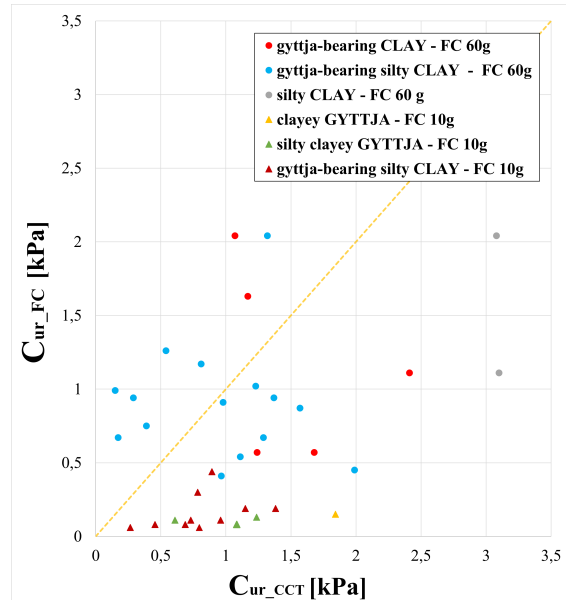


Figure 6.4: Comparison c_{ur} derived from CCT and FC, for soil classification having mixed soil content

When dividing the data according to soil characterization, the clay results are starting to form a slight linear behavior parallel to the 1:1 line, see figure 6.3. Clay containing silt or gyttja show results that are more dispersed, see figure 6.4. Values recorded by the CCT generally yielded a $c_{ur,CCT}$ higher than $c_{ur,FC}$, especially seen in the clay, in plot 6.3. The values obtained from the 10 g fall cone, used for samples with low remodulated shear strength, record a higher variability for the CCT, where the FC records a minimum value around 0.02. This would show that this remoulding procedure by CCT can not record a fully remodeled state at this low remoulded shear strength.

When plotting the sensitivity following results are derived, see plot 6.5. Here, it is prominent that the FC records the more sensitive clays at a greater extent compared to the CCT. Because of the continuous overestimation of $c_{ur,CCT}$, the result from the CCT generally underestimates the sensitivity.

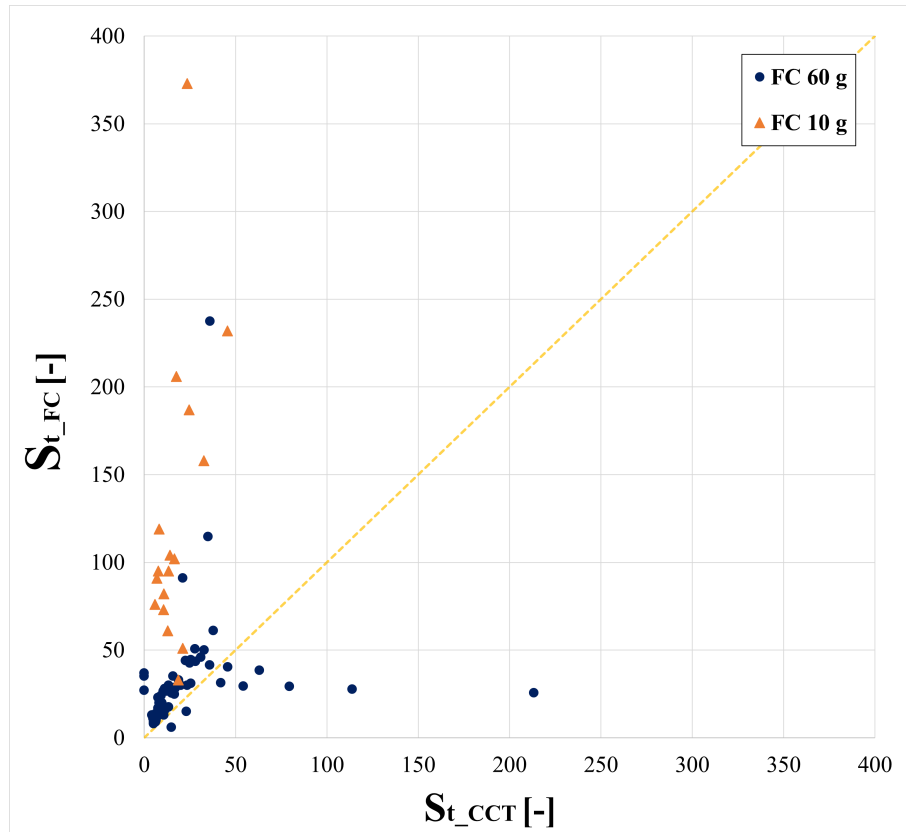


Figure 6.5: Comparison of sensitivity derived from CCT and FC, divided by 60g cone marked in dots or 10g cone marked in triangles

However, some data points are overestimating $S_{t,CCT}$, looking at Figures 6.6 and 6.7 showing a close-up of the sensitivity plot divided by soil characterization, the full size versions are found in appendixes A.4 and A.5.

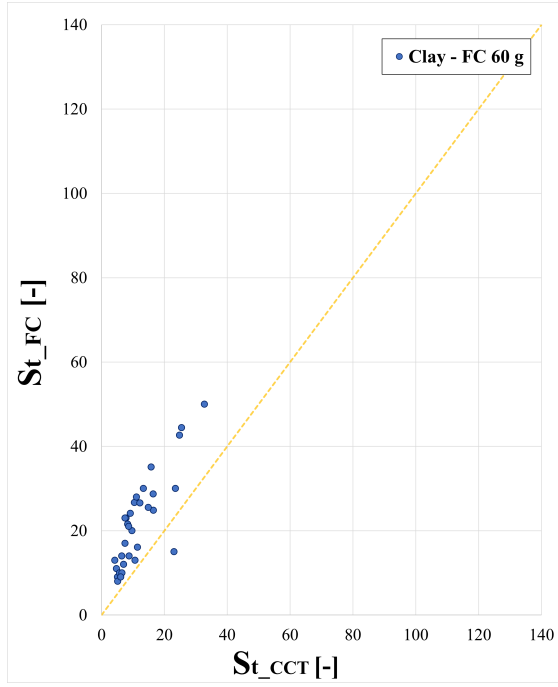


Figure 6.6: Closeup of sensitivity derived from CCT and FC for samples classified as clay

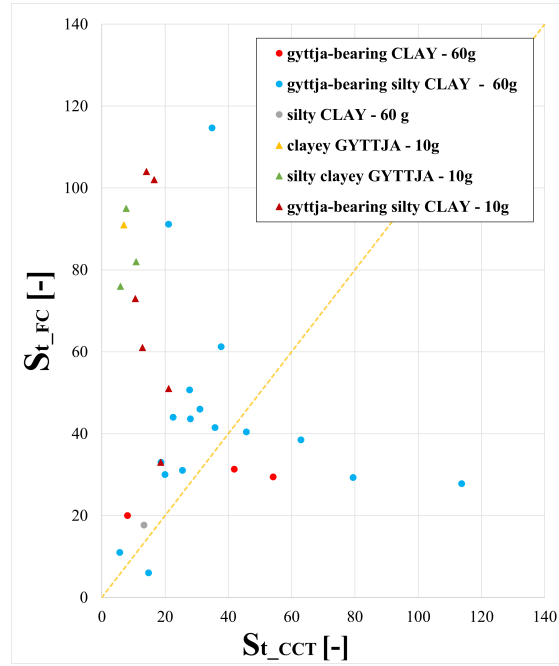


Figure 6.7: Closeup of sensitivity derived from CCT and FC for sample classified as having mixed content

In the close-up clay plot, almost all values except for two points are found above the yellow 1:1 line. In the close-up mixed soil plot the results are more scattered, but the majority of the points are found over the 1:1 line.

6.1.1 Comparison Against Index Parameter

The following plots compare how CCT and FC correspond to the quasi-index w_n/w_l . It describes how the natural water content relates to the liquid limit and how close the soil is to a flow-like state, which can be an indicator of potential structural instability. The FC plot 6.9 shows an increasing trend between sensitivity and w_n/w_l . At higher $S_{t,fc}$ values, a greater variability in w_n/w_l is observed. This indicates that while sensitive soils often have high natural water contents relative to the liquid limit, sensitivity is also affected by other factors. However, the CCT plot 6.8 does not appear to capture the same behaviour, as the $S_{t,CCT}$ data are seemingly randomly scattered across the w_n/w_l interval. This may also add to the indication that the CCT does not fully capture the structural collapse of the soil during remoulding.

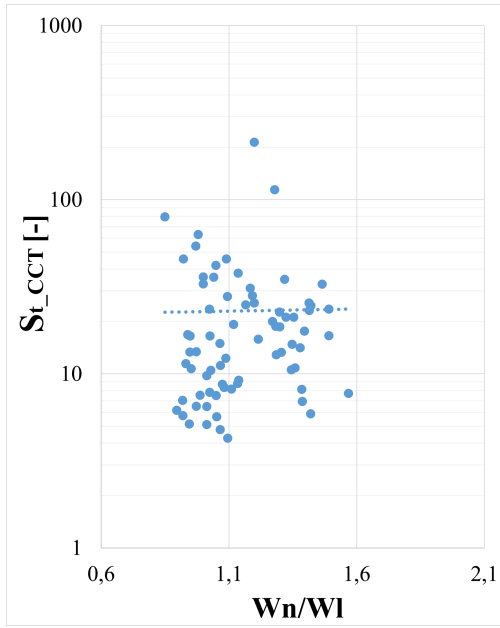


Figure 6.8: Sensitivity derived from CCT against quasi index w_n/w_l

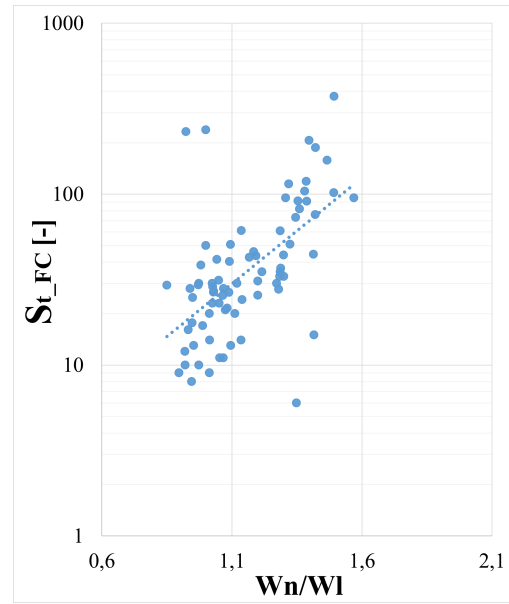


Figure 6.9: Sensitivity derived from FC against quasi index w_n/w_l

The following figures illustrate how density correlates with sensitivity for both methods. The FC results 6.11 show a weak relationship between density and sensitivity, which is reasonable as sensitivity is mainly governed by soil structural degradation rather than density. Density does not necessarily reflect the soil's structural arrangement, but generally a lower density could reflect on higher water content. The CCT results 6.10 show a slight increasing trend between sensitivity and density. This behavior is not consistent with the FC results and could therefore be method related. It may indicate that higher density affect the CCT remoulding process and limit a full structural break down in denser soils. The previous results also points toward that the CCT does not properly remould the soil, the index results further could add to this theory.

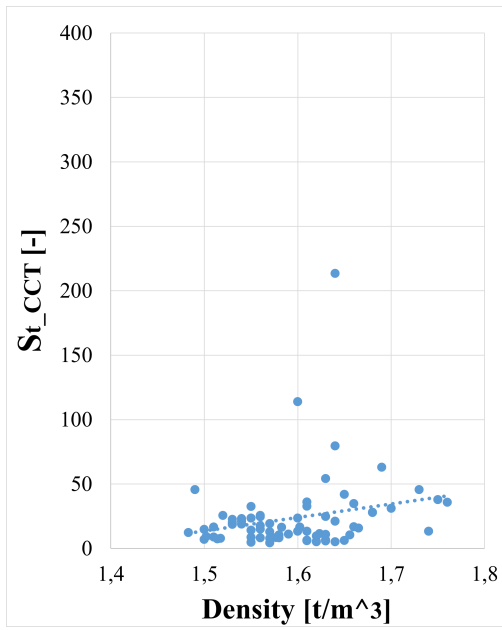


Figure 6.10: Sensitivity derived from CCT against density

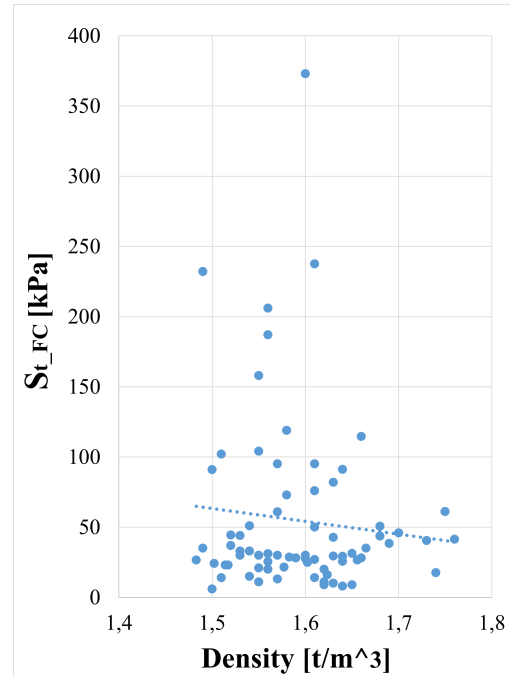


Figure 6.11: Sensitivity derived from FC against density

For both the CCT and FC methods, the results indicate a similar general trend of decreasing sensitivity with increasing natural water content, which represents the amount of water present in the soil. At lower w_n , remoulding may result in a greater relative reduction in shear strength, leading to higher sensitivity. At higher w_n the difference between undisturbed and remoulded shear strength may become less distinct, resulting in lower sensitivity. For the FC results, a slight decreasing trend is observed with a larger scatter for S_t over the same w_n . The CCT exhibits a steeper trend compared to the FC and a slight denser scatter is seen at higher values of w_n 6.12.

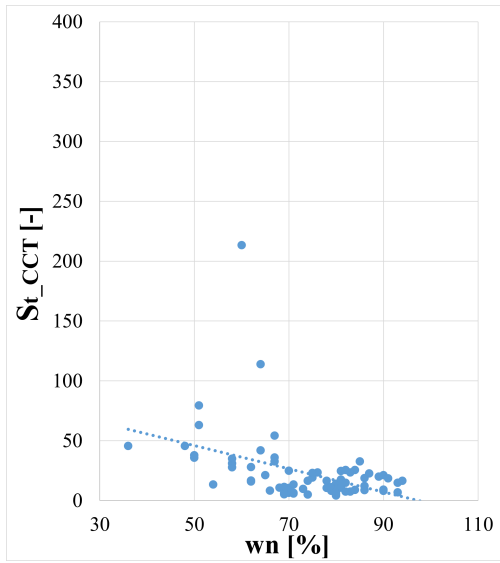


Figure 6.12: Sensitivity derived from CCT against water content w_n

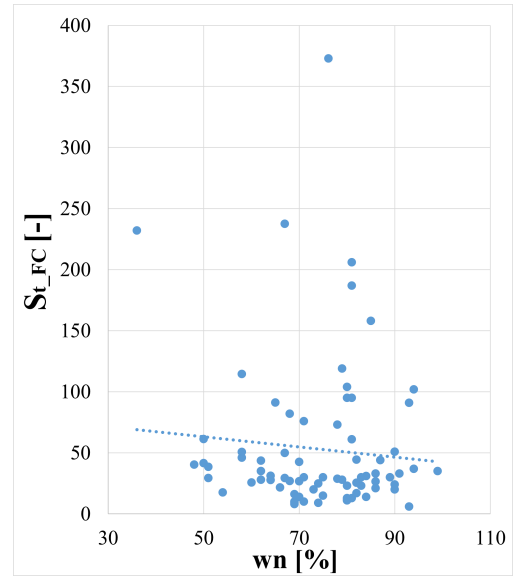


Figure 6.13: Sensitivity derived from FC against water content w_n

Both CCT and FC show a decreasing trend in sensitivity with increasing liquid limit, which represents the water content at which the soil transitions towards a liquid-like consistency and reflects the soil's plasticity. A lower w_L may indicate lower plasticity and a soil that is more influenced by structural effects. However, the relationship is generally weak, as liquid limit primarily reflects soil plasticity rather than soil structure.

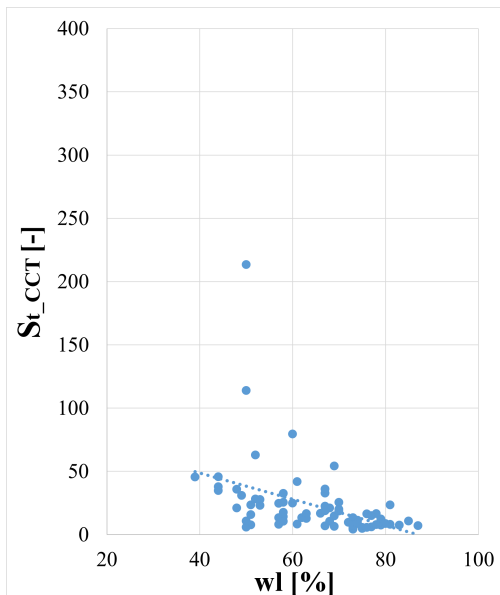


Figure 6.14: Sensitivity derived from CCT against liquid limit w_l

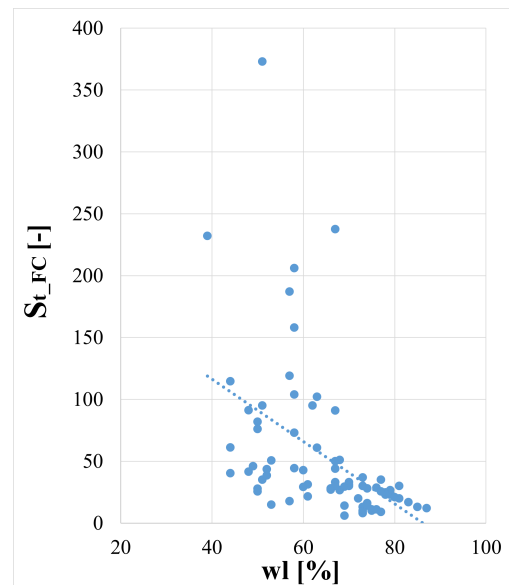


Figure 6.15: Sensitivity derived from FC against liquid limit w_l

Overall, the results suggest that the FC method provides a more consistent representation of sensitivity and its relationship with index parameters. In contrast, the CCT method shows weaker correlations, particularly for structure-related indicators such as w_n/w_L , indicating that the remoulding process may not fully capture structural collapse. Since sensitivity is dependent on the breakdown of soil structure during remoulding, incomplete structural disturbance may lead to an underestimation of the true sensitivity behaviour.

6.2 Cumulative Work and Rapidity Index Results

Based on the sensitivity analysis, the rapidity evaluation was restricted to samples classified as clay or claydominated soils, since these showed the best correspondence between CCT and FC, whereas mixed soils gave less consistent results. With the the remoulding index - cumulative work curve from the clay and clay dominated samples, the derivation of W_{95} and W_{85} and R_E could be done. Furthermore, 10 out of 32 clay samples were excluded from the analysis due to insufficient loop data, meaning a reliable interpolation of W_{95} , W_{85} could not have been calculated. The results are presented in table 6.1

Table 6.1: Calculated values of W_{85} , W_{95} and rapidity index R_E .

Sample	Tube	Depth [m]	W_{85} [J]	W_{95} [J]	R_E [-]
A1	Upper	5	8,17	19,58	2,40
A1	Upper	8	15,04	32,41	2,16
A2	Lower	4	17,49	34,79	1,99
A2	Lower	5	14,51	34,33	2,37
A2	Lower	6	12,41	30,56	2,46
A2	Lower	8	10,26	28,26	2,75
A2	Lower	10	9,48	29,49	3,11
B2	Upper	4	18,98	32,09	1,69
B2	Upper	6	17,32	29,44	1,70
B2	Upper	10	14,57	32,18	2,21
B2	Upper	12	15,48	36,49	2,36
B2	Upper	14	14,78	32,50	2,20
B2	Upper	20	17,32	39,71	2,29
K	Upper	6	4,74	8,16	1,72
K	Upper	7	10,26	19,51	1,90
K	Upper	8	13,48	32,31	2,40
K	Upper	9	20,63	37,30	1,81
K	Upper	10	14,42	30,39	2,11
C2	Lower	3	13,24	28,80	2,18
C2	Middle	4	13,31	26,43	1,99
C2	Middle	6	11,93	26,26	2,20
C2	Lower	8	8,78	18,92	2,15

Overall, the results show that the selected clay soil samples display a clear variation in both remoulding energy and rapidity index. While W_{95} reflects the cumulative

work required to approach a near fully remoulded state, the ratio R_E indicates in how rapidly the remoulding process develops between 85% and 95% remoulding. The results therefore point towards that sample with similar remoulding energy may still differ in terms of rapidity index.

6.2.1 Comparison Between Cumulative Work at 95% Remoulding W_{95} Against Geotechnical Parameters

The following chapter will present the correlation between W_{95} and remoulded shear strength and sensitivity for fall cone and CCT respectively, as well as density and quasi index w_n/w_l .

Figure 6.16 and figure 6.17 illustrate the comparison between W_{95} and remoulded shear strength for CCT and fall cone test. Both figures show a positive trend. The relation between W_{95} and CCT show a correlation of 0,581, whereas the relationship between W_{95} and fall cone is 0,254.

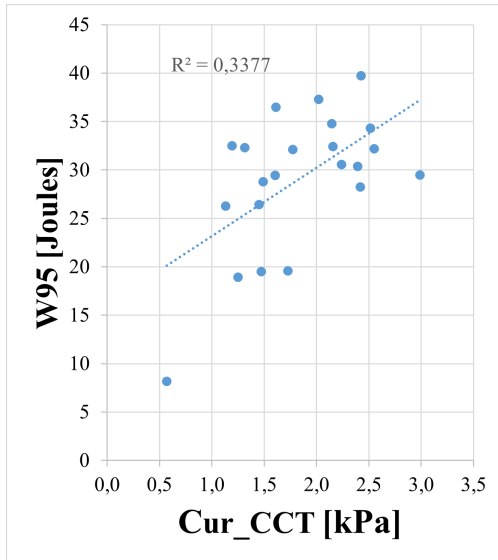


Figure 6.16: Comparison between W_{95} and C_{ur} derived from CCT

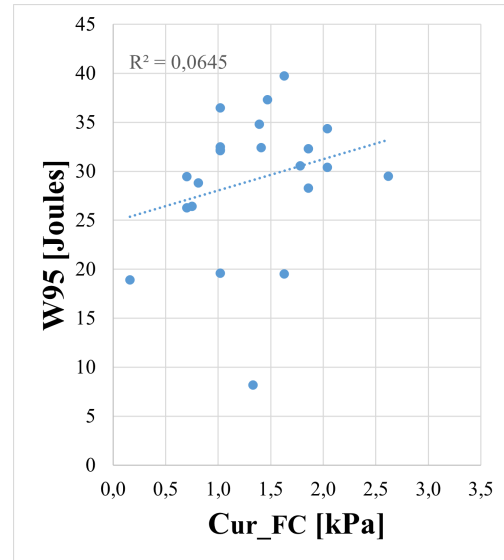


Figure 6.17: Comparison between W_{95} and C_{ur} derived from FC

The relationship between W_{95} and sensitivity for CCT and fall cone is illustrated in figure 6.18 and figure 6.19. Both figures show a weak negative trend, the stronger relation can be observed for the CCT where the correlation is -0,389. In contrast, the correlation between the fall cone is -0,296.

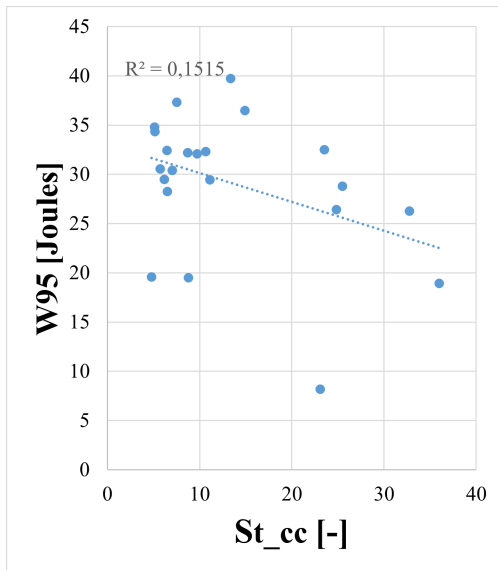


Figure 6.18: Comparison between W_{95} and sensitivity derived from CCT

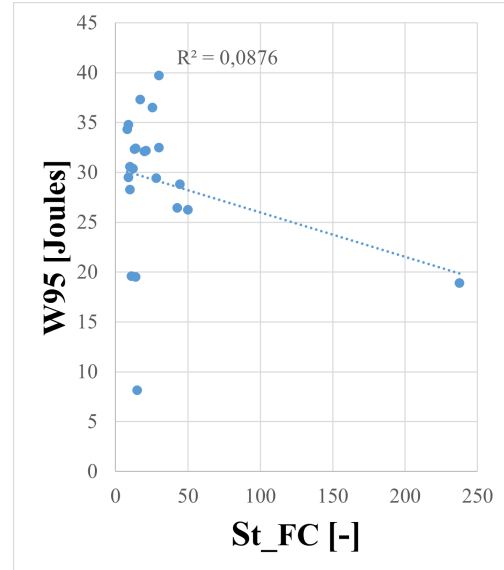


Figure 6.19: Comparison between W_{95} and sensitivity derived from fall cone

Figure 6.20 presents the correlation between W_{95} and density. The results show a weak positive trend with a correlation coefficient of 0,182.

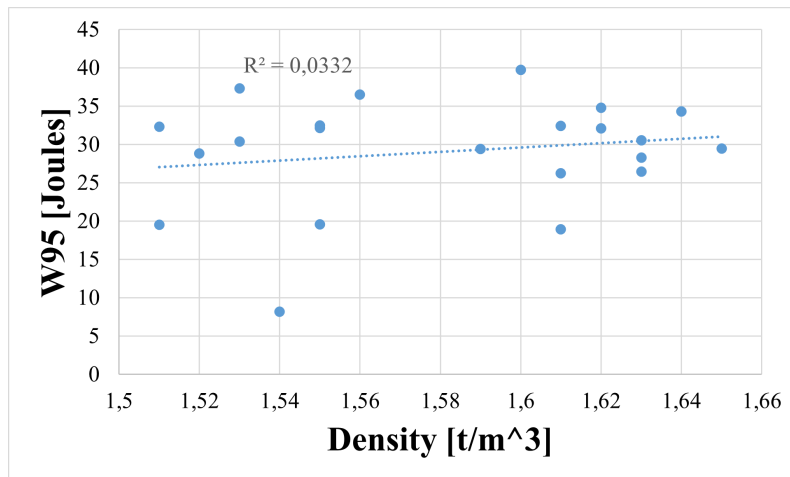


Figure 6.20: Comparison between W_{95} and density

The relationship between W_{95} and the quasi-index is shown in figure 6.21. A relatively strong negative correlation was observed with a coefficient of -0,752. Which suggests that samples with higher natural water content relative to their liquid limit generally requires less cumulative work to reach near fully remoulding.

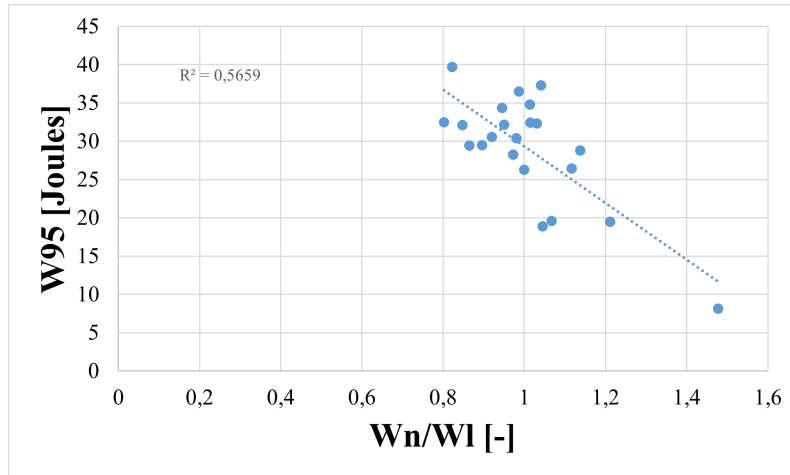


Figure 6.21: Comparison between W_{95} and quasi-index, W_n/W_l

6.2.2 Comparison Between Rapidity Index Against Geotechnical Parameters

The rapidity index, R_E , for each clay sample was compared to selected geotechnical parameters using Pearson's correlation coefficient R . This chapter presents the relations between R_E and the undrained shear strength, remoulded shear strength and sensitivity for both the fall cone and CCT. Additionally, the density and quasi-index is also compared.

Figure 6.22 and figure 6.23 present the relationship between the rapidity index R_E and remoulded shear strength obtained from the CCT and fall cone. In both cases, a positive trend can be observed. The comparison with CCT resulted in a correlation of 0,538 while the comparison with fall cone gave 0,529. The results indicate a moderate positive relationship, suggesting that samples with higher remoulding strength often yield higher R_E .

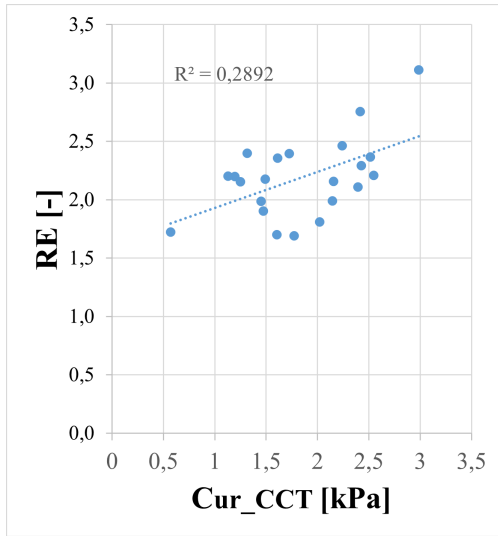


Figure 6.22: Comparison between RE and remoulded shear strength for CCT

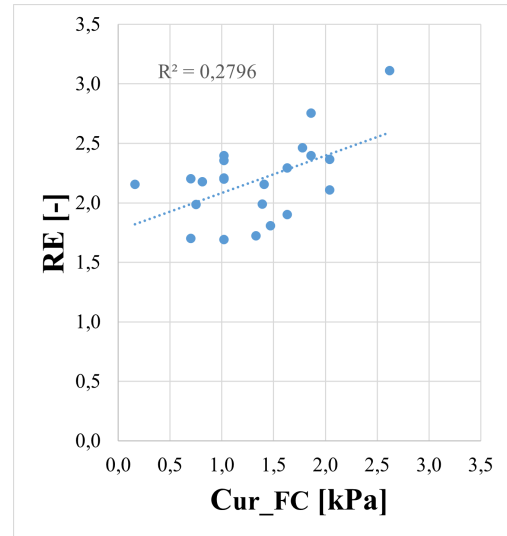


Figure 6.23: Comparison between RE and remoulded shear strength for FC

Figure 6.24 and figure 6.25 show the comparison between the rapidity index R_E and sensitivity derived from the CCT and fall cone test. The fitted trend line indicate a weak negative relation between R_E and sensitivity for respective method. For sensitivity from CCT, the correlation is -0,217 and for fall cone, -0,087. One sample deviates from the rest and if being removed, the correlation between fall cone sensitivity and R_E is -0,252.

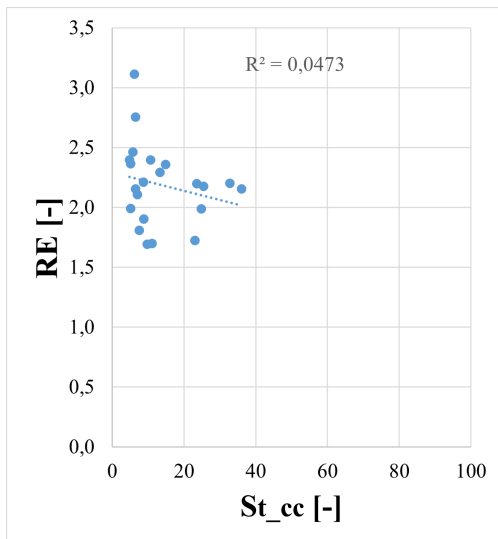


Figure 6.24: Comparison between RE and sensitivity derived from CCT

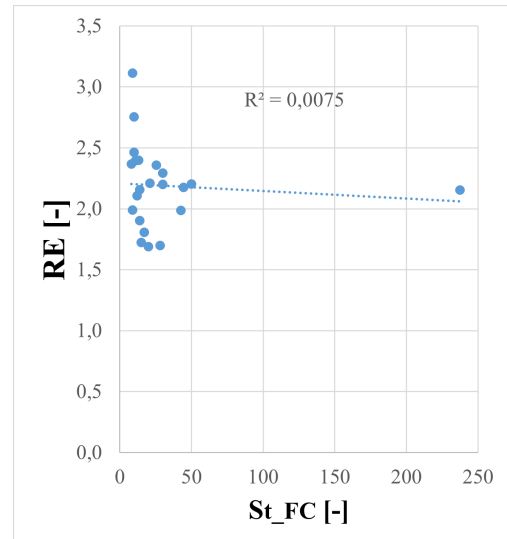


Figure 6.25: Comparison between RE and sensitivity derived from FC

Figure 6.26 illustrates the correlation between rapidity index R_E and density. A weak positive trend was observed with a correlation of 0,338.

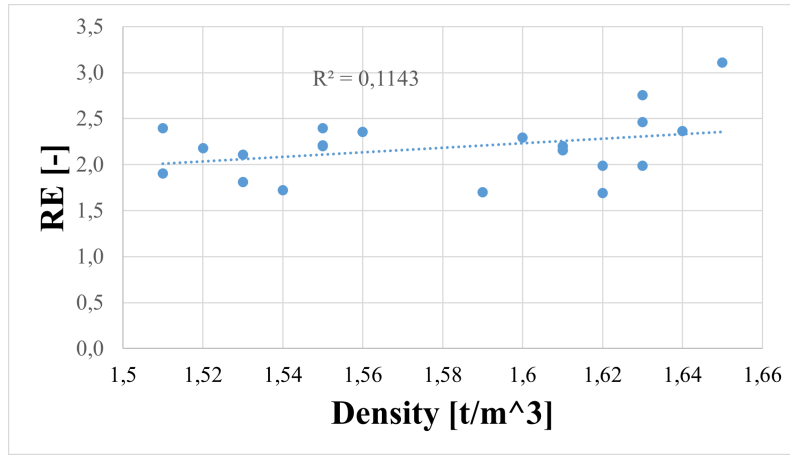


Figure 6.26: Comparison between RE and density

The relation between rapidity index R_E and the quasi-index is presented in figure 6.27. The fitted trendline indicates a weak negative correlation of -0,317.

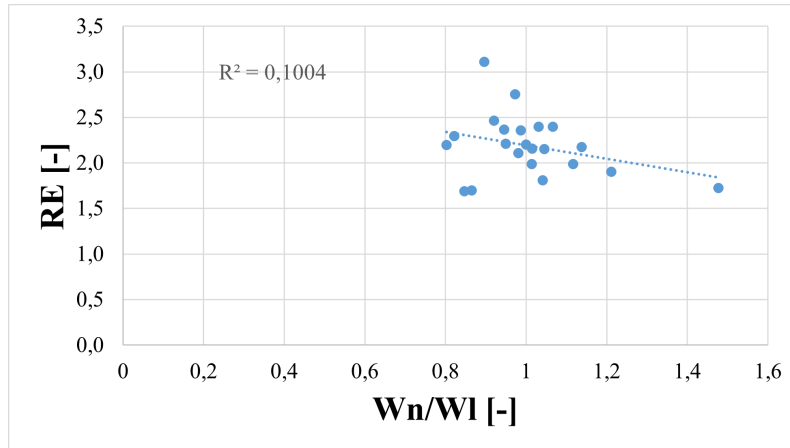


Figure 6.27: Comparison between RE and quasi-index, Wn/Wl

6.3 Results for Kaolin Clay of the Remoulding Processes

Table 6.2 presents the FC and CCT results for the silty kaolin clay and clayey kaolin clay as well as their respective loading process. Each sample was cut three times with the CCT, whereas the last cut included the remoulding process. Between each cut, a loss of shear strength is noted. This indicates disturbances in the sample with repeated cutting.

For the silty kaolin, the highest $c_{u,cc}$ values were obtained at a consolidated water content of 57% and a horizontal pressure of 275 kPa. In this specific test, the peak values decreased between each cut, from 47,17 kPa to 39,70 kPa.

Table 6.2: Results summary of CCT and FC for the kaolin tests.

Type of Kaolin	Type of experiment	Mixed w_n [%]	Consolidated w_n [%]	Days	Vertical pressure [kPa]	Cut	Peak $c_{u,cc}$ [kPa]	$c_{u,fc}$ [kPa]
Silty Kaolin	Manual loading	60	57	10	275	1	47,17	40,58
						2	44,14	
						3	39,79	
		70	49	5	155	1	17,53	23,94
						2	17,34	
						3	16,83	
		70	49	10	135	4	16,70	25,51
						1	25,80	
						2	23,89	
		70	49	10	165	3	20,67	22,18
						1	16,99	
						2	15,91	
Clayey Kaolin	Incremental loading	Unknown	26	15	155	3	15,08	18,15
						1	21,75	
						2	19,75	
						3	19,43	
						4	18,75	

For the silty kaolin samples with 49% consolidated water content, the CCT peak strength $c_{u,cc}$ doesn't show a clear increase with increasing vertical pressure or number of days the sample has been exposed to the pressure. The test with 135 kPa vertical pressure gave higher peak values than the tests with 155 kPa and 165 kPa. The FC tests gave a similar response, where not definite trend could be observed.

Overall, the results show that the FC and CCT values are in a similar range, but does not match entirely for each test condition. For the clayey kaolin with a 26% consolidated w_n and that was incrementally loaded, gave a lower and more stable peak $c_{u,cc}$ value compared to the previously mentioned silty kaolin sample. The peak strength decreases from 21,75 kPa to 18,75 kPa in the fourth cut with a fall cone value of 18,15 kPa.

Figure 6.28 presents the result from a remoulded CCT of the silty kaolin with 70% water content compacted under 10 days with a horizontal pressure of 165 kPa. For the silty kaolin, the CCT remoulded process indicates that the thread lost contact with the sample already after the first downward movement. After the initial peak, the measured resistance drops to around zero, indicating that the thread had created an open path, or cavity. This could be observed during the test. Similar remoulding response were observed for the rest of the silty kaolin.

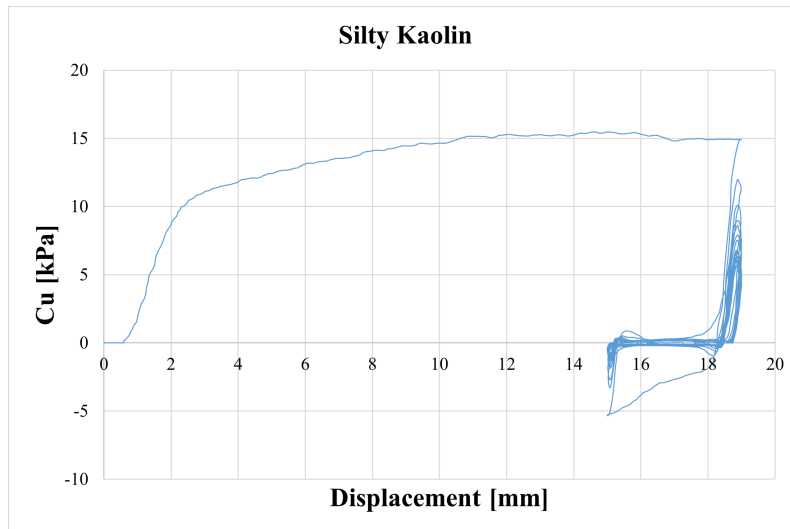


Figure 6.28: Remoulded CCT process for silty kaolin with 70% water content

For the clayey kaolin, the CCT results differs from the silty kaolin by maintaining some measurable resistance during the remoulding process, which is presented in figure 6.29. During the first upwards movement, the measured resistance reaches approximately 11 kPa. However, the following loops do not reach the same resistance level and decreases drastically afterwards. This could suggest that the thread initially remained in contact with the soil, but the repeated cycling gradually created a path with reduced contact. The remoulding performed using the FC showed no change in shear strength, as the same value was recorded for both the consolidated and remoulded states which yielded 16 kPa.

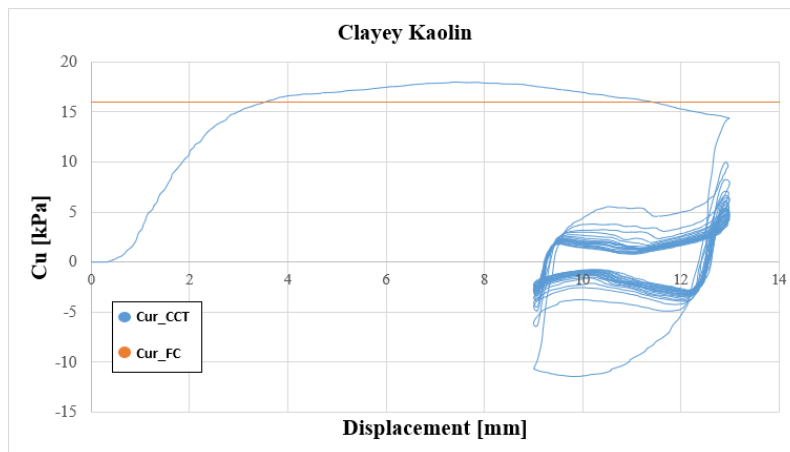


Figure 6.29: Remoulded CCT for clayey kaolin with 70% water content

7

Discussion

7.1 The Possibility of Deriving Sensitivity from the CCT

The results obtained from comparisons of FC and CCT remoulded shear strength, sensitivity, and index parameters suggest that the CCT may not fully remould the sample, thus leaving a remaining structural contribution in the measured resistance. When conducting the remoulding by CCT, it is not fully clear what mechanism is being recorded and to what extent. By the CCT remoulding, the degradation of the soil structure is likely less extensive than during the global remoulding performed manually in the FC method. The CCT measurement represents a local response based on a small tested volume, whereas the FC test represents a globally remoulded and fully mixed sample. Consequently, the volume affected by remoulding differs between the methods. As the wire only interacts with a narrow local zone of the sample, small heterogeneities in particle composition or structure may disproportionately influence the measured c_{ur} . This behaviour appears particularly evident in soils containing silt or organic material, where the results are considerably more scattered than in more homogeneous clay samples. The varying degree of remoulding between samples suggests that the CCT wire response is partly material-dependent, especially in soils containing coarser fractions or heterogeneous components.

However, when observing the c_{ur} divided by soil type, a slight trend is starting to develop for the clay, which is marked as an orange line in plot 7.1. This parallel displacement could also support the theory that the soil is not fully remoulded during the CCT procedure. It further adds to the indication that heterogeneity of the soil might contribute to a source of uncertainty in the yielded results.

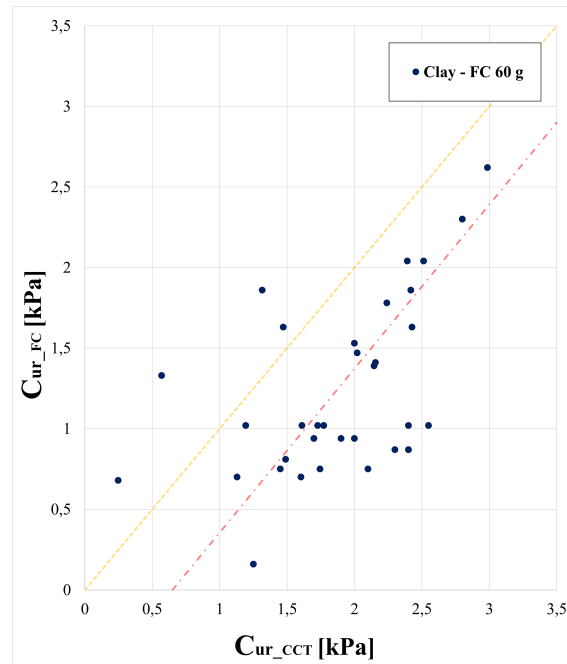


Figure 7.1: Potential trend forming for c_{ur} in clay

The tendency towards a linear behaviour that is observed in the clay, which is comparatively more homogeneous than the mixed soil, may indicate that the remoulding process has some degree of reproducibility. The observation that the CCT better corresponds to the soil classification clay is conditional on the use of the 60°-60g cone. Based on this, the method could potentially be calibrated or modified to approach a more fully remoulded state. The improved agreement observed for clay samples may possibly be related to how the FC method was originally developed and empirically calibrated for relatively homogeneous Swedish inorganic clays within specific consistency ranges. These soils could therefore better satisfy the assumptions underlying both FC and the remoulding behaviour observed in the CCT.

In contrast, soils containing silt, gyttja or organic material seem to exhibit more complex mechanical behavior and greater structural heterogeneity, resulting in increased scatter between the methods. Soils that exhibit expectational high sensitivity are the ones with mixed content. When comparing the CCT remoulding method against the 30°-10g cone, the CCT does not capture low c_{ur} . However, there are some uncertainties associated with the FC test when applied to highly sensitive clay, partly because it starts to fall outside the empirically derived domain and partly due to operational bias, as momentary values are more difficult to capture in very soft soils. Perhaps, the CCT remoulding process could be improved by adjusting it to soil properties, similar to the use of different cones in the FC test.

A phenomenon noticed during the laboratory process is that clay containing larger

particles, for example sand, tend to indicate an almost zero value. A theory is that these types of soil become mouldable, creating a cavity in the sample during the remodelling process and subsequently artificially increasing the sensitivity. This could possibly be further supported by the remoulding results for the silty kaolin compared to the clayey kaolin, where the CCT could not read the values of the silty kaolin due to the development of a cavity. Another theory regarding the remoulding by CCT is that the wire records a type of polishing effect rather than a fully remoulded shear strength. Along the work it has been noticed that different soil types appear to exhibit different degrees of polishing when looking at the cut. Stiffer soils seem to develop smoother surfaces during the remoulding interval thus not recording a fully remoulded state.

As the $c_{ur,fc}$ values along with the index parameters were collected from tests performed approximately six months earlier. A source of uncertainty is in the comparison between the data, which could cause outliers in the data points. However, this cannot be confirmed or denied retrospectively. Additional uncertainty arises from the compared values not originating from the same part of the soil sample. Due to limited available material, values from the middle tube were sometimes compared with values from the upper or lower tubes, where natural soil variability may have influenced the results. Additionally, the visual soil classification used in the data processing was based on a previous data hence a different material. Meaning that soils classified as for example silty clay have been sorted as such in this report, but might not correspond to the material tested by CCT. Furthermore, several CCT samples collected from middle tubes were only partly filled. Such samples allow greater swelling during storage, increasing the risk of storage-related disturbance effects.

7.2 Interpretation of W_{95} and The Rapidity Index R_E

The moderate positive correlation of 0,581 in figure 6.16 between W_{95} and remoulded shear strength $c_{ur,cct}$ for CCT indicate soils that achieves a higher c_{ur} during the remoulding process often requires more energy input to reach a near fully remoulded state. However, the results could be misleading and should be analyzed with caution, due to W_{95} being derived from $c_{ur,cct}$, meaning both parameters are not fully independent from each other. A more non biased correlation is achieved when comparing W_{95} and remoulded shear strength for fall cone $c_{ur,fc}$, with a positive correlation of 0,254, detailed in figure 6.17. A weaker trend compared to the CCT but more representative due to the independent factor between the two parameters.

The comparison between W_{95} and sensitivity for both methods, which is presented in figure 6.18 and figure 6.19. The trend pointed towards a weak negative correlation for the CCT and FC, yielding -0,389 and -0,296, respectively. The same conclusion can

be drawn that the sensitivity derived from the CCT has a stronger correlation due to not being fully independent from W_{95} . Nonetheless, for both method, the weak negative correlation suggests that the remoulding energy does not entirely describe the sensitivity in a soil. As multiple soil samples have the same sensitivity but requires a varying amount of energy input to reach near fully remoulding. Similar findings were reported by Berghel and Hagrydh (2023), who observed a negative correlation between remoulding energy and sensitivity derived from the vane shear test. An important note is that the vane shear test and the CCT do not apply remoulding work in the same way, and the resulting energy measures should therefore not be interpreted as equivalents. As mentioned earlier, CCT only disturbs the soil in a small area relative to the sample size, so the measurement is more localized. Whereas, vane shear test remoulds at a larger soil volume and gives more of a global response.

Figure 6.20 illustrates a weak positive relation between W_{95} and density, yielding a correlation of 0,182. Although the trend direction is consistent with the assumption that denser and stiffer soil should generate greater resistance during the CCT and thereby increasing the cumulative work, the observed correlation is very low. This suggest that density alone can not explain the variation in W_{95} . Nevertheless, the low correlation between the two parameters indicate that density does not appear to be a major controlling factor for W_{95} .

The strong negative correlation of -0,752 between W_{95} and quasi-index, shown in figure 6.21, points toward that sample with higher water content relative to their liquid limit generally requires less cumulative work to reach W_{95} . A possible explanation is that soils close to their liquid limit have a softer consistency and therefore offer less resistance during the remoulding process.

When analyzing the comparison between R_E and remoulded shear strength for CCT and FC, the correlation showed a moderate positive trend, 0,538 and 0,529 respectively. The similarity in R value implies that the result is not restricted to a single test method, instead it might reflect an underlying relationship between R_E and $C_{ur,CCT}$. A possible explanation is that soils with higher remoulded shear strength retain a greater resistance, even after substantial remoulding, and therefore requires additional work to reach 95% remoulding from 85%.

Furthermore, the correlation, -0,217 in figure 6.24 and -0,087 in figure 6.25 for CCT and FC respectively, between sensitivity and R_E showed a poor negative trend line. For CCT, the method yielded a higher correlation, however the result might be skewed for the better due to the biased nature between the two parameters CCT sensitivity and R_E . Therefore, a more unbiased result is the comparison between FC sensitivity and R_E , which resulted a much lower correlation. An important note is

that one sample deviates from the others, which distorts the results enormously and an exclusion of that sample yields a correlation of -0,251. Nevertheless, similar to W_{95} , the weak relation between the two parameters implicate that sensitivity does not fully explain the energy that is requires to go from 85% remoulding to 95%.

This can further be supported with previous findings according to Dehlbom and Lundström (2020). The authors state that there is no certain correlation between brittleness and sensitivity. In this context, brittleness describes how rapidly the shear strength decreases after peak shear strength has been reached, whereas rapidity refers more generally to how the remoulding process develops with continued disturbance on soil. Although brittleness and R_E are not identical, both conclusions point toward that degradation behavior can not be explained by sensitivity alone.

Following the weak correlation observed between R_E and sensitivity, the relation between R_E and density also show a similar weak correlation. Figure 6.26 yielded a weak positive correlation of 0,338, implying denser soil might require more work to reach near fully remoulding starting at 85% remoulding. A possible explanation for the weak positive trend is that denser soils may have a more compact structure and therefore retain slightly greater resistance. Even though, the results show some kind of correlation, additional tests need to be conducted to draw a conclusive conclusion.

Similarly to the relationship observed between W_{95} and quasi-index, R_E also showed a negative trend. However, the correlation is much weaker, with a value of -0,317, suggesting that the quasi index has less impact on the rapidity index than on the cumulative work required to reach 95% remoulding.

7.3 Kaolin response to remoulding process

The results in table 6.2 showed that developing a kaolin clay recipe suitable for evaluating the remoulding process was difficult. The tested mixtures did not produce a sufficiently consistent response between CCT and FC, which suggests that the preparation procedure had a large influence on the material behavior. This implies that the challenge was not only in the kaolin itself, but also due to several other factors such as the consolidation time, W_n , how the material was mixed and amount of applied vertical pressure. When increasing W_n for the silty kaolin, there were no change in FC remoulded behaviour since the shear strength before and after remouldin remained the same. For a kaolin with higher clay content the CCT gave results, but the FC remoulded shear strength did not differ from the original shear strength.

As the kaolin clay is a man-made material, it is possible that the interparticular bonds broke when remoulding natural clay samples had not been formed. Another

theory is that the ceramic clay is created to be possible to remould multiple times while keeping its properties. Otherwise, it would not be possible to create anything with the clay if it lost its strength when working with it. Hence, when developing kaolin mixtures for geotechnical purposes, some form of addition to the mixture may be required to create interparticle bonding that more closely resembles natural clay and enables remoulding.

8

Conclusion

The results indicate that the CCT results using this laboratory scheme cannot reliably reproduce the fully remoulded shear strength required for sensitivity determination according to the conventional fall cone method. A major uncertainty remains regarding what mechanical response the wire actually measures during the remoulding process. The observations suggest that the CCT may primarily induce a local disturbance rather than a complete global remoulding of the sample volume. Furthermore, indications of a polishing effect were observed after CCT remoulding. Visual inspection after testing suggested that the degree of polishing varied between soil types, implying that the phenomenon may be material dependent. However, this was not systematically investigated within the of this study.

Nonetheless, a tendency towards a more approximately linear behaviour was observed for comparatively homogeneous clay, particularly when evaluated using the 60°–60 g cone. This suggests that the CCT remoulding process may exhibit a degree of reproducibility under certain soil conditions, which also to some extent reflect on the FC limitations. Due to several uncertainties related to sample heterogeneity, storage disturbance, visual soil classification, and differences in tested material volumes, the results should be interpreted as a more general trend. Hence, it is not possible to draw a definite conclusion from these results. Further studies using controlled sampling procedures and preferably homogeneous soil materials are required to evaluate whether the CCT can be developed into a reliable method for sensitivity assessment in comparison with the FC. Nonetheless, the subtle trend observed in the clay results makes the CCT remoulding approach interesting for further investigation, as it may lead to methodological refinements and contribute to the identification and understanding of underlying relationships.

The rapidity analysis by comparing the energy required to reach 95% remoulding W_{95} and rapidity index R_E to multiple index parameters, showed less convincing results. Even though, majority of the comparisons showed promising results and

could be supported with previous findings, the uncertainty in CCT when capturing the remoulded process makes the rapidity concept fall flat. Since the method could not reliably create a fully remoulded state and be comparable to FC, the derived work and rapidity based parameters can not yet be regarded as robust enough. In addition, the rapidity analysis was only performed on clay sample which highlight the limitation with the current CCT framework and the findings does not represent all soil types.

Nevertheless, the results suggest that the rapidity approach has potential for further development. The fact that W_{95} and R_E showed some degree of correlation, although not fully convincing, with some geotechnical parameters which implies that the CCT may capture meaningful aspects of the remoulding process, at least for clay samples. Therefore, the results does provide a base line for further refinement of the method.

Even if the CCT remoduling preoces from this investigation may not yet be fully suitable as a direct method for sensitivity determination, the recording process itself still shows considerable potential. The continuous measurements obtained during the test describe how the shear resistance evolves throughout the remoulding process, rather than only providing a single remoulded value. Such information may provide a more detailed representation of the remoulding process than sensitivity alone, as sensitivity is ultimately a relatively simplified index parameter based only on the ratio between undisturbed and remoulded shear strength.

As for the kaolin clay, even though the study did not result in a final reference recipe, the results still helped identify important limitations when trying to create a reference clay.

8.1 Further Work

Since the remoulding process in the CCT is beginning to show a developing trend under more homogeneous soil conditions, it would be interesting to further investigate the remoulding process by CCT. As homogeneous clay appears to show the best agreement with the 60°–60 g cone, the 30°–10 g cone may need to be treated differently within the testing procedure. This may indicate that different soil types exhibit different response to this type of remoulding, which could potentially be taken into account through separate methodological considerations or adjustments. Since rapidity is based on the assumption that the remoulding process is successful, a true rapidity assessment is not obtained until this is achieved.

A further assessment is to compare the CCT remoulding prosses to more methods, such as laboratoy vane, T-bar or Ball test. Potentially, the CCT as a reference against itself by runnig a standard test in a previously remoulded sample e.g.

mixing it by hand. However, by this method the soil thixotropy should be carefully considered.

The observed polishing effect is also interesting to investigate more systematically in future studies. During the laboratory work, it was observed that samples with different visual appearances could still belong to the same soil classification, while seemingly similar soils, particularly clays containing silt or organic material, could generate different remoulding responses. Variations in surface “glossiness” after remoulding were also noted, potentially reflecting differences in soil composition and structure. Furthermore, the remoulding curves obtained during the CCT procedure showed distinct shapes for different materials, which may contribute to future material characterization or soil classification.

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A

Appendices

A.1 Incremental Loading (IL) Results - Axial Strain Over Time for Kaolin Clay

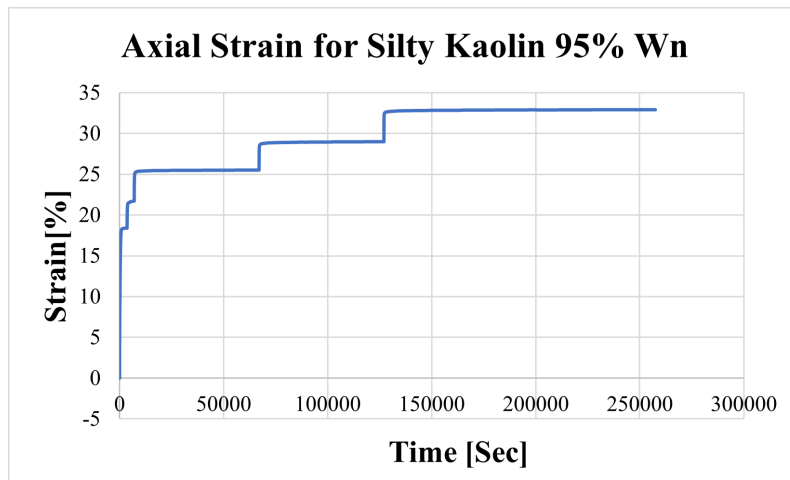


Figure A.1: Axial Strain from incremental loading under 3 days for Silty Kaolin clay with 95% mixed W_n

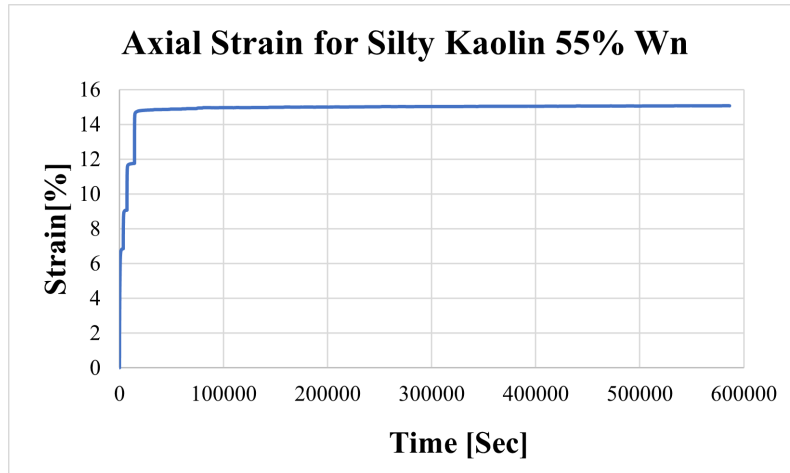


Figure A.2: Axial Strain from incremental loading under 7 days for Silty Kaolin clay with 55% mixed W_n

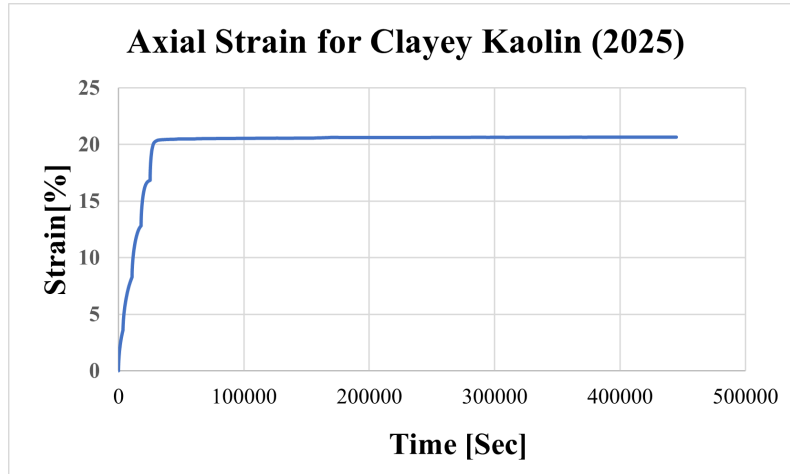


Figure A.3: Axial Strain from incremental loading under 5 days for Clayey Kaolin 2025, unknown W_n

A.2 Sensitivity Plot Divided by Soil Classification

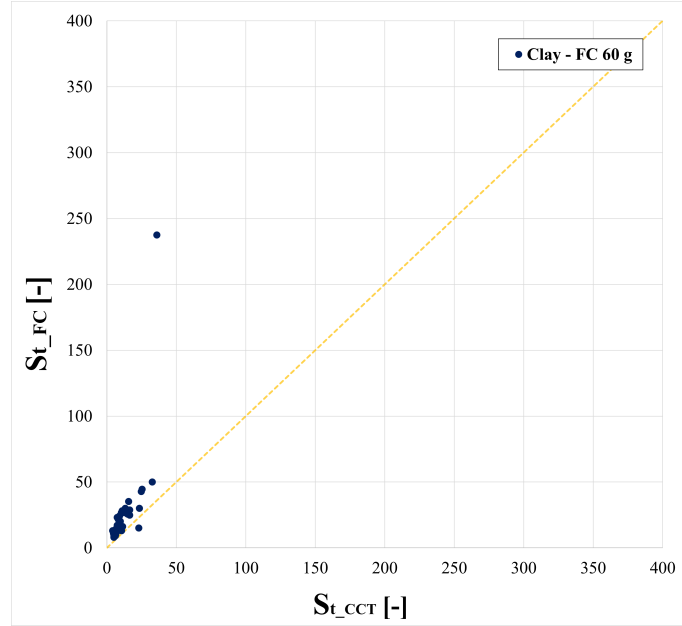


Figure A.4: Axial Strain from incremental loading for Silty Kaolin clay with 55% mixed W_n

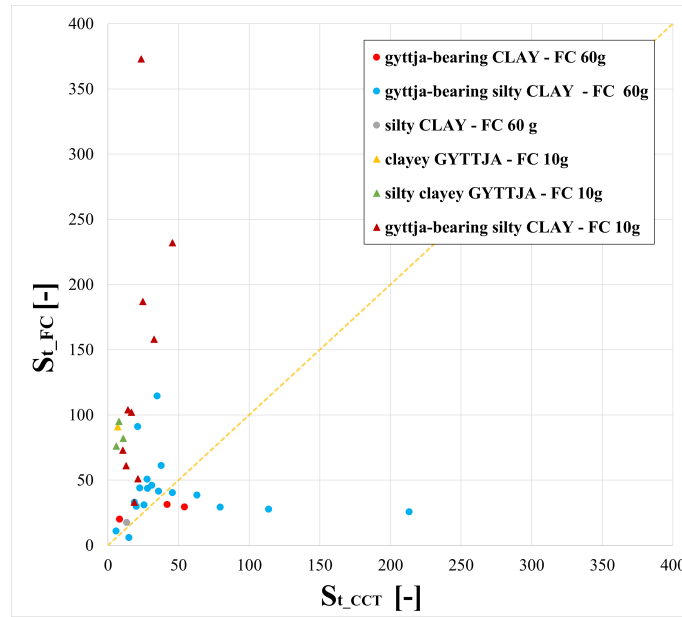


Figure A.5: Axial Strain from incremental loading for Silty Kaolin clay with 55% mixed W_n

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