



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# The Energy Needed to Completely Break Down Shear Strength in SW Swedish Clay

Utilizing field vane test for determining remoulding energy

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

**MAGDALENA BERGHEL**

**SANNE HAGRYDH**

**DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING**

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023

[www.chalmers.se](http://www.chalmers.se)



MASTER'S THESIS 2023

# The Energy Needed to Completely Break Down Shear Strength in SW Swedish Clay

Utilizing field vane test for determining remoulding energy

MAGDALENA BERGHEL  
SANNE HAGRYDH



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY

Department of Architecture and Civil Engineering  
*Division of Geology and Geotechnics*  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2023

The Energy Needed to Completely Break Down  
Shear Strength in SW Swedish Clay  
Utilizing field vane test for determining remoulding energy  
MAGDALENA BERGHEL  
SANNE HAGRYDH

© MAGDALENA BERGHEL & SANNE HAGRYDH, 2023.

Supervisor: Martin Persson, Norconsult and the Department of Earth Sciences at  
the University of Gothenburg  
Examiner: Mats Karlsson, Chalmers University of Technology

Master's Thesis 2023  
Department of Architecture and Civil Engineering  
Division of Geology and Geotechnics  
Chalmers University of Technology  
SE-412 96 Gothenburg  
Telephone +46 31 772 1000

Cover: Left picture, drilling rig in Gothenburg. Right picture, vane used for field  
vane test. Pictures taken by the authors.

Typeset in L<sup>A</sup>T<sub>E</sub>X  
Printed by Chalmers Reproservice  
Gothenburg, Sweden 2023

The Energy Needed to Completely Break Down  
Shear Strength in SW Swedish Clay  
Utilizing field vane test for determining remoulding energy  
Magdalena Berghel  
Sanne Hagrydh  
Department of Architecture and Civil Engineering  
Chalmers University of Technology

## **Abstract**

Southwestern Sweden is an area which is prone to landslides due to sensitive clay. Several notable landslides have been recorded in the region, including the Surte landslide in 1950 and subsequent events in Göta, Tuve, Småröd, and Lökeberg. Clays with high sensitivity are sensitive to vibrations and disturbances, which could lead to a collapse of the microstructure and thus liquefaction. However, sensitivity alone does not provide a complete understanding of the risks of clay liquefaction and therefore development of the parameter is needed. The remoulding energy required to fully break down clay shear strength is a potentially important parameter, and further research is needed, particularly for Swedish-sensitive clay due to a gap in the research. Overall, this investigation addresses the need for a comprehensive understanding of clay behaviour and shear-strength degradation in sensitive clays, with the potential to enhance the knowledge base for stability assessments and mitigate the risks associated with the widespread distribution of sensitive clays.

The investigation presented in this thesis aims to estimate the remoulding energy of clay using field vane tests. The methodology is based on the shear stress and shear strain behaviour of clay, where the strain energy involved in the remoulding is assumed to be the remoulding energy. Similarly, this behaviour can be obtained from vane shear tests. Seven locations from SW Sweden were analyzed, all close to Gothenburg. The results were correlated to soil parameters obtained from piston sampling. Additionally, the results were compared to findings of previous research on Norwegian, Canadian and Finnish clay.

The thesis shows promising results in applying the field vane test to SW Swedish clay for determining the remoulding energy. The results for southwest-Swedish clay are of a smaller magnitude compared to previous research on Canadian and Norwegian clay. The remoulding energy shows correlations to several parameters but further research is suggested to develop the method and correlations. To further utilize the method it is important to conduct the field vane shear tests in a consistent manner. The findings lead to an increased understanding of the behaviour of clay during remoulding. This can in the future reduce uncertainties and lower the required safety factors for geotechnical engineering.

Keywords: field vane test, remoulding energy, shear strength, sensitive clay, sensitivity



## Acknowledgements

We would like to extend our heartfelt gratitude to all those who have generously helped and made valuable contributions throughout the duration of this project. We wish to express special gratitude to Norconsult AB for their great help. It is with immense appreciation that we recognize the outstanding support and unwavering commitment of Martin Persson. His engaged involvement, active participation, and invaluable contributions have played a primary role in this thesis. A special and heartfelt thank you goes out to Johan Brunberg for his tremendous assistance. Additionally, we would like to express our sincere appreciation to Mats Karlsson for his guidance and expert advice.

Magdalena Berghel & Sanne Hagrydh, Gothenburg, June 2023



# List of Acronyms

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

LL	Liquid limit
MSB	Swedish Civil Contingencies Agency
NGI	Norwegian Geotechnical Institute
PI	Plasticity index
PL	Plastic limit
SGI	Swedish Geotechnical Institute
SGU	Geological Survey of Sweden
SiS	Swedish Standards Institute
SL	Shrinkage limit



# Contents

<b>List of Acronyms</b>	<b>ix</b>
<b>List of Figures</b>	<b>xiii</b>
<b>List of Tables</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Purpose and aim . . . . .	4
1.2 Delimitations . . . . .	5
<b>2 Sensitive clay and landslides</b>	<b>7</b>
2.1 Clay in southwest Sweden . . . . .	7
2.2 Formation and characteristics of quick clay . . . . .	10
2.3 Landslides in sensitive clay . . . . .	12
<b>3 Investigations of clay behaviour</b>	<b>15</b>
3.1 Index parameters and sensitivity . . . . .	15
3.2 Remoulding energy . . . . .	18
3.2.1 Laboratory methods . . . . .	18
3.2.2 Analytical approaches . . . . .	20
3.2.3 In-situ approaches . . . . .	21
3.3 Implementation of vane shear tests . . . . .	22
<b>4 Methodology</b>	<b>25</b>
4.1 Study areas . . . . .	25
4.2 Field vane test . . . . .	26
4.3 Estimation of the energy . . . . .	27
<b>5 Study areas</b>	<b>29</b>
5.1 Kastellegården, Kungälv . . . . .	33
5.2 Kärra, Gothenburg . . . . .	34
5.3 Nobelplatsen, Gothenburg . . . . .	36
5.4 Anneberg, Kungsbacka . . . . .	37
5.5 Varla, Kungsbacka . . . . .	38
5.6 Kungsbackaån, Kungsbacka . . . . .	40
5.7 Svinholmen, Kungsbacka . . . . .	41

<b>6</b>	<b>Results</b>	<b>43</b>
6.1	Correlations to other parameters . . . . .	45
6.1.1	Shear strength . . . . .	47
6.1.2	Water content and liquid limit . . . . .	48
6.1.3	Energy in relation to depth . . . . .	49
6.2	Time and speed dependency . . . . .	52
6.3	Comparison with previous findings . . . . .	56
<b>7</b>	<b>Discussion</b>	<b>59</b>
7.1	Correlations . . . . .	59
7.2	Time and speed dependency . . . . .	61
7.3	Advantages and disadvantages of field vane test . . . . .	62
7.4	Comparison with previous findings . . . . .	63
7.5	Variation between study areas . . . . .	64
7.6	Areas of improvement . . . . .	66
7.7	Further research . . . . .	67
<b>8</b>	<b>Conclusion</b>	<b>69</b>
	<b>Bibliography</b>	<b>71</b>
	<b>Appendices</b>	<b>75</b>
A	Field vane test results . . . . .	75
B	Correlation values . . . . .	81

# List of Figures

1.1	Areas with fine-grained soils in Sweden and the varying probability for landslides. The scale extends from red to yellow, with red being the highest risk for landslides and yellow as the lowest risk. Grey, shaded areas are composed mainly of glacial till or bedrock. Modified from SGU (2020b).	2
2.1	Generalized stratigraphy of the Gothenburg area, modified from Stevens et al. (1991)	9
2.2	Change of the marine limit in the Gothenburg area during the past 14000 years, retrieved from (SGU, 2022a)	10
2.3	Principles for quick-clay formation, modified from Brenner et al. (1981)	11
3.1	Consistency limits for soils, modified from Larsson (2008)	16
3.2	Results for remoulding energy from all performed tests on the St-Thurbie clay 12 m, modified from Tavenas et al. (1983)	20
3.3	Idealised stress-strain behaviour of sensitive clays, area B representing the remoulding energy, modified from Thakur and Degago (2013)	21
3.4	Comparison of the electric field vane test results and previous findings, modified from Thakur et al. (2015)	22
3.5	Result from a typical field vane test, with rod friction included	23
4.1	Vane used during field vane test	26
4.2	Extrapolation approach of a vane shear test, marked area A as limit state energy and area B as remoulding energy	28
5.1	Map of western Sweden, with the investigated study areas marked out (SGU, 2022b)	30
5.2	The paleogeographic situation of the marine limit 13000 cal. BP in western Sweden, retrieved from (SGU, 2022a)	31
5.3	The paleogeographic situation of the marine limit 7000 cal. BP in western Sweden, retrieved from (SGU, 2022a)	32
5.4	The paleogeographic situation of the present marine limit year in western Sweden, retrieved from (SGU, 2022a)	33
5.5	Geology of Kastellegården, Kungälv, with borehole NC903 marked out, retrieved from (SGU, 2020d)	34
5.6	Geology of Kärra, Gothenburg, with borehole CH1 marked out, retrieved from (SGU, 2020d)	35

5.7	Geology of Nobelplatsen, Gothenburg, with borehole NC2 and NC3 marked out, retrieved from (SGU, 2020d) . . . . .	36
5.8	Geology of Anneberg, Kungsbacka, with borehole 1801M marked out, retrieved from (SGU, 2020d) . . . . .	37
5.9	Geology of Varla, Kungsbacka, with borehole NC201 and NC206 marked out, retrieved from (SGU, 2020d) . . . . .	39
5.10	Geology of Kungsbackaån, Kungsbacka, with borehole NC2301 marked out, retrieved from (SGU, 2020d) . . . . .	40
5.11	Geology of Svinholmen, Kungsbacka, with borehole NC213 marked out, retrieved from (SGU, 2020d) . . . . .	42
6.1	Distribution of the observed clay. The dashed area represents the Swedish classification of quick clay, sensitivity and remoulded shear strength from the fall cone test . . . . .	43
6.2	Normalized energy versus sensitivity determined with fall cone test, correlation value -0.21 . . . . .	46
6.3	Remoulding energy from standard and improved approach versus sensitivity, correlation value -0.21 . . . . .	47
6.4	Limit state energy plotted versus shear strength obtained from field vane test, correlation value 0.94 . . . . .	47
6.5	Remoulding energy from standard and improved approach plotted versus shear strength obtained from field vane test with associated linear trendlines, correlation value 0.57 . . . . .	48
6.6	Remoulding energy versus water content, correlation value -0.75 . . . . .	49
6.7	Remoulding energy versus liquid limit, correlation value -0.63 . . . . .	49
6.8	Normalized energy plotted against depth, correlation value -0.44, with a linear trendline fitted to the standard and improved data points . . . . .	50
6.9	Plot of the limit state energy versus depth, for the different study areas . . . . .	51
6.10	Total energy versus bulk density, for 6, 7 and 8 meters depth, with a correlation value of 0.790 . . . . .	52
6.11	Plot of the rotational speed versus the time to failure, with a correlation value of -0.48 . . . . .	54
6.12	Plot of the rotational speed versus the total energy, for both improved and standard tests, correlation value 0.56 . . . . .	55
6.13	Plot of the sensitivity versus the time to failure is reached, correlation value 0.87 . . . . .	55
6.14	Plot of the rotational speed versus depth, for the different study areas . . . . .	56
6.15	Remoulding energy estimated with 2 % and 40 % plasticity index plotted with previous findings . . . . .	57
6.16	Results for Kärra plotted with previous findings . . . . .	58

# List of Tables

3.1	Swedish sensitivity definitions of soil . . . . .	17
4.1	The Swedish standards used during laboratory test . . . . .	25
5.1	Presenting the investigated study areas . . . . .	29
5.2	Laboratory results from Kastellegården, borehole NC903 . . . . .	34
5.3	Presenting the coordinates for borehole NC903 . . . . .	34
5.4	Laboratory results for Kärra, borehole CH1 . . . . .	35
5.5	Presenting the coordinates for borehole CH1 . . . . .	36
5.6	Laboratory results for Nobelplatsen, borehole NC3 . . . . .	36
5.7	Presenting the coordinates for the boreholes . . . . .	37
5.8	Laboratory results for Anneberg, borehole 1801M . . . . .	38
5.9	Presenting the coordinates for the borehole in Anneberg, Kungsbacka . . . . .	38
5.10	Laboratory results for Varla, borehole NC206 . . . . .	39
5.11	Presenting the coordinates for the boreholes . . . . .	39
5.12	Laboratory results for Kungsbackaån, borehole NC2301 . . . . .	41
5.13	Presenting the coordinates for borehole . . . . .	41
5.14	Laboratory results for Svinholmen, borehole NC213 . . . . .	42
5.15	Presenting the coordinates for the borehole . . . . .	42
6.1	Results of all calculated energies for each study area and depth . . . . .	44
6.2	Calculated mean values of depth and total energy for the two different field vane test approaches . . . . .	45
6.3	Used rotational speeds for the field vane tests for each site and depth together with time to failure . . . . .	53

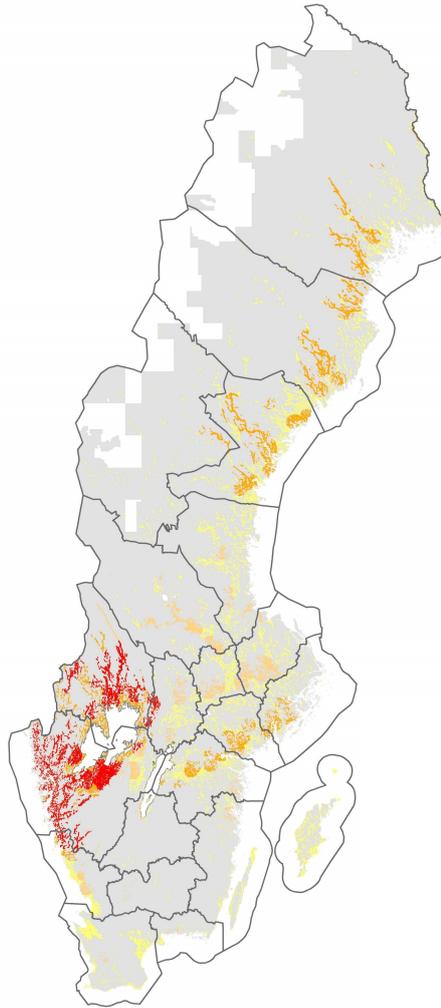


# 1

## Introduction

Several large quick-clay landslides have occurred in the Göta River valley and other areas in southwestern Sweden. The 1950 Surte landslide struck about 15 kilometres north of Gothenburg and was followed by additional events, e.g., in Göta in 1957, Tuve in 1977, Småröd in 2006 and Lökeberg in 2019 (SGI, 2020, 2022c). The Surte landslide consisted of about three million cubic meters of clay, of which the majority was quick clay. 27 years later, the Tuve landslide was triggered in the northern part of Gothenburg (SGI, 2022d). Also in this area, high-sensitivity clay and quick clay were present. Human impact is mentioned as a potential cause of the disturbance in most of the aforementioned landslides. Sweden and Norway have a similar soil structure and therefore similar problems with high-sensitive clay, quick clay and landslides. In Norway, the majority of the landslides which occurred between 2010 and 2018 were caused due to human activity (L'Heureux et al., 2018).

Much of the soil structure and resulting properties can be explained by the sedimentary environments during glaciation and deglaciation. Also, the post-depositional processes in the glaciomarine and marine clays are decisive in clay behaviour. After the Weichsellian deglaciation parts of Sweden were submerged under sea level as the crust was still depressed after the load of kilometres of ice, resulting in the marine deposition of clay (Rankka et al., 2004). Isostatic uplift later caused the clay deposits to rise above sea level. Due to rainfall and groundwater fluxes, the deposits were subjected to post-depositional processes such as cation leaching. Thus, parts of the deposits successively transformed into quick clay. It has been determined that southwestern Sweden, particularly the Göta River valley, contains significant amounts of sensitive clay and is at risk for landslides (SGI and MSB, 2021). SGU (2020b) has produced a map for landslide-prone areas in Sweden, see figure 1.1.



**Figure 1.1:** Areas with fine-grained soils in Sweden and the varying probability for landslides. The scale extends from red to yellow, with red being the highest risk for landslides and yellow as the lowest risk. Grey, shaded areas are composed mainly of glacial till or bedrock. Modified from SGU (2020b).

The definition of quick clay varies between Sweden, Norway and Canada. The Swedish quick-clay definition is that the sensitivity needs to be over or equal to 50 while the remoulded shear strength is below 0.4 kPa (Rankka, 2003). Canada has adopted Norway's definition of quick clay, which is a remoulded shear strength below 0.5kPa and sensitivity above 30 (Torrance, 2013). The term sensitivity is the ratio between the undisturbed and the fully remoulded undrained shear strength. Clays with a sensitivity of over 30, are sensitive to strong vibrations and disturbances. This can reduce a significant part of the shear strength causing the entire microstructure to collapse and liquefy (SGI and MSB, 2021). This property increases the probability of failure since vibrations and disturbances due to earthquakes, infiltration of heavy rain and anthropogenic activities can cause pore-pressure elevation and sudden loss of clay shear strength. As a result of this, landslides could occur.

Sensitivity does not include an estimation of the required energy to fully remould clay nor does it include how fast the reduction occurs (Larsson & Åhnberg, 2012). Many clays with high sensitivity are not considered to pose a high risk of retrogressive landslides if it is found that a significant amount of energy is required to break down the clay shear strength (Dehlbom & Lundström, 2020). Therefore sensitivity is not always sufficient for estimating risks for the liquefaction of clay (Larsson & Åhnberg, 2012). Other parameters are of importance when determining the risks of liquefaction and it is also important to increase knowledge about how sensitive clay will behave when exposed to disturbances. To get a full understanding of disturbances and landslides in sensitive clay one must understand the mechanisms involved in the process from an intact solid state to a remoulded fluid state.

There is some research within the area of the disintegration of clay, but few have determined the remoulding energy to fully break down clay shear strength. In 1974, Rolf Söderblom investigated a new approach and parameter to the classification of quick clay called *rapidity* (Söderblom, 1974). The method failed to make it into geotechnical practice, possibly because it is a largely subjective approach (Callander and Smalley, 1984). It does not directly estimate the needed energy to completely reduce the shear strength of clay. In 2013, Thakur and Degago (2013) states that the remoulding energy could be a useful parameter when determining the extent of landslides. In a master's thesis by Sundström and Waerme (2022), it is stated that it might be of interest to determine how much energy is needed for the clay to lose its shear strength. Most of the previous research regarding remoulding energy has investigated Norwegian and Canadian soft-sensitive clay, but almost no research is performed on Swedish-sensitive clay. This implies that additional investigations are needed for Swedish clay to fill a research gap.

Because of the widespread distribution of sensitive clays and the potentially devastating and costly consequences, it is necessary to increase the geotechnical understanding of clay characteristics with respect to disturbance and shear-strength degradation. Investigation of other possible methods is of interest and would increase knowledge of sensitive clays and their characteristics. This knowledge could contribute to lowering the uncertainties in stability calculations while introducing more detail. It is said to be a promising approach to studying the remoulding process of sensitive clays (Thakur et al., 2015).

Recently an investigation by Thakur (2017) was performed to evaluate the remoulding energy by using a field vane test. The approach determined the stress-vane rotation relationship of clay using the field vane test based on knowledge regarding clay's stress-strain relationship. The energy needed to fail and to fully remould was then estimated by calculating the area under the vane test curve. The article presents promising results and that the field vane test could be used for this purpose. The results showed that the method was applicable to Norwegian-sensitive clays. It further states that the method needs further tryouts to validate the results, by testing different in-situ conditions. Dehlbom and Lundström (2020) has suggested that this method should be investigated on Swedish clays.

To contribute to the research, the method suggested by Thakur et al. (2015) will be developed and applied on southwest-Swedish clay. The investigation will include field vane tests and routine analysis from piston sampling. These results will be evaluated in terms of remoulding energy and possible correlations to soil parameters. It will also be compared to previous research within the area.

### 1.1 Purpose and aim

The purpose of this thesis is to expand knowledge regarding the shear-strength degradation properties of clay. The thesis will contribute to existing research by providing a broader understanding of clay dynamics and a better basis for the assessment of areas prone to landslides.

The aim is to investigate the required amount of energy needed to disturb clay to a full shear-strength breakdown by looking at sensitive clay from seven different southwest-Swedish locations.

To reach the aim, the report strives to answer the following:

- How much energy is needed to disturb or fully remould the shear strength of clay estimated from field vane tests?
- What relationships are there between the estimated energy and soil parameters evaluated from piston sampling?
- How can the remoulding energy (measured in  $\text{kNm/m}^3$ ) be compared to previous research?
- How does the required energy for fully remoulding the shear strength vary geographically and how can the variation be explained in geological terms?
- How suitable is field vane testing for estimating the remoulding energy?

First, a study covering general information about the origin of clay and in more detail about sensitive clay, especially in Scandinavia with emphasis on southwestern Sweden, was conducted. A simplified literature study of previous research was performed to evaluate the existing knowledge regarding the remoulding of clay. Remoulding of clay using field vane tests was also investigated further.

To achieve the aim, data were obtained from laboratory tests and field tests from seven different study areas. The data were evaluated and calculations to determine the remoulding energy were conducted. The results were then compiled and compared to identify similarities and differences both for the different study areas but also to previous research.

## 1.2 Delimitations

The thesis is limited to remoulding by field vane tests, no other method was investigated. Geographically, the area for the investigated clays is limited to southwestern Sweden. The soil type for this thesis is limited to sensitive clays. The groundwater level and dry crust are not considered for this thesis. The brittleness in clay is not taken into consideration.

Due to constraints, the study areas were not individually chosen by the researchers but rather obtained with the assistance of collaborating companies and the academic institution. The number of study areas investigated in this thesis was limited in terms of time and availability. Therefore the number of study areas investigated is seven.

The extent of analysis of the soil is limited to routine analysis. Additional analyses are limited to what has been done for the specific project. Due to this, the information from each site is limited and additional information could not be obtained. The execution of the field vane test could not be affected.

The economic aspect is not considered when evaluating and suggesting how to measure the remoulding energy, nor it is considered when suggesting improvements.



# 2

## Sensitive clay and landslides

The following chapter presents a literature study of clays, focusing on the genesis of clay deposits in southwestern Sweden and the post-depositional formation of clay and quick clay. The chapter also presents the behaviour of quick clay and findings from previous studies regarding remoulding energy. The behaviour of sensitive clay during different types of disturbances and previous landslide events triggered by human activities is also presented.

### 2.1 Clay in southwest Sweden

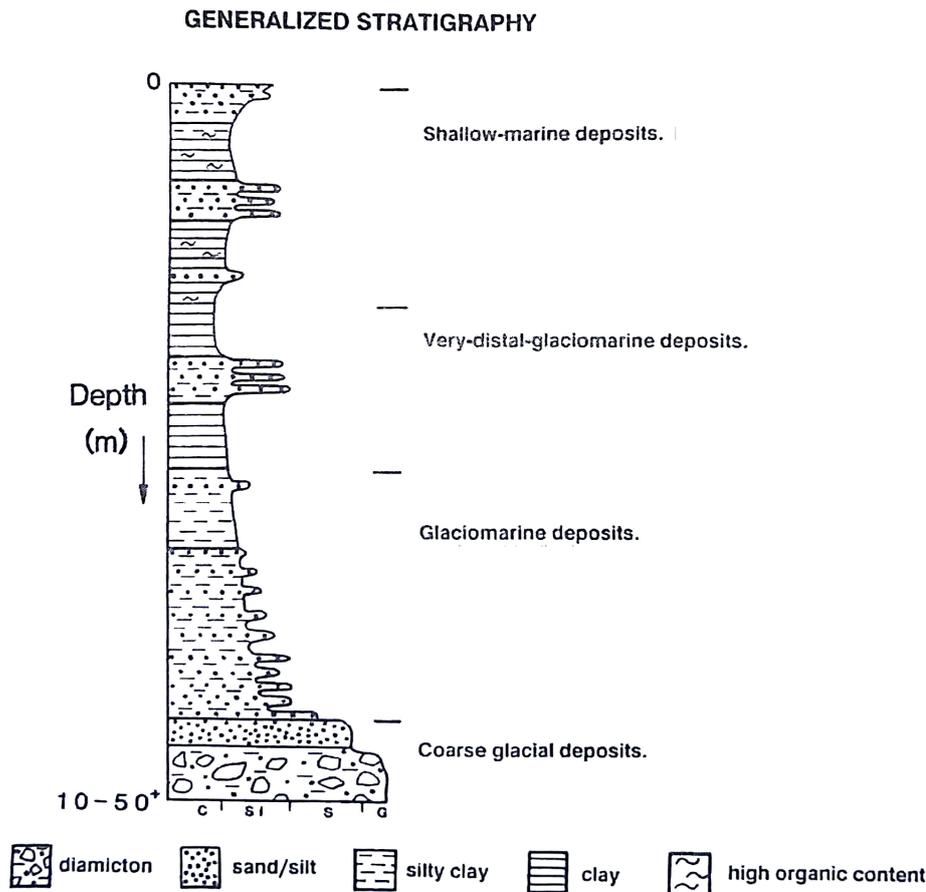
Clay is a generic term for a type of soil that has generally been deposited in glaciomarine and lacustrine sedimentary settings (SGI, 2022b). It is a type of soil where more than 40 percent consists of fine soil and 40 percent of these are clay particles with a grain size of less than 0.002 mm in diameter (Rankka et al., 2004). Clay generally has a high water content and the main difference between clay and quick clay is the relation between water content, consistency limits and activity. Quick clay occurs in places similar to Sweden in terms of geology and climate, e.g. Norway, northern Russia and Canada (Rankka, 2003). The research regarding quick clay and its occurrence has been ongoing since 1940, mainly in Sweden, Norway and Canada, and major studies were conducted during the 50s and 60s. In 1946 Rosenqvist presented a theory regarding quick clay (Rosenqvist, 1946). This theory discussed that the leaching of salts in marine clay results in quick clay.

In Sweden, the existing soil types were mainly formed during and after the latest glaciation, which ended about 10 000 years ago (SGU, 2020a). The deglaciation took almost 12,000 years (SGU, 2020c). This is estimated from the time that the ice began to retreat from northern Germany until the last remnants of ice disappeared from northern Sweden. The deglaciation in Sweden together with Norway, Finland, Canada and Russia represent areas that are characterized by the isostatic uplift that occurred after the glaciers retreated. This has caused similarities regarding the occurrence of quick clay (Brenner et al., 1981).

After the last glaciation, clay particles were deposited where water velocities were low (Rankka et al., 2004). Initially, deposition occurred in glaciomarine settings, proximal to the ice front. The sediments were formed with varying structures, depending on the salinity and the concentration of particles. The deglaciation followed

by the isostatic land uplift has driven the consolidation and thereby improved the clay strength (Stevens et al., 1991). In terms of age in a geological sense, all sediments which are quick are young (Rankka et al., 2004). Since the clay was deposited during and after the deglaciation, the clay can be found only beneath the marine limit. The greatest part of the deposits is found at elevations which are approximately 80 percent of the marine limit.

Commonly observed stratigraphical features and sedimentary environments in the Gothenburg area are presented in figure 2.1. These can be used to help understand and predict the variability of the geotechnical properties which occur (Stevens et al., 1991). It should be noted that the figure is strongly generalized, but usually recognizable since the considered area has a similar evolution due to the Weichselian deglaciation. Closest to the bedrock, the layer of coarse glacial deposits occurs (Stevens et al., 1991). This layer has a high-bearing capacity and consists of sand and diamicton. The depth of these clay layers in the Gothenburg area is mightiest in the valleys and can be between 50 to 100 meters deep (Bergström et al., 2022). The following layer is glaciomarine deposits (Stevens et al., 1991). These are characterized by a stratigraphic reduction of clay and water content downward, as silt and sand lenses increase. Very-distal-glaciomarine deposits follow this layer, as seen in figure 2.1. This layer consists of regionally correlative deposits of fine-grained clays and has very high water content. These alternate with one or two intervals with a coarser texture and a higher anisotropy. Locally, the shallow-marine deposits are distinguished by layers of clay with a high water content that frequently occurs alongside silty to sandy parts.



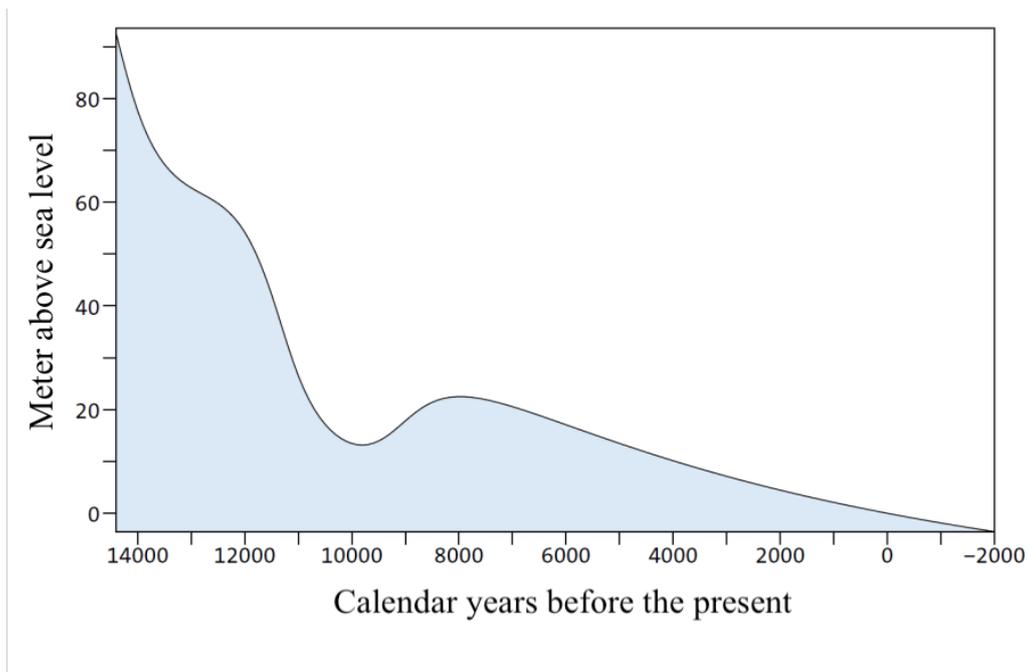
**Figure 2.1:** Generalized stratigraphy of the Gothenburg area, modified from Stevens et al. (1991)

The isostatic uplift has changed the marine limit over time, and as for now the land rise in the Gothenburg area is approximately 3 mm/year (Bergström et al., 2022). The occurrence, landforms and characteristics of the Quaternary deposits reflect the dynamics of the ice sheet in the area. It does also reflect the formation environment of the soil types together with the development in the area after the glacial processes subsided. Time is an important factor in the difference between the clay. Time and thereby climate affects the organic content, where one clay consists of more organic material, compared to the other one (SGU, 2020e). The older clay has been exposed to erosion which causes a higher degree of consolidation. This results in a difference majorly in terms of mineral content and particle shape. Most of the mechanical properties are strongly affected by the particle size, shape and structure.

The collapse of this characteristic soil structure can either occur gradually or catastrophically (Stevens et al., 1991). The major key to anticipating the collapse is knowledge regarding the leaching of the pore-water, which is due to coarser layers in the stratigraphy, as figure 2.1 presents. Several changes in the post-depositional conditions could be expected to affect the geotechnical characteristics. Flocc aggregation would increase the effective particle size, which results in increased per-

meability, strength and density. It is most likely that the shear strength of the clay sediment is mainly dependent upon the original floc bonds that formed during deposition Stevens et al. (1991).

On the west coast of Sweden, there are several events during the deglaciation that has affected the sedimentation process (Larsson & Sällfors, 1995). One is the drainage of the Baltic Ice Lake, and another is the transgression from about 9000 to 7000 years ago where the shoreline rose and the conditions for sedimentation changed drastically. Figure 2.2 shows the change in the marine limit during the past 10000 years. After the deglaciation, the land uplift has caused the sedimentation to stop, except for lakes and seas. Due to this, the youngest clay has only been above the marine limit for the past days to 1000 years. This has caused variations in the consolidation of the clay. By consolidation, the natural water content in the soil is reduced (Larsson, 2008). A decrease in volume is caused by hydrodynamic delayed water extrusion from the soil pores. When this process occurs the load changes from the pore pressure to an increased effective stress in the soil.



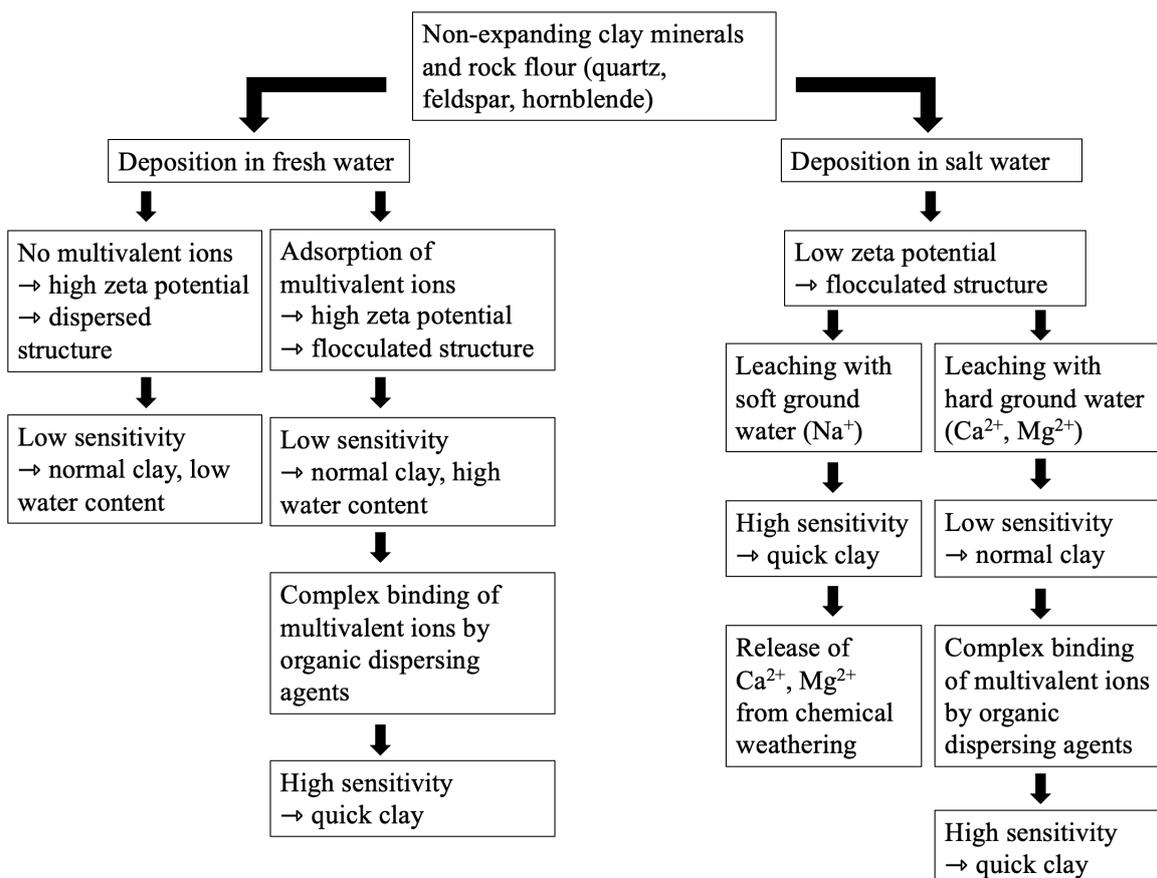
**Figure 2.2:** Change of the marine limit in the Gothenburg area during the past 14000 years, retrieved from (SGU, 2022a)

## 2.2 Formation and characteristics of quick clay

In general, all clays which were deposited in salt water can become quick as a result of leaching (Rankka et al., 2004). This is limited by the availability of fresh groundwater, the duration of the potential leaching and conditions for seepage of water through the clay. Factors which restrain the formation of quick clay are, according to Rankka et al. (2004), weathering and consolidation. By weathering, ions are released which bounds to the clay particles' negatively charged surface and edges and

thereby prevent the leaching process. This could be the reason why quick clay never occurs in or directly beneath the dry crust. Ion composition in pore water has been shown to be of importance for the formation of quick clay. Additionally, pH has been shown to have an impact on the remoulded shear strength. Talme (1968) showed that when a basic solution was added the remoulded shear strength decreased, and when an acid solution was added the remoulded shear strength increased.

A precondition for the formation of quick clay is that the sediment consists of non-swelling minerals with low activity (Rankka et al., 2004). In 1953 Skempton introduced the term activity of clay. The activity of clay is the ratio between the plasticity index and clay content. The leaching of salt affects the sensitivity, if the saltwater in clay which originates from seawater is remoulded the clay particles can not aggregate into larger aggregates again. This results in a reduction of the water holding capacity, which reflects in the liquid limit. A decrease in the undisturbed undrained shear strength could potentially be brought on by the leaching as well. This result also entails reducing the remoulded shear strength and increasing sensitivity. Figure 2.3 presents a schematic overview of the principles for the formation of quick clay. Varying principles are presented, dependent on where the clay was deposited.



**Figure 2.3:** Principles for quick-clay formation, modified from Brenner et al. (1981)

A characteristic of quick clay is that the water content is higher than the liquid limit, which results in the liquid behaviour of the clay (Rankka et al., 2004). The microstructure of the clay particles has a structure which can be compared to a house of cards. This enables the possibility for quick clay to be transformed into a liquid state. The result of a disturbance is that the structure collapses. The collapse results in a liquefaction of the clay and the clay is remoulded.

The specific behaviour of quick clay, the sudden liquefaction, can be explained using rheological terms. The rheological properties of some soils can be compared to fluid rheology (Zhu et al., 2017). Generally, rheology for soils can be divided into two categories, fluid and plasticity rheology. Soft soils can be better compared to rheology properties of fluids, and sand and more coarse soils are associated with plasticity rheology.

Sensitive clay is a strain-softening material, once the peak shear strength is reached, the material has a decrease in shear strength with increasing deformation. This behaviour can be explained as shear thinning since the clay decreases in viscosity with increasing shear stress (Zhu et al., 2017). This can be noticed during quick-clay landslides, the clay is exposed to a critical level of stress via large deformations, which transform the clay into a highly viscous fluid (Khaldoun et al., 2009).

Sweden, Norway and Canada are often compared due to their similar soil structure and they have more in common than they differ. Due to this, there is interest to compare research from these different countries. Although some differences should be noted. The influences upon quick-clay formation vary between the countries. Norway has groundwater flow regimes that are well-suited for the leaching of clay profiles. Norway compared to Sweden has larger variations in topography and this provides better conditions for groundwater flow. Additionally, the fjords of Norway provide good conditions for the clay to be deposited in calm water. Clay from eastern Canada is generally more plastic and more over-consolidated (L'Heureux, 2012). They also tend to have a higher normalized undrained strength in relation to vertical effective stress, compared to the clay in Norway. Karlsrud et al. (1985) related this to the cementation effects which occur in Canadian clay. It would therefore be expected that the required energy to remould the Canadian clays would be higher compared to Norwegian clays. Additionally, the Swedish clay is very similar to Norwegian one, but there are differences in relief, clay mineralogy and deposition environment.

### 2.3 Landslides in sensitive clay

There are different types of landslides which could occur in sensitive clay, but the two main types are stepwise and uninterrupted (Torrance, 2013). In the stepwise landslide, enough liquified debris slides away, resulting in an unstable slope, which is unsupported due to the liquified debris. This results in another failure of the slope that lows away. For uninterrupted landslides, the velocity of the event is enough to continue which results in a continuous series of failure slides that flows away from the scarp.

A downhill progressive landslide starts in the upper part of the slope and propagates downhill as a result of initial local instability (Bernander, 2011). Uphill progressive slides are where the initial local instability occurs in the lower part of the slope and then propagates uphill. Bernander (2011) states that laterally progressive slides are when local instability occurs anywhere in a slope and propagates sideways along the elevation contours. Additionally, the term progressive failure is sometimes stated to be the opposite of retrogressive failure, and in other contexts, it refers to the mechanism which leads to a retrogressive failure. The retrogressive slides refer to the sequential retreat of the back scarp (Torrance, 2013).

The two largest known quick-clay landslides in Sweden have occurred in the Göta älv valley, which is an area around the Göta River in southwestern Sweden. In 1950 a landslide occurred approximately 15 kilometers north of Gothenburg (SGI, 2020). Another landslide occurred in the northern part of Gothenburg in 1977, in the district called Tuve (SGI, 2022d). For the landslide which occurred in 1950, piledriving had been done in the slope some days before the landslide. Additionally, a train had passed by a few minutes before the slide. The landslide in Tuve, several factors are mentioned as causes for the slide. The exploitation of the area and the steeply sloping rock below the clay layers are some of them. The landslide in Småröd in 2006, Sweden, was caused by a too-large deposit of fill masses (SGI, 2022e). There were deficiencies in risk assessment, communication and management that caused the accident in 2006.

The Norwegian Geotechnical Institute reports of several landslides that have occurred in quick clay (NGI, 2022). The largest known landslide until now, in Norway occurred in 1893, Verdalsraset, and 55 million cubic meters collapsed. The latest one, in Gjerdrum, occurred in 2020 and cost 11 people's lives (Olje- og energidepartementet, 2021). These two landslides together with many more in Norway resulted in severe consequences due to the occurrence of quick clay. According to L'Heureux et al. (2018), 90 percent of the landslides in Norway between 2010 and 2018 were caused due to human activity.

According to an investigation where friction piles were tested in soft sensitive clay performed by Roy et al. (1981), the undrained shear strength in the clay close to the pile decreased immediately after driving. The test showed that the shear strength recovered when the produced excess pore pressures during driving dissipated, after about 600 h. Due to the induced excess pore pressures, the article states that there is a relationship between pile driving and changes in clay behaviour. Aas (1975) states that the pile driving for a factory building in Drammen in 1971, caused a loss of the safety factor, where it sank from 1.3 to 1.0. This was caused due to increased horizontal pressure due to excess pore pressure. As a result a slide occurred and slid out in the Drammen River.

In 1990, at Tre-styckevattnet in Sweden, a landslide was triggered due to ground vibrations (Bernander, 2011). An embankment of the nearby highway needed additional stability, and a berm was constructed in 1989. After about a year after the berm was constructed, a soil layer was added to enable vegetation. During this

construction phase, both bulldozers and vibratory rollers were used. The vibrations created by the machines were assumed to be the trigger for the landslide. However, the safety factor for the slope was already close to 1 in 1989, and the vibrations were the triggering agent. Another landslide due to vibratory rollers, happened in Norway in 2014. The landslide was triggered by the vibrations and since it was located near the coast, a tsunami was triggered by the landslide (Norwegian Water Resources and Energy Directorate, 2014). After this, an article investigated the impact of vibratory rollers near sensitive soils, done by Johansson et al. (2017). The article resulted in a recommended vibration limit for work near slopes with sensitive clays, based on an assumed zone of influence of a vibratory roller.

Bernander (2011) states that existing slopes are basically stable as long as they remain undisturbed by human activity and unaffected by significant intrinsic deterioration phenomena. It is important to emphasize that many of the mentioned events are connected to other triggers. According to a summarization of previous landslides by Bernander (2011), many of the events have occurred due to a combination of heavy precipitation and some triggering agent such as pile driving, rock blasting or earth fills. This implies, that landslides are often due to a combination of events and not a single activity.

A report by SGI (2022a) states that Sweden will face more precipitation and an increase in runoff due to climate change in the future. The report further presents how landslides and erosion will be affected by these climate changes. The safety factor of slopes will decrease by an average of 18% until the year 2100. The report also presents that Southwestern Sweden will face the highest cost consequences due to an increase in landslides. This implies that climate change, and other triggers for landslides, still are important factors when discussing stability.

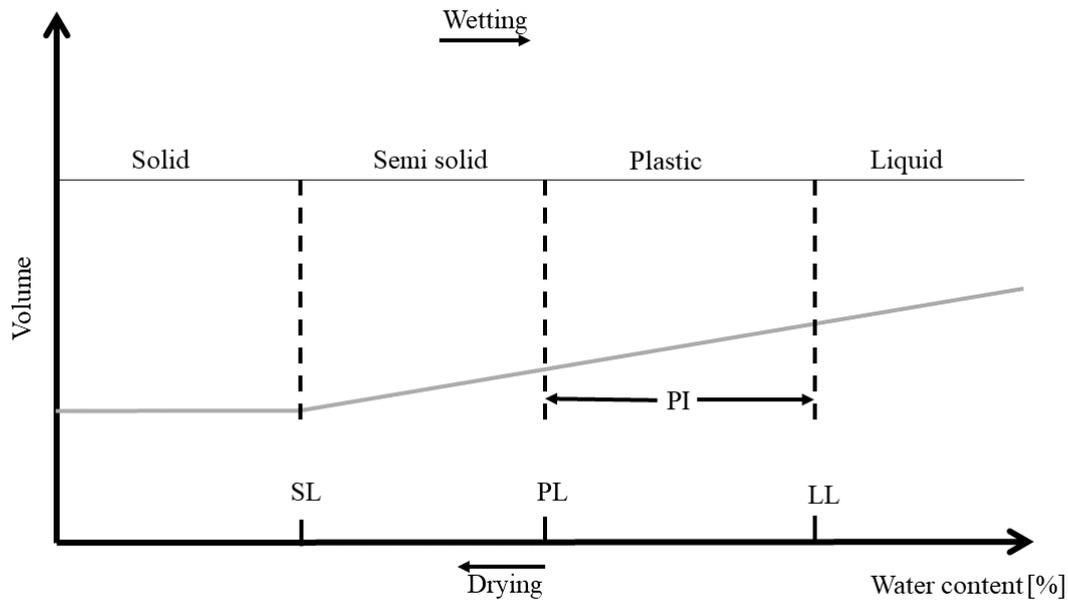
# 3

## Investigations of clay behaviour

The following chapter provides a concise overview of how the behaviour of clay can be studied using index parameters and sensitivity. Additionally, it explores various methods for determining the remoulding energy of sensitive clay. Finally, the chapter presents information regarding vane shear tests.

### 3.1 Index parameters and sensitivity

To better understand the clay properties and behaviour in geotechnical engineering, laboratory investigations are usually performed to complement field investigations. Fine-grained soils can be classified by studying consistency, the content of clay and clay minerals and water content (Larsson, 2008). Critical water contents of the soil are determined by using Atterberg limits, also called consistency limits and these are presented in figure 3.1. These include liquid limit,  $w_L$ , plastic limit,  $w_p$  and shrinkage limit,  $w_s$ . The shrinkage limit is the highest limit of water content where the soil volume does not change. The plastic limit is the minimum water content for which the soil can be moulded and behave plastically. Lastly, the liquid limit is the highest water content the soil can have before becoming liquid. This is the limit that is most commonly used in Sweden.



**Figure 3.1:** Consistency limits for soils, modified from Larsson (2008)

From the liquid limit and plastic limit the plasticity index  $I_p$  can be determined by using equation 3.1. The plasticity index is the range of water content where the fine-grained soil remains plastic. From the plastic limit, liquid limit and natural water content, the liquidity index  $I_L$  can be determined by using equation 3.2. The liquidity index is always larger than 1 for quick clays (Dehlbom & Lundström, 2020). Kenney (1976) studied Norwegian and Canadian clays and saw that there is a linear correlation between the liquidity index and the logarithm of sensitivity. This linear correlation was also found for Swedish clays (Larsson & Åhnberg, 2012).

$$I_p = w_L - w_p \quad (3.1)$$

$$I_L = \frac{w_n - w_p}{w_L - w_p} \quad (3.2)$$

Previous investigations by Tavenas et al. (1983) showed that the more plastic the clay is, the less remoulding energy is needed to decrease its shear strength. This implies that the plastic limit is an interesting parameter when discussing and studying the energy needed to remould clay. However, in Sweden, this parameter is not so often determined since it is varying too little for Swedish clays (Dehlbom & Lundström, 2020). Instead, liquid limit is usually used and is considered a more important parameter when studying different correlations.

Instead of using the plastic limit, Sweden sometimes uses a quasi-liquidity index which is the ratio of the natural water content and liquid limit (Dehlbom & Lundström, 2020). The quasi-liquidity index is usually more than 1.1 when the sensitivity

is over 50 and therefore it can be used to indicate quick clay. However, it is not enough reliable to map and determine quick clay.

Another parameter important for the understanding of clay behaviour is sensitivity. In Sweden, the sensitivity  $S_t$  is determined with equation 3.3, with  $c_u$  as undrained shear strength and  $c_{ur}$  as remoulded shear strength. A soil's sensitivity is then defined according to the criteria listed in table 3.1.

$$S_t = \frac{c_u}{c_{ur}} \quad (3.3)$$

**Table 3.1:** Swedish sensitivity definitions of soil

Classification	Criteria
Low sensitivity	$S_t < 8$
Medium sensitivity	$8 \leq S_t < 30$
Very high sensitivity	$S_t \geq 30$
Quick clay	$S_t \geq 50$ and $c_{ur} \leq 0.4$ kPa

There are several methods to determine the sensitivity of clay. In Sweden, the most common approach is to use the fall cone test (Dehlbom & Lundström, 2020). The undrained undisturbed and remoulded shear strength is measured from piston samples. To get the remoulded shear strength, the sample is stirred until no lower shear strength can be obtained. Other methods have also been investigated for the determination of sensitivity, like sounding methods and using resistivity measurements (Rankka et al., 2004).

One of these other methods to determine the sensitivity is to perform a vane shear test, either in situ or on samples in a laboratory. Firstly, a vane shear test is performed to measure the undisturbed undrained shear strength. The vane is then recommended, according to the Swedish standard, to rotate at least 10 rotations (SiS, 2020). Then the remoulded shear strength is measured. However, both field and laboratory vane shear tests have shown underestimated results of sensitivity in comparison to different methods (Eden & Kubota, 1961). The vane shear tests are also limited due to that low shear strength values can not be determined with enough accuracy.

The T-bar penetration test is another possible method to determine the sensitivity. The test works similarly to the cone penetration tests, but the conical tip is replaced with a T-bar. The T-bar tip can be used to study how the soil is deforming by running the tip up and down, usually 10 times, at a certain depth and studying the changes in resistance. Yafrate et al. (2009) investigated how the sensitivity can be predicted from a T-bar penetration test using equation 3.4, with  $q_{in}$  and  $q_{rem}$  as initial and remoulded penetration resistance.

$$S_t(Tbar) = \frac{q_{in}^{1.4}}{q_{rem}} \quad (3.4)$$

## 3.2 Remoulding energy

Söderblom (1969) presents a theory of the influence of salt on the sensitivity of quick clay. The paper also covers some aspects and theories of quick clay and its formations. 5 years later, *New Lines in Quick Clay Research* is presented by Söderblom (1974). In this paper, two types of quick clays are mentioned, rapid quick clay and slow quick clay. These terms refer to the amount of work needed to break down the clay structure. Söderblom (1983) states in *Studies of the Rapidity Number* that a new parameter is needed to describe the quick clay when it requires high remoulding energy. The parameter is suggested to be the remoulding work, and it is also stated by Professor Reh binder in Stockholm in 1970 that experiments regarding this have been conducted in USSR. But for this experiment, no measurements and equipment were to be found.

According to Söderblom (1974) it is not necessary to get an absolute value for the remoulding energy, a relative number would be sufficient. Therefore, he suggests using the term rapidity as a parameter for quick clay. Söderblom investigated the rapidity by using Casagrande's liquid limit device. A sample of clay were set into the bowl and then after 250 percussions one would determine a rapidity number, dependent on the visual effect and deformation of the sample. The scale for the rapidity number is between 1 and 10, where 1 is thought to be the most stable one, and 10 is the most fragile, rapid one. By Söderblom (1974) it is suggested that a rapidity of 8 or more, together with a sensitivity of at least 50 would be a new definition of quick clay. The suggested method failed to make it into geotechnical practice, possibly because it is a largely subjective approach and does not directly estimate the needed energy to completely remould the shear strength of clay (Callander and Smalley, 1984). Furthermore, Callander and Smalley (1984) states that the measurement is unsuitable in its present form for Canadian soils due to the strong inter-particle cementation of these.

Since then, researchers have been studying to find a concept on how to determine the remoulding energy. Research has shown that the remoulding energy can be estimated with different approaches such as laboratory, field, and empirical methods (Thakur, 2017). Several methods have been tested for the estimation of remoulding energy for landslides and how to simulate the energy of the processes that occur in a landslide. The energy required to completely remould sensitive clay is referred to as remoulding energy. The term refers to the process of remoulding and not only to the remoulding that results in a landslide. However, the term is not established and can therefore go by the name of disaggregation energy, disintegration energy, degradation energy or strain energy as well.

### 3.2.1 Laboratory methods

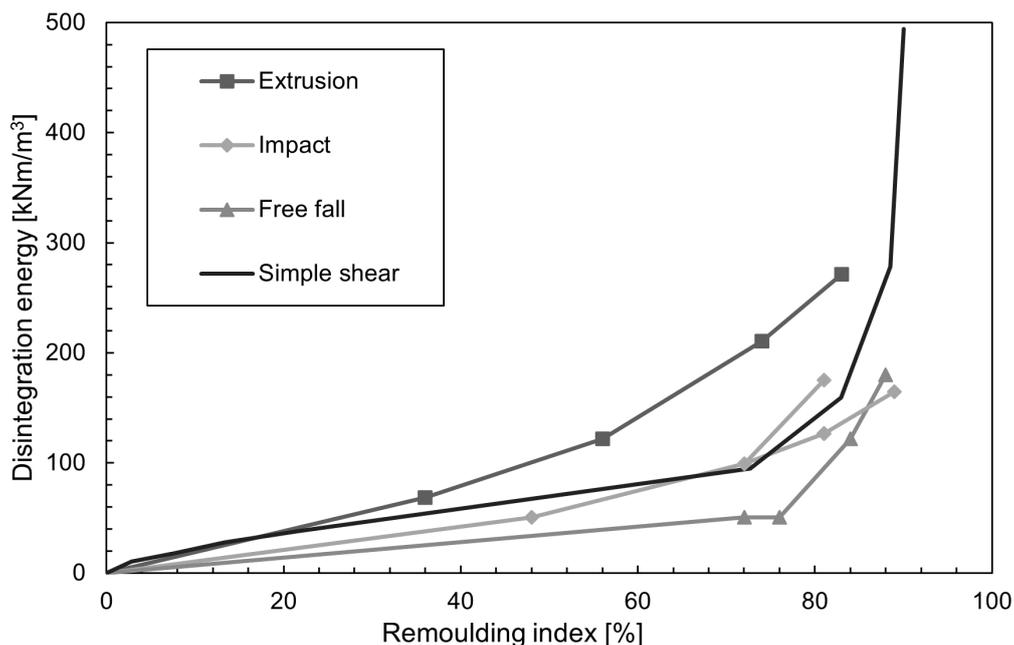
In an article by Tavenas et al. (1983), several laboratory tests were performed to estimate the remoulding energy in sensitive clay. Seven different Canadian sensitive clays were tested using four methods described as free fall, impact, extrusion, and simple shear. In the fall test, clay specimens were rolled from different heights of an

inclined board. The remoulding energy was therefore considered to be equal to the potential energy. The impact test was performed by dropping an aluminium ram on the specimens. Similarly, the potential energy of the aluminium ram was considered to be equal to the remoulding energy, using the weight of the ram and the drop height. The third test, extrusion, used an apparatus where the clay specimens were forced through a conical file. The energy applied to the sample was considered to be the extrusion force. The last test, shearing, used a simple shear box where the shear deformations were created by oscillating the sides. The force for oscillation was measured and considered equal to the remoulding energy.

The results of how much energy is needed depend on the degree of remoulding also called the remoulding index (Tavenas et al., 1983). The remoulding index is defined as the ratio between  $(c_{up} - c_{ux})$  and  $(c_{up} - c_{ur})$  and ranges between 0 and 1, from fully intact to fully remoulded. The ratio for defining the index includes  $c_{ux}$  which is the undrained shear strength between  $c_{up}$  and  $c_{ur}$ . For all tests, fall cone tests were used to determine the intact, partly remoulded and remoulded shear strength. Also, the article presents that the remoulding energy seemed to be non-uniform within the sample, and a recommendation for defining average energy per unit volume was made. The remoulding energy was also normalized using equation 3.5, with  $W_N$  as the normalized energy and  $\sigma'_p$  as pre-consolidation pressure.

$$W_N = \frac{\text{Energy per unit volume}}{0.013\sigma'_p} \quad (3.5)$$

The results for the most sensitive clay from all tests can be seen in figure 3.2. The method that required the highest amount of energy for remoulding turned out to be the extrusion, however, the friction probably contributed to an overestimation of the energy (Tavenas et al., 1983). The report concludes that the test of simple shear was generally the most suitable method. However, some limitations with the shearing test were found. No correction was done for the friction and variations in water content could not be avoided.



**Figure 3.2:** Results for remoulding energy from all performed tests on the St-Thurbie clay 12 m, modified from Tavenas et al. (1983)

### 3.2.2 Analytical approaches

When a landslide in sensitive clay occurs, the change in potential energy is equal to the strain energy needed to remould the soil and the energy in the slide movement (Thakur et al., 2017). This is explained using an analytical approach and the equation 3.6, where  $\Delta E^P$  is the potential energy,  $\Delta E^R$  the remoulding energy and  $\Delta E^K$  is the frictional and kinetic energy.

$$\Delta E^P = \Delta E^R + \Delta E^K \quad (3.6)$$

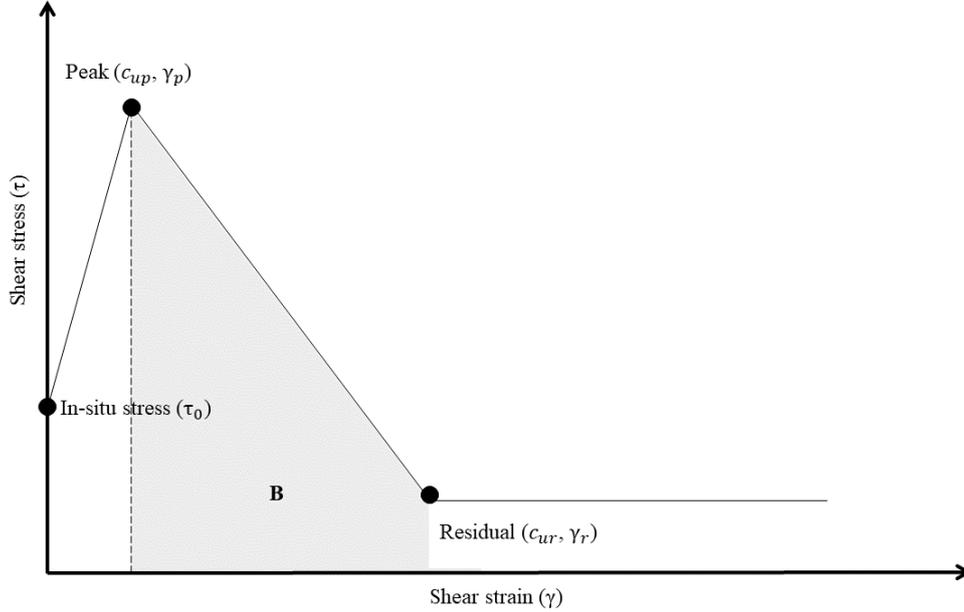
Based on the results performed by Tavenas et al. (1983), a pragmatic approach using equation 3.7 was proposed by Leroueil et al. (1996) to calculate the remoulding energy. This approach was later validated by using data from 22 Canadian-sensitive clay landslides by Locat et al. (2008).

$$\Delta E^R = 16C_{up}I_P \quad (3.7)$$

The article by Thakur and Degago (2013) defines how to estimate the remoulding energy using equation 3.8. This function is represented as area B in figure 3.3. The curve represents the idealised behaviour of sensitive clay, first elastic hardening and then strain-softening behaviour. The graph presents shear stress  $\tau$  vs shear strain  $\gamma$  with  $c_{up}$  and  $c_{ur}$  as undrained shear strength at peak and residual states. This

analytical solution was validated by using data from 18 Norwegian-sensitive clay landslides.

$$E^R = c_{ur}(\gamma_r - \gamma_p) + \frac{1}{2}(c_{up} - c_{ur})(\gamma_r - \gamma_p) \quad (3.8)$$



**Figure 3.3:** Idealised stress-strain behaviour of sensitive clays, area B representing the remoulding energy, modified from Thakur and Degago (2013)

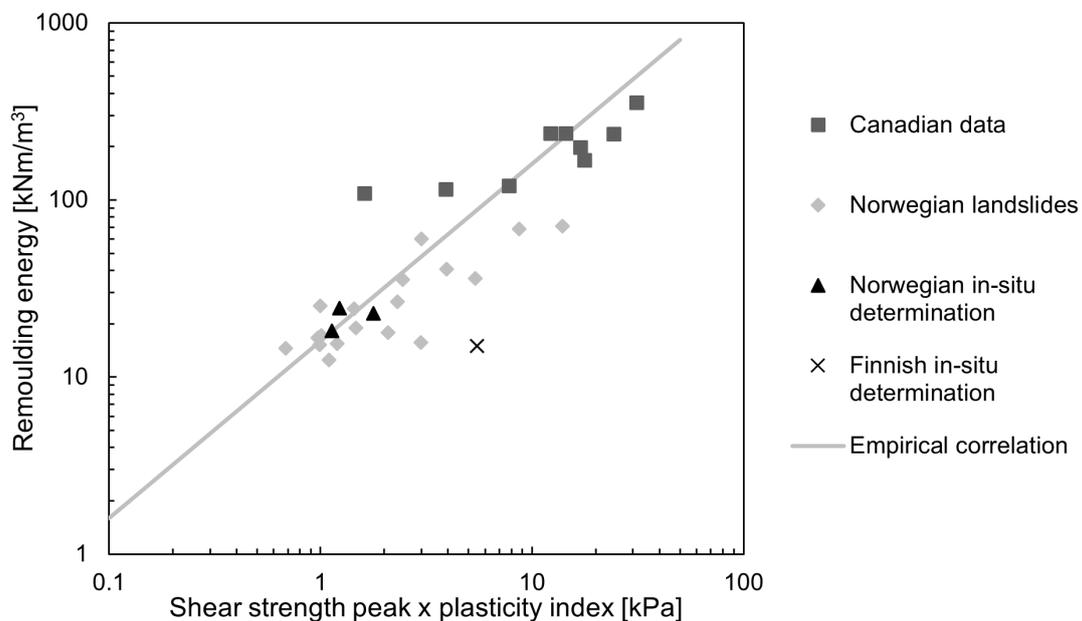
This definition of remoulding energy takes several factors into account, such as the undrained shear strength, the strain softening index  $n$  ( $n = \frac{\gamma_r}{\gamma_p}$ ) and the strain at the fully disintegrated state (Thakur et al., 2017). The definition then implies that a single parameter or factor, such as sensitivity, is not sufficient to estimate or correctly define the ability of sensitive clay to remould. The article also presents that other parameters could affect the remoulding energy, for example, plasticity index and liquid limit.

### 3.2.3 In-situ approaches

In addition to analytical and laboratory approaches, the remoulding energy can also be estimated from in-situ tests (Thakur et al., 2015). In a study performed by Thakur et al. (2015) the remoulding energy was estimated in situ, using an electric vane shear apparatus. They performed tests on three low plastic-sensitive soft clays in central Norway, which were the Tiller, Klett and Fallan clay. The in-situ field vane test can interpret the stress-strain behaviour of sensitive clays and by using equation 3.9, calculate the shear stress (Thakur et al., 2015). The equation includes  $T_{tot}$ , which is the total torque and  $D$  which is the diameter of the vane. The article assumes that  $T_{tot}$  per unit volume is equivalent to remoulding energy.

$$\tau = \frac{6 T_{tot}}{7 \pi D^3} \quad (3.9)$$

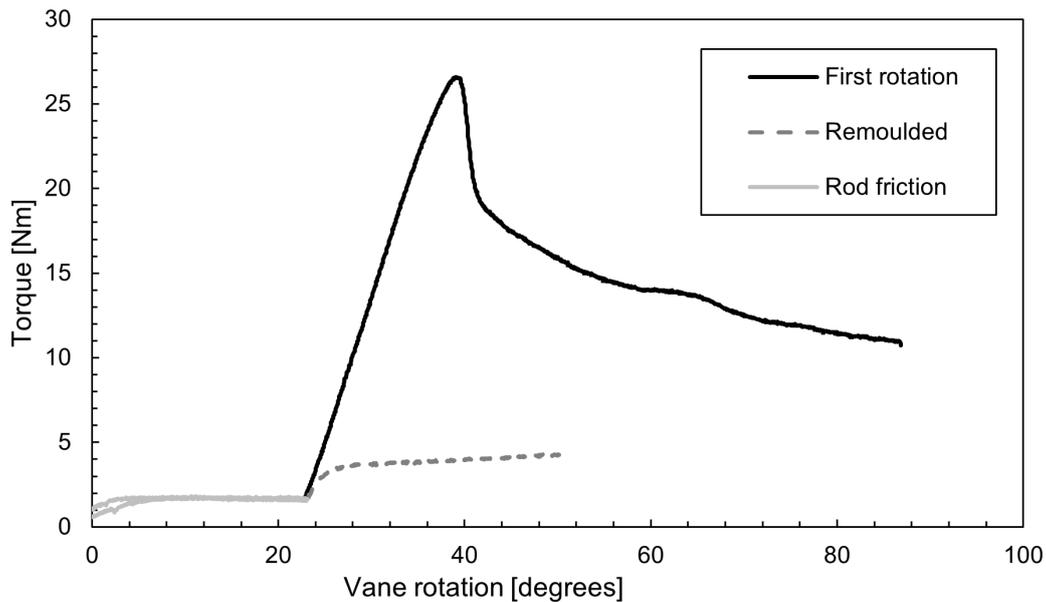
The test used a vane with a diameter of 65 mm and a height of 135 mm. Continuous measuring was taken while the vane rotated to 360°, about 7.4-8.5 m below ground surface (Thakur et al., 2015). The interpreted results were based on a set of assumptions, such as that soil was undrained, isotropic strength conditions, no progressive failure and that the failure surface was of cylindrical shape. During the test, the investigators encountered some limitations, the undrained shear strength did not change after a rotation of 90° and therefore, the results were extrapolated by using a linear extrapolation after 90°. The results were compared with previous investigations, such as the former mentioned Canadian laboratory data, the empirical correlation and the analytical solution and these results can be seen in figure 3.4 (Locat et al., 2008; Tavenas et al., 1983; Thakur & Degago, 2013). The comparison showed that the new data were in a similar range and trend as previous results. The graph also presents that Canadian-sensitive clays seem to require more energy to fully remould.



**Figure 3.4:** Comparison of the electric field vane test results and previous findings, modified from Thakur et al. (2015)

### 3.3 Implementation of vane shear tests

The vane shear test is most commonly used to determine the undrained shear strength of clay. As previously explained, the vane shear test can be used for both the determination of sensitivity and remoulding energy. A typical field vane test result can be seen in figure 3.5.



**Figure 3.5:** Result from a typical field vane test, with rod friction included

The vane shear test used today is similar to the vane borer invented in 1947 by Lyman Cadling (Cadling & Odenstad, 1950). The invention was investigated in a report which also states that the vane borer can be used to obtain the remoulded shear strength. However, this invention was not the first one, investigations for vane shear tests started already during the 1930s’.

The vane shear test is a relatively simple and quick test for measuring the shear strength of soils (Dehlbom & Lundström, 2020). However, it is only applicable to clay. The vane shear test can accurately measure the shear strength of the soil and provide data on its resistance to deformation and changes in structure. The test is also a cost-effective method of determining the shear strength compared to other laboratory tests.

It should be noted that there are several factors that could influence the results of field vane shear tests. This could be, among other things, vane dimension, installation, time, mode of failure, rod friction and local pore pressure drainage (Thakur et al., 2015). A discussed problem with the vane shear test is the disturbance to the soil during the insertion of the vane into the soil. It is known that the vane installation causes both remoulding and changes in stresses both directly and with time. Especially when testing high-sensitive clay and quick clay that is sensitive to small disturbances. Torstensson (1973) states that the rotational speed is affecting the peak of the curve. It is shown that the peak gets less defined with a decreasing rotational speed. Thereby the result is affected on the rotational speed used for the tests. The Swedish standard does not specify a speed but suggests in what time span the failure should be reached (SiS, 2020). It is suggested that the time to failure should be within 1 to 3 minutes, with 2 minutes as the reference value. The time is defined as when the vane is activated until the failure is reached.

Field vane tests in Norway are conducted similarly to the Swedish standard. The following is a guidance from Statens vegvesen (2021) for how field vane tests should be conducted in Norway. When the vane has been pushed down to the desired depth it should be at least 2 minutes before the test is started, but no more than 5 minutes. Then the vane is turned until failure is reached, with a rotational speed of about  $0.2^\circ$  per second. The failure should be obtained within 1 to 3 minutes. From this, a maximal shear strength will be obtained. The remoulded shear strengths are measured after 25 turns by hand are conducted. Thereafter the vane is turned 90 degrees and a remoulded shear strength is noted. Then the vane is turned 4 turns by hand and the shear strength is measured again after 90 degrees. This is repeated once more and the lowest obtained value from the 3 measurements is set to be the remoulded shear strength. The major difference between the Norwegian and the Swedish vane shear test is that Norway has a suggested rotational speed. Additionally, Norway also measures the remoulded shear strength several times to limit uncertainties and get the absolute lowest shear strength. From SiS (2020) which Sweden uses it is just stated to measure the remoulded shear strength. It does not suggest multiple measurements of the remoulded shear strength as the Norwegian does (Statens vegvesen, 2021).

# 4

## Methodology

To investigate the remoulding energy in sensitive clay using field vane tests, a series of field vane tests were conducted. These results were supplemented with data from previously performed field vane tests. Some of the field vane tests were improved to generate a more accurate stress-strain relationship for sensitive clay. The improvements involved rotating the vane until no further changes in the measurements of undrained shear strength were observed. However, it was not expected for the clay to reach a completely remoulded state during the initial rotation due to possible drainage of excess pore water pressure. Furthermore, the improved tests were also conducted with a remoulded approach, which will be further detailed in the subsequent field vane test chapter. Additionally, the results were compared and evaluated with results from laboratory tests. The standards used during the laboratory tests can be seen in table 4.1.

**Table 4.1:** The Swedish standards used during laboratory test

Test	Standard	Source
Visual classification	SS-EN ISO 14688-1, -2	SiS (2018a)
Bulk density	SS-EN ISO 17892-2:2014	SiS (2014b)
Water content	SS-EN ISO 17892-1:2014	SiS (2014a)
Liquid limit	SS-EN ISO 17892-12:2018	SiS (2018b)
Fall cone test	SS-EN ISO 17892-6:2017	SiS (2017)

Study visits were done to observe and gain practical knowledge about field vane tests. Additionally, routine-analysis results obtained from a commercial laboratory were utilized. The routine analyses were performed on piston samples, including determining density, water content, liquid limit and sensitivity using the fall cone test. The results were used for correlating the remoulding energy results to the index parameters.

### 4.1 Study areas

The study areas investigated were primarily chosen to represent the geological environment of southwestern Sweden. This was done to relate the results to a broader context, by studying clay with different properties from a range of depths. The

selection was further based on available data from field vane tests and laboratory results. Additionally, the choice of study areas was influenced by the availability of geological data and supplementary information necessary to address the research questions. This selection process ensured that the chosen locations provided suitable conditions and data for investigating remoulding energy in sensitive clay.

The data utilized for all study areas was a combination of previously conducted field vane tests and laboratory tests with newly acquired data. The study areas were further divided into two groups: one with data from field vane tests performed according to standard procedures, and the other group with data from improved field vane tests.

### 4.2 Field vane test

The field vane shear test was conducted according to the Swedish standard (SiS, 2020). To enable the tests, dry crust and filling were pre-drilled. Then the test was performed at least five times the diameter of the pre-drilled hole below the bottom of the hole. The vane consists of four rectangular blades, 65 x 130mm, fixed at a 90° positioned to each other, see figure 4.1.



**Figure 4.1:** Vane used during field vane test

The vane was pushed down to the desired depth with a constant speed of less than 1 m/min. The test was performed about 2-5 minutes after reaching the intended

depth. The time interval considered is from the activation of the vane until the peak is reached. The time to failure should be within 1 to 3 minutes, with 2 minutes as the reference value. The electric field vane test is equipped with a slip coupling which measures the friction from the rod.

As explained in the previous chapter 3.2.3 regarding remoulding energy, Thakur et al. (2015) states that the total torque per unit volume retrieved in the vane shear test is equivalent to the remoulding energy of the clay. The equation 3.9 can be written as equation 4.1 to determine the undrained shear strength from the field vane test. The peak shear strength was retrieved from the test by measuring the maximum torque.

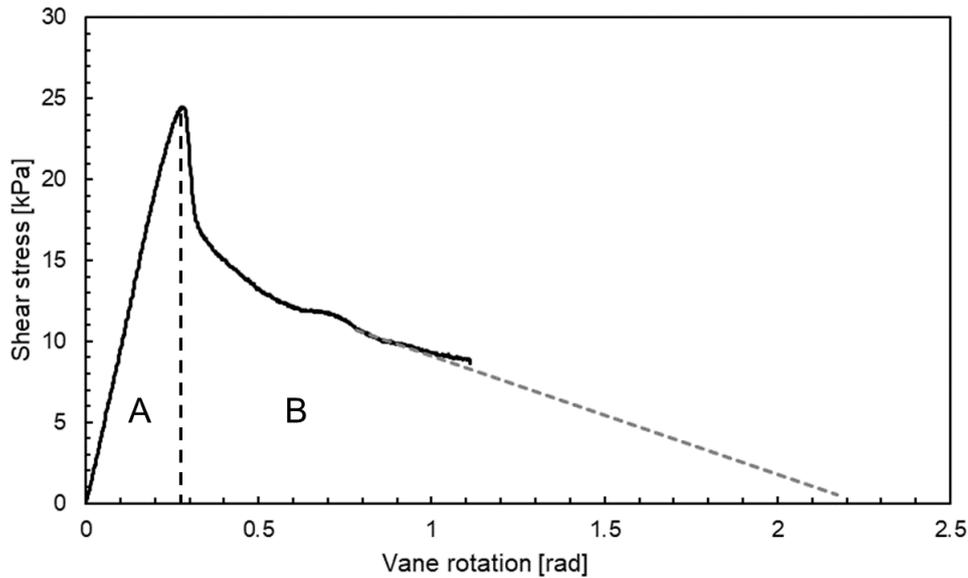
$$c_{up} = \frac{6 T_{tot,max}}{7 \pi D^3} \quad (4.1)$$

To get the remoulded shear strength, the measuring equipment was detached. The vane was then quickly rotated 20 turns to remould the clay. The vane was then turned counterclockwise a short distance (about 15 degrees) so that the slip coupling engages. The measuring equipment was then reattached and the remoulded shear strength was determined.

It should be noted that it is not possible to ensure that the tests performed at the study areas were conducted according to the Swedish standard (SiS, 2020).

### 4.3 Estimation of the energy

After collecting all the data from the performed and previous vane shear tests, the data was evaluated. Vane shear tests conducted at specific depths, along with corresponding routine analysis of the clay, were selected for further analysis. The field vane tests used for the estimation of energy are presented in Appendix A. Firstly, all the results from the field vane tests were extracted by rod friction by estimating the friction at each depth. Since most of the selected tests stopped after a distinct peak was reached, the data had to be extended through linear extrapolation. This extrapolation technique was also applied to the improved tests to accurately model a stress-radial displacement curve. The extrapolation was performed from the tail end of the graph with the same slope until the remoulded shear strength was reached, as illustrated in figure 4.2. Most of the tests did not involve a remoulding phase, so these were supplemented with the remoulded shear strength measured from the fall cone test.



**Figure 4.2:** Extrapolation approach of a vane shear test, marked area A as limit state energy and area B as remoulding energy

After the extrapolation, the areas under the curves were calculated. As shown in figure 4.2, area A up to the peak is referred to as the limit state energy, while area B after the peak represents the remoulding energy. The total amount of energy is then the sum of the two areas. The calculated remoulding energy was normalized following a similar approach as explained in the previous chapter (3.2.1). However, in this case, the remoulding energy was normalized using the limit state energy, as given by equation 4.2.

$$W_N = \frac{\text{Disintegration energy}}{W_{LS}} \quad (4.2)$$

Due to differences in the field vane tests, two different types of results were generated, and thus they required slightly different processing approaches. The standard field vane tests were typically stopped after reaching the peak shear strength, which necessitated additional extrapolation. As a result, the calculated areas for these tests may have a lower level of reliability compared to the tests that were improved with a more extended stress-radial displacement curve.

These results were then correlated to the results from the routine analyses, by performing a statistical analysis with the statistical software SPSS Statistics. The calculated energies were correlated using Pearson correlation to the index parameters. Furthermore, in one of the study areas, the plastic limit was obtained. From this data, the plasticity index could be calculated by using equation 3.1. Which was used for comparison with previous research findings.

# 5

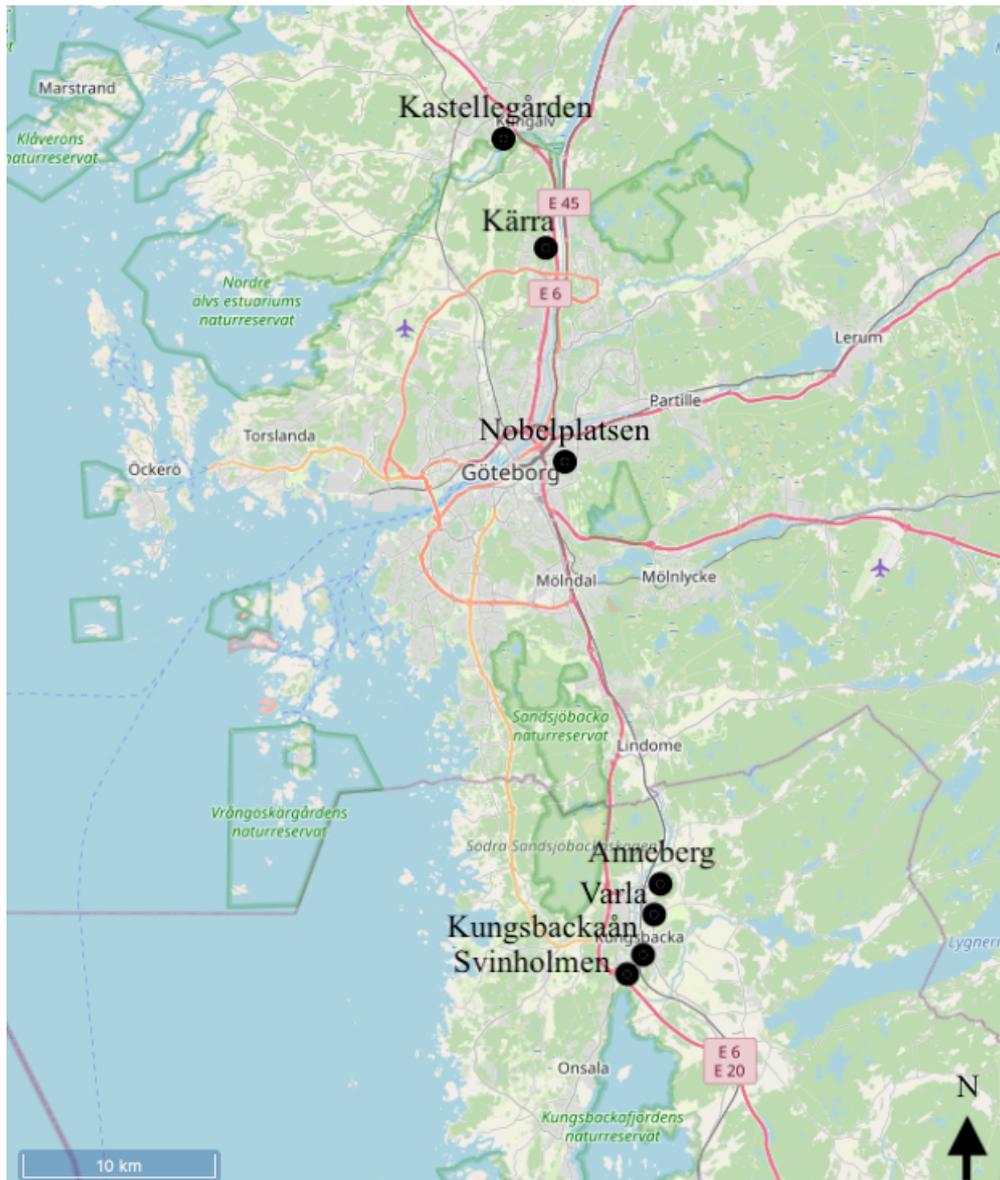
## Study areas

The following chapter presents the geology and a summary of the soil properties from the different study areas. Coordinates for the investigated boreholes are also presented, using the coordinate systems SWEREF 99 12 00 and RH2000. A map presenting an overview of the study areas in southwest Sweden can be seen in figure 5.1. A summary of all study areas and methods can be seen in table 5.1. In this table, the standard method refers to the Swedish standard used to conduct the field vane tests (SiS, 2020). Whereas the improved one implies that the vane was turned until there was no visible change in shear strength. Everything else was conducted according to the Swedish standard (SiS, 2020). It should be noted that in the following chapter when the sensitivity is presented, it is determined from the fall cone test.

**Table 5.1:** Presenting the investigated study areas

<b>Study area</b>	<b>Type of field vane test</b>
Kastellegården, Kungälv	Standard
Kärra, Gothenburg	Improved
Nobelplatsen, Gothenburg	Improved
Anneberg, Kungsbacka	Improved
Varla, Kungsbacka	Standard
Kungsbackaån, Kungsbacka	Standard
Svinholmen, Kungsbacka	Standard

## 5. Study areas



**Figure 5.1:** Map of western Sweden, with the investigated study areas marked out (SGU, 2022b)

Figure 5.2 presents the marine limit of 13000 calendar years before present. From this, it can be seen that all the investigated study areas were below the marine limit.



**Figure 5.2:** The paleogeographic situation of the marine limit 13000 cal. BP in western Sweden, retrieved from (SGU, 2022a)

The marine limit 7000 years calendar years before the present is presented in figure 5.3, timewise to the postglacial marine transgression seen in figure 2.2. Here it can be seen that Nobelplatsen is above the shoreline at the time.

## 5. Study areas



**Figure 5.3:** The paleogeographic situation of the marine limit 7000 cal. BP in western Sweden, retrieved from (SGU, 2022a)

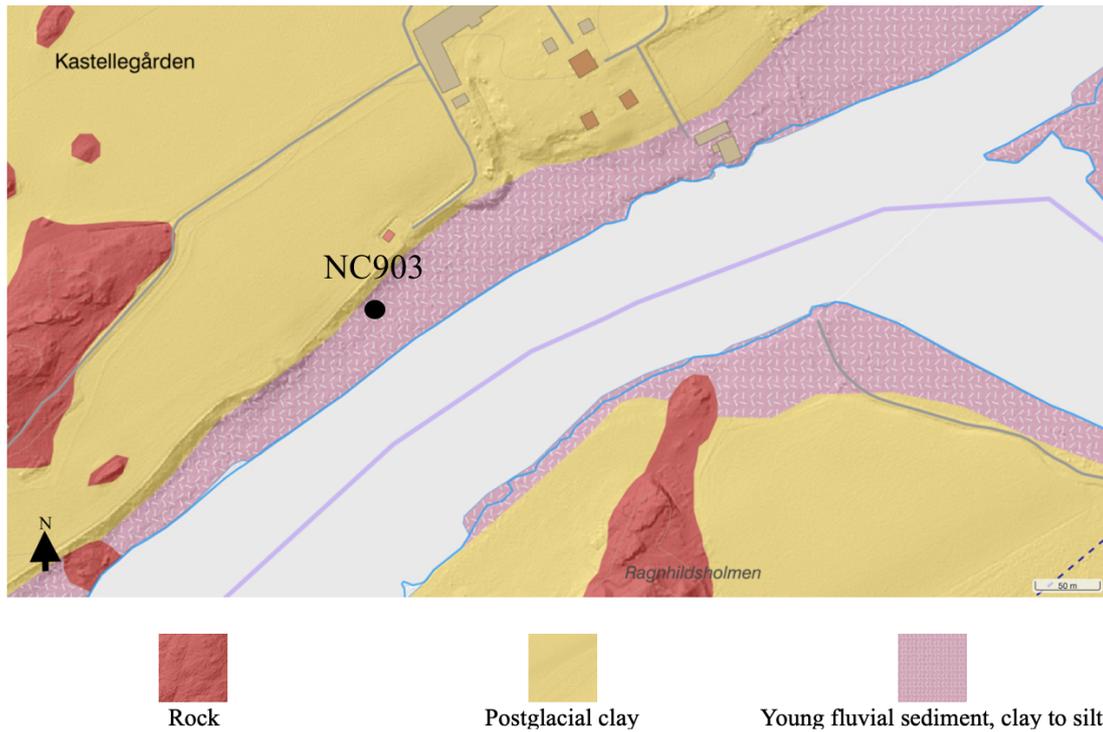
Lastly, figure 5.4 presents the marine limit of today. From this figure, it can be seen that all of the study areas are above the shoreline.



**Figure 5.4:** The paleogeographic situation of the present marine limit year in western Sweden, retrieved from (SGU, 2022a)

## 5.1 Kastellegården, Kungälv

Kastellegården is located north of Gothenburg in the municipality of Kungälv. In figure 5.5 the location of the borehole can be seen, together with the soil layers. According to the laboratory results the soil mainly consists of silty clay. The tests were conducted on the 14<sup>th</sup> of Mars 2023. Additionally, piston samples for routine analysis at the laboratory were taken in borehole NC3. The results from these can be seen in table 5.2. Table 5.3 presents the coordinates for the borehole.



**Figure 5.5:** Geology of Kastellegården, Kungälv, with borehole NC903 marked out, retrieved from (SGU, 2020d)

**Table 5.2:** Laboratory results from Kastellegården, borehole NC903

Depth	$w$ [%]	$w_L$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
3	55	40	36	0.55	20
4	63	56	28	0.62	17
5	65	53	32	0.59	19
6	59	51	30	0.62	19
7	61	47	37	0.55	21

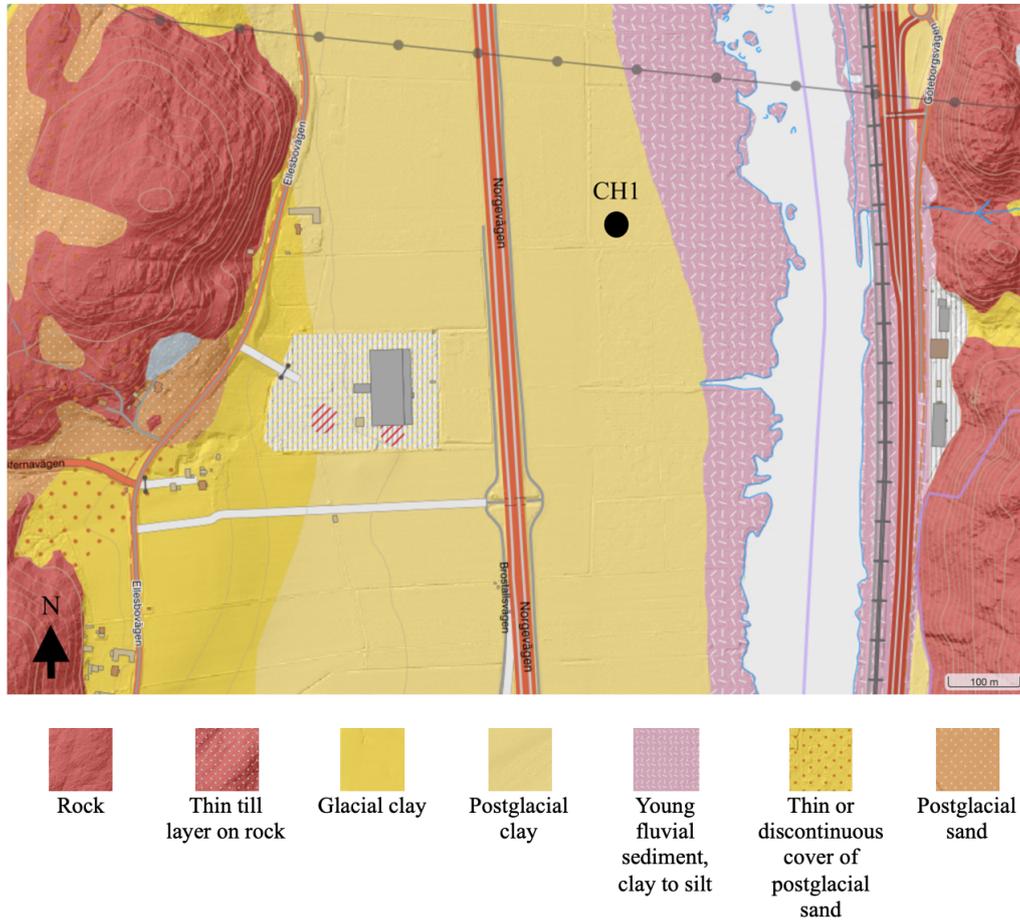
**Table 5.3:** Presenting the coordinates for borehole NC903

Borehole	Method	X	Y	Z
NC903	Vane	6414371.7228	146257.9182	1.0498
NC903	Piston	6414371.7228	146257.9182	1.0498

## 5.2 Kärra, Gothenburg

The study area Kärra is located north of Gothenburg, next to Göta River in the municipality of Gothenburg. In figure 5.6 the location for the borehole can be seen, together with the soil layers. The tests were conducted on the 2<sup>th</sup> of May 2023.

Additionally, piston samples for routine analysis at the laboratory were taken at the site. The results from these be seen in table 5.4. Table 5.5 presents the coordinates for the borehole. Soil classification from the piston samples was not determined.



**Figure 5.6:** Geology of Kärä, Gothenburg, with borehole CH1 marked out, retrieved from (SGU, 2020d)

**Table 5.4:** Laboratory results for Kärä, borehole CH1

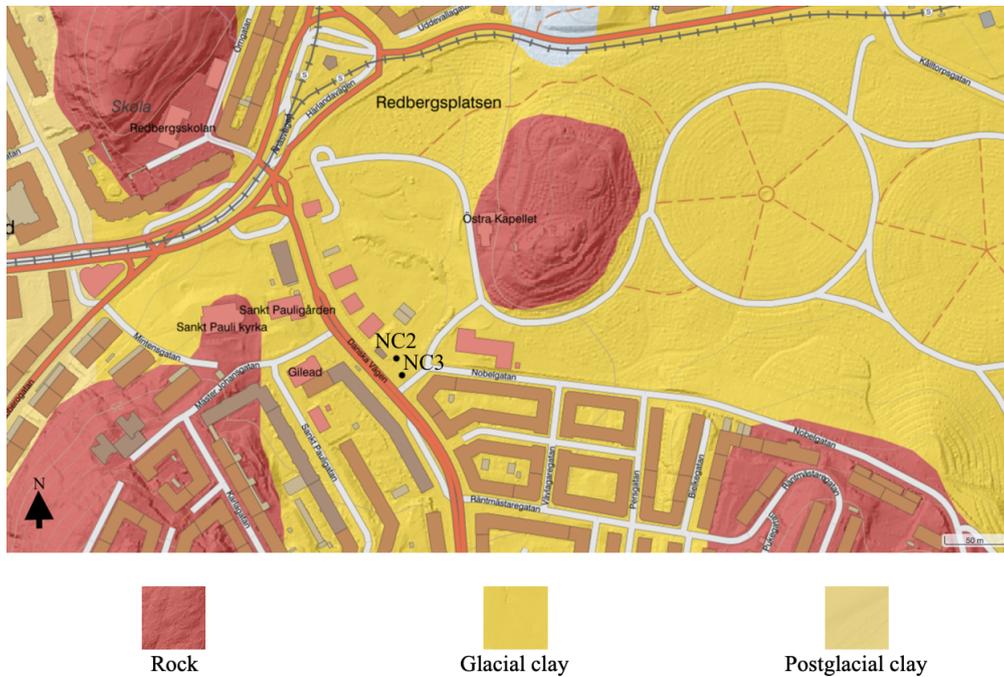
Depth	$w$ [%]	$w_L$ [%]	$w_P$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
2	97	78	30	8	1.45	12
4	89	76	29	12	0.90	10
6	81	76	26	7	1.50	10
8	76	74	31	6	1.97	13
10	72	73	29	9	2.37	23
12	65	68	24	10	2.69	24
15	85	78	27	12	1.57	19
20	64	68	23	14	2.01	28

**Table 5.5:** Presenting the coordinates for borehole CH1

Borehole	Method	X	Y	Z
CH1	Vane	6410351.371	150530.404	1
CH1	Piston	6410351.371	150530.404	1

### 5.3 Nobelplatsen, Gothenburg

The site Nobelplatsen is located in the centre of Gothenburg. The site mainly consists of silty clay but there are some sand lenses throughout the layers. In figure 5.7 the location of the boreholes can be seen, together with the soil layers. The tests were conducted 5<sup>th</sup> of April 2023. Additionally, piston samples for routine analysis at the laboratory were taken in borehole NC3. The results from these can be seen in table 5.6. Table 5.7 presents the coordinates for the boreholes.

**Figure 5.7:** Geology of Nobelplatsen, Gothenburg, with borehole NC2 and NC3 marked out, retrieved from (SGU, 2020d)**Table 5.6:** Laboratory results for Nobelplatsen, borehole NC3

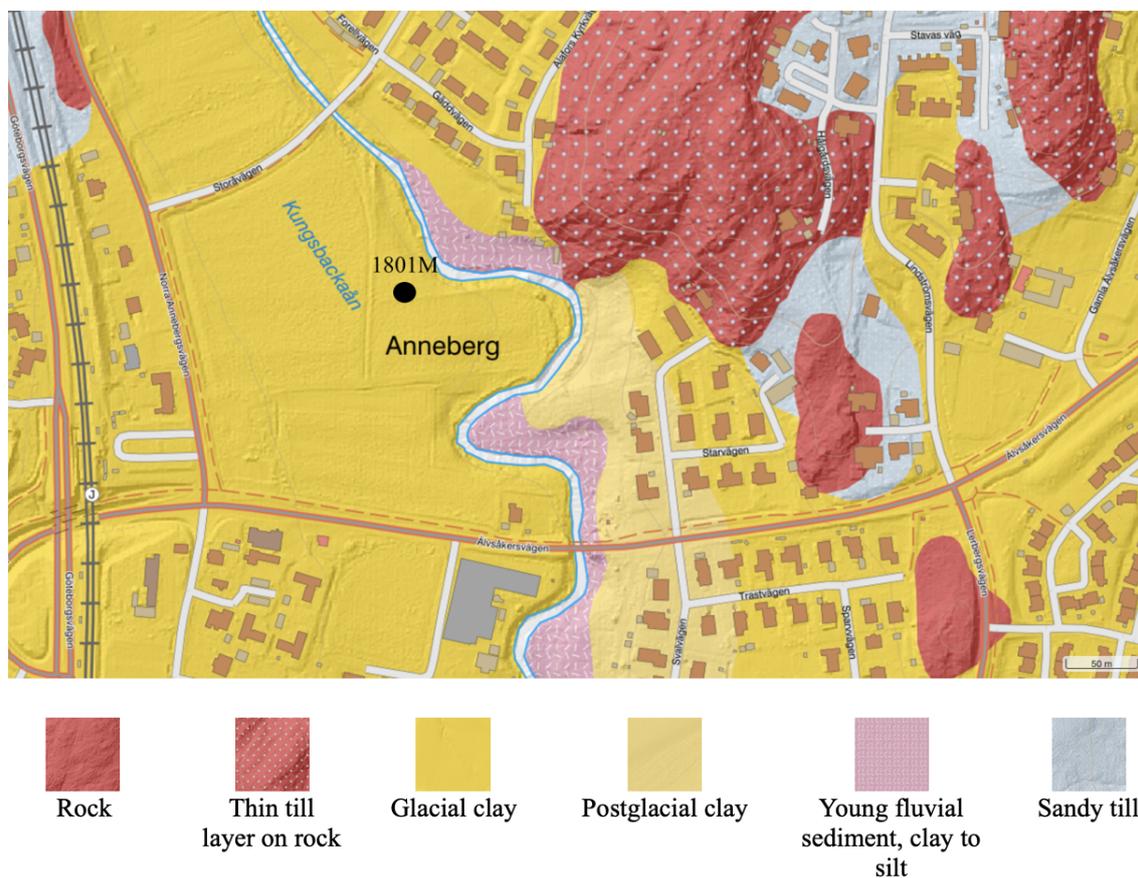
Depth	$w$ [%]	$w_L$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
4	45	45	25	0.79	20
6	44	43	18	1.13	20
7	43	43	22	1.3	28

**Table 5.7:** Presenting the coordinates for the boreholes

Borehole	Method	X	Y	Z
NC2	Vane	6399462.9984	150360.1445	19.6333
NC3	Piston	6399457.1050	150362.8965	19.6055

## 5.4 Anneberg, Kungsbacka

Anneberg is an area located south of Gothenburg in the municipality of Kungsbacka. In figure 5.8 the location of the boreholes can be seen, together with the soil layers. The vane tests were conducted 20<sup>th</sup> of June 2019. From the laboratory test, it is stated that the soil layers mainly consist of silty clay and gyttja silty clay. Additionally, piston samples for routine analysis at the laboratory were taken in borehole 1801M. The results from these can be seen in table 5.8. Table 5.9 presents the coordinates for the borehole.



**Figure 5.8:** Geology of Anneberg, Kungsbacka, with borehole 1801M marked out, retrieved from (SGU, 2020d)

**Table 5.8:** Laboratory results for Anneberg, borehole 1801M

Depth	$w$ [%]	$w_L$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
7	81	69	61	0.21	13
11	78	70	105	0.21	22
20	67	74	219	0.17	37

**Table 5.9:** Presenting the coordinates for the borehole in Anneberg, Kungsbacka

Borehole	Method	X	Y	Z
1801M	Vane	6380067.772	156290.129	6.347
1801M	Piston	6380067.772	156290.129	6.347

## 5.5 Varla, Kungsbacka

The study area Varla is located south of Gothenburg in the municipality of Kungsbacka. In figure 5.9 the location for the borehole can be seen, together with the soil layers. From the routine analysis, it can be seen that the site contains gyttja clay. The field vane tests were conducted at 20<sup>th</sup> of February 2023. Additionally, piston samples for routine analysis at the laboratory were taken in borehole NC206. The results from these can be seen in table 5.10. Table 5.11 presents the coordinates for the borehole.



**Figure 5.9:** Geology of Varla, Kungsbacka, with borehole NC201 and NC206 marked out, retrieved from (SGU, 2020d)

**Table 5.10:** Laboratory results for Varla, borehole NC206

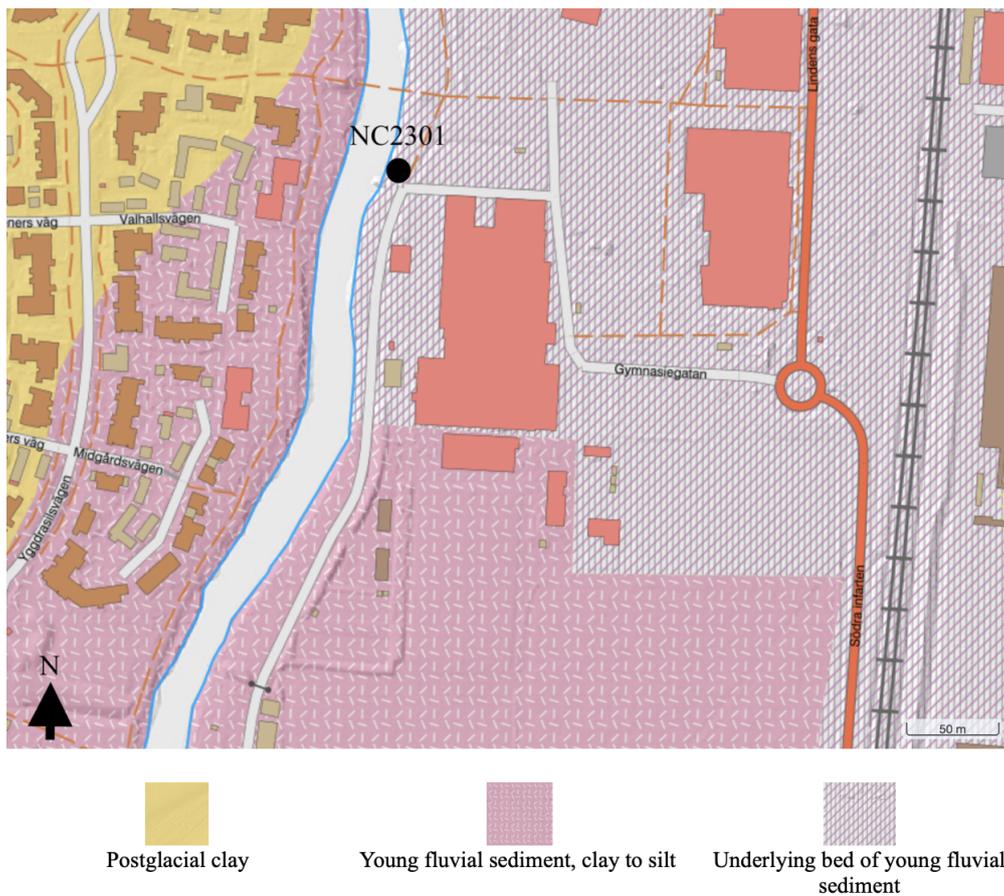
Depth	$w$ [%]	$w_L$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
4	88	90	13	1.24	16
5	87	82	17	0.96	16
6	93	88	14	1.04	15
7	94	86	22	0.89	19
8	88	88	12	1.5	18

**Table 5.11:** Presenting the coordinates for the boreholes

Borehole	Method	X	Y	Z
NC201	Vane	6376393.3419	1154224.7723	2.4492
NC206	Piston	6376360.6445	154377.8231	3.6106

## 5.6 Kungsbackaån, Kungsbacka

The study area Kungsbackaån is located south of Gothenburg in the municipality of Kungsbacka. In figure 5.10 the location for the borehole can be seen, together with the soil layers. According to the laboratory results the soil mainly consists of gyttja clay, gyttja silty clay and silty clay. The tests were conducted on the 12<sup>th</sup> of Mars 2023. Additionally, piston samples for routine analysis at the laboratory were taken in borehole NC2301. The result from these can be seen in table 5.12. Table 5.13 presents the coordinates for the borehole.



**Figure 5.10:** Geology of Kungsbackaån, Kungsbacka, with borehole NC2301 marked out, retrieved from (SGU, 2020d)

**Table 5.12:** Laboratory results for Kungsbackaån, borehole NC2301

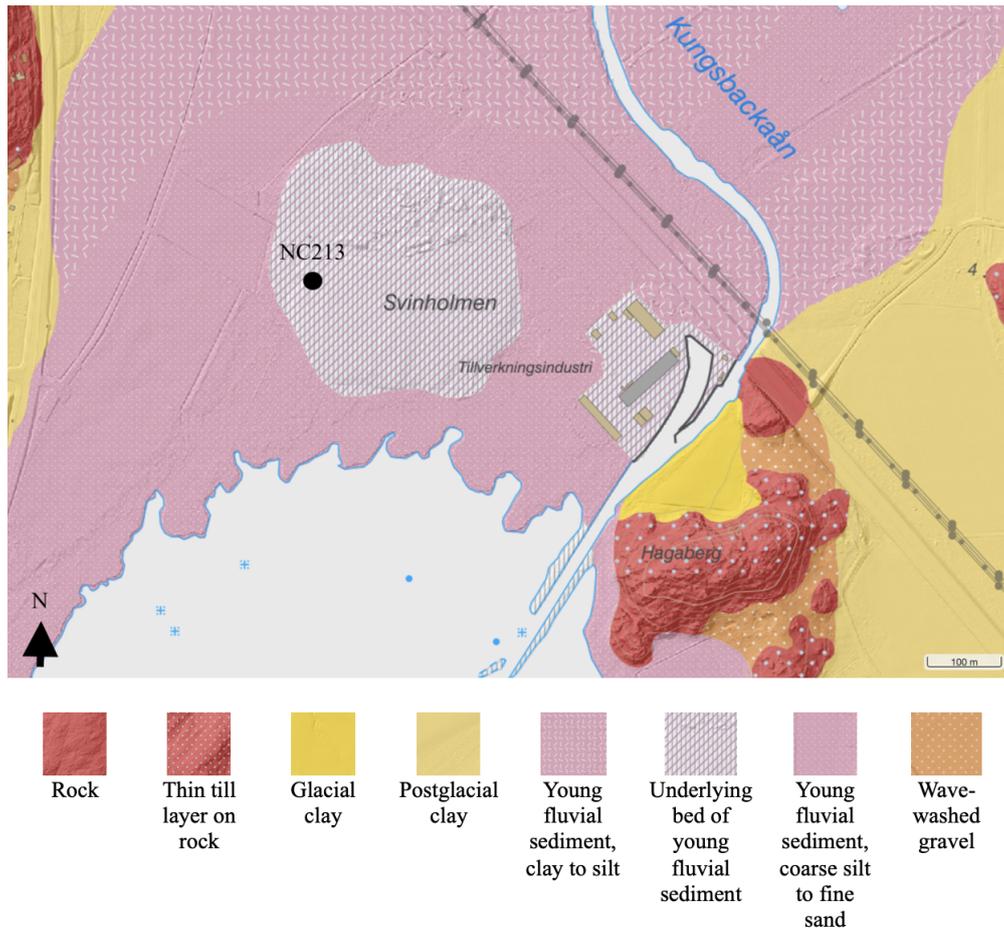
Depth	$w$ [%]	$w_L$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
3	101	83	18	0.55	10
4	96	85	18	0.71	13
5	97	87	18	0.89	16
6	95	86	15	0.96	14
7	92	84	17	0.96	17
8	93	92	12	1.36	16
10	83	87	12	1.66	19
12	82	84	14	1.85	26
15	78	85	11	2.34	27
18	75	76	17	1.50	26
20	75	76	18	1.85	33

**Table 5.13:** Presenting the coordinates for borehole

Borehole	Method	X	Y	Z
NC2301	Vane	6373481.0340	154452.2960	1.3380
NC2301	Piston	6373481.0340	154452.2960	1.3380

## 5.7 Svinholmen, Kungsbacka

Svinholmen is an area located south of Kungsbacka. Some of the area has previously been used as a landfill. The site mainly consists of clay, as seen in figure 5.11. From the laboratory results it is stated that at a depth between 9 and 20 meters, there is gyttja silty clay. Additionally, piston samples for routine analysis at the laboratory were taken in borehole NC213. The results from these can be seen in table 5.14. The tests were conducted on the 2<sup>nd</sup> of Mars, 2023. Table 5.15 presents the coordinates for the borehole.



**Figure 5.11:** Geology of Svinholmen, Kungsbacka, with borehole NC213 marked out, retrieved from (SGU, 2020d)

**Table 5.14:** Laboratory results for Svinholmen, borehole NC213

Depth	$w$ [%]	$w_L$ [%]	$S_t$	$c_{ur}$ [kPa]	$c_u$ [kPa] (not corrected)
9	79	87	7	2.60	19
10	84	82	15	1.36	20
12	83	83	12	1.59	19
14	84	85	12	1.59	20
16	81	84	11	1.85	20
18	76	80	12	1.98	24
20	77	74	17	1.20	21

**Table 5.15:** Presenting the coordinates for the borehole

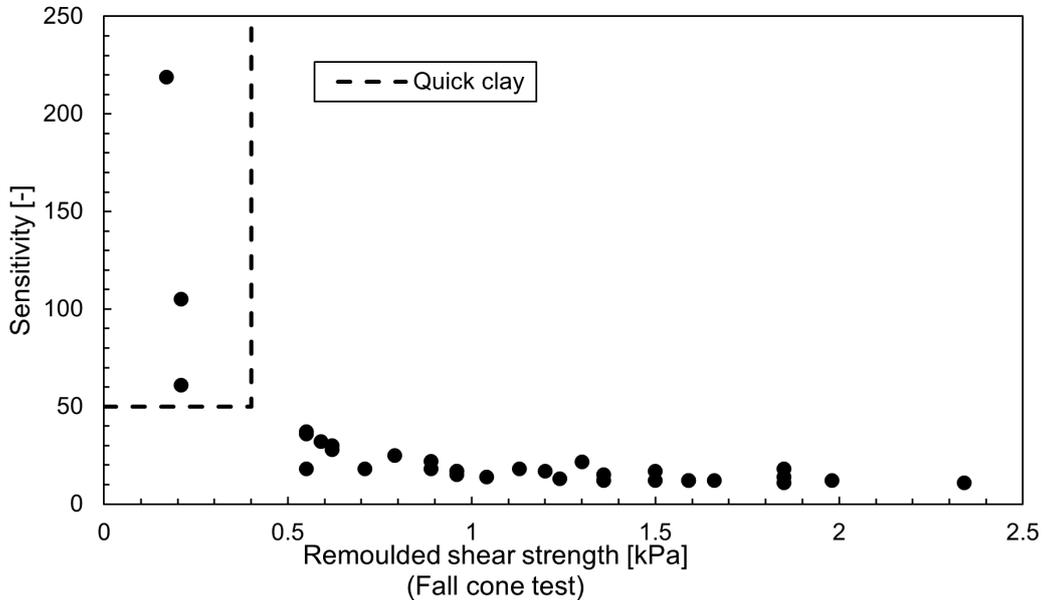
Borehole	Method	X	Y	Z
NC213	Vane	6371666.436	153892.546	2.000
NC213	Piston	6371666.436	153892.546	2.000

# 6

## Results

In this chapter, the findings obtained from the investigation of remoulding energy in sensitive clay through the field vane tests are presented. The correlations identified between remoulding energy and index parameters are presented. Furthermore, the time dependency of the field vane test is examined, comparisons with previous research findings and highlighting any notable differences between the standard and improved vane tests. Additionally, separate investigations of the study area Kärra with additional data were conducted to cover a broader range of parameters.

From figure 6.1 the sensitivity distribution of all investigated clay is presented. As the dashed box presents, only three of the investigated clay samples classifies as quick clay according to the Swedish definition.



**Figure 6.1:** Distribution of the observed clay. The dashed area represents the Swedish classification of quick clay, sensitivity and remoulded shear strength from the fall cone test

In table 6.1 all the calculated energies are presented.

## 6. Results

**Table 6.1:** Results of all calculated energies for each study area and depth

Study area	Depth [m]	Total energy [kNm/m <sup>3</sup> ]	Limit state energy [kNm/m <sup>3</sup> ]	Remoulding energy [kNm/m <sup>3</sup> ]	Normalized energy [-]
Kastellegården	3	11.15	3.94	7.21	1.83
Kastellegården	4	8.32	3.50	4.82	1.37
Kastellegården	5	8.52	3.08	5.44	1.77
Kastellegården	6	9.96	3.38	6.58	1.95
Kastellegården	7	12.97	6.68	6.30	0.94
Kärra	2	15.98	1.67	14.31	8.59
Kärra	4	16.44	1.51	14.92	9.86
Kärra	6	12.41	2.00	10.41	5.22
Kärra	8	18.27	3.19	15.09	4.74
Kärra	10	21.43	5.20	16.23	3.12
Kärra	12	31.35	8.39	22.96	2.74
Kärra	15	29.64	9.93	19.70	1.98
Kärra	20	26.09	11.84	14.25	1.20
Nobelplatsen	4	20.14	2.72	17.42	6.39
Nobelplatsen	6	19.44	3.29	16.14	4.90
Nobelplatsen	7	18.85	7.25	11.60	1.60
Anneberg	7	5.64	1.72	3.92	2.28
Anneberg	11	6.00	3.37	2.63	0.78
Anneberg	18	11.99	7.29	4.70	0.64
Kungsbackaån	3	5.29	1.43	3.86	2.71
Kungsbackaån	4	5.85	1.88	3.96	2.11
Kungsbackaån	5	4.58	1.75	2.83	1.62
Kungsbackaån	6	4.99	1.90	3.10	1.63
Kungsbackaån	7	4.88	2.19	2.69	1.23
Kungsbackaån	8	5.04	2.41	2.63	1.09
Kungsbackaån	10	7.21	3.60	3.60	1.00
Kungsbackaån	12	11.55	5.84	5.71	0.98
Kungsbackaån	15	13.09	7.86	5.22	0.66
Kungsbackaån	18	16.90	9.70	7.20	0.74
Kungsbackaån	20	22.84	13.79	9.05	0.66
Varla	4	2.88	1.18	1.70	1.43
Varla	5	2.81	1.22	1.59	1.30
Varla	6	3.24	1.29	1.96	1.52
Varla	7	2.68	0.98	1.69	1.73
Varla	8	3.33	1.18	2.15	1.83
Svinholmen	10	10.24	2.96	7.28	2.46
Svinholmen	12	13.77	3.20	10.57	3.30
Svinholmen	14	11.60	4.04	7.55	1.87
Svinholmen	16	12.19	5.52	6.67	1.21
Svinholmen	18	13.72	6.96	6.75	0.97
Svinholmen	20	15.03	6.66	8.37	1.26

Since the field vane tests were performed in two slightly different ways, the results were then also checked to find similarities and differences. A detailed investigation of this will be presented in this chapter. Table 6.2 presents a summary of the depth and total energy mean values for the two approaches. From this, one can see a significant difference in results between the improved and the standard approach results. The total energy is about twice as large for the improved one compared to the standard one.

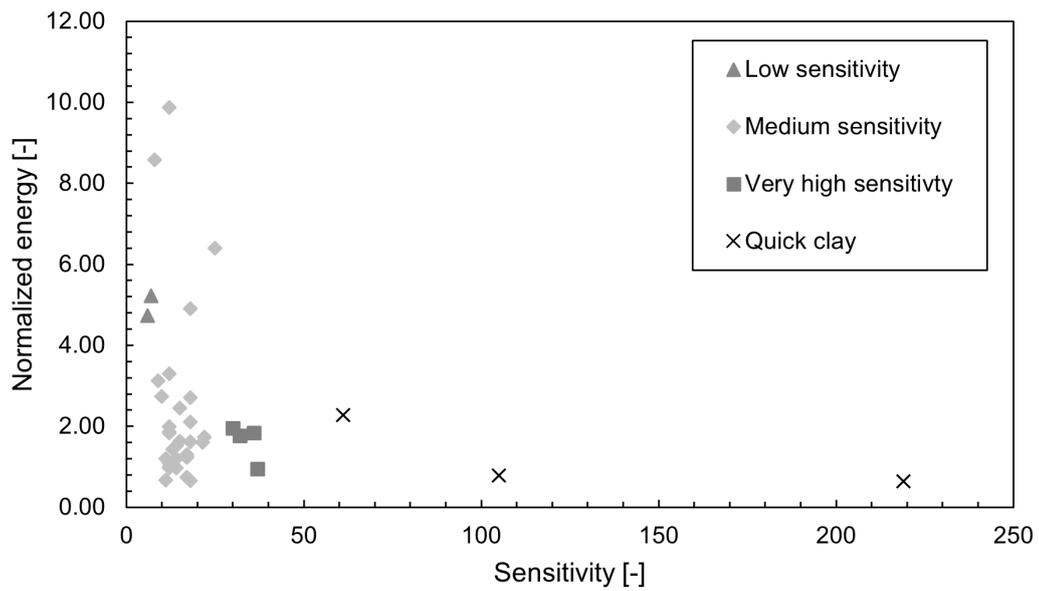
**Table 6.2:** Calculated mean values of depth and total energy for the two different field vane test approaches

Mean values	Improved	Standard
Depth [m]	9.3	9.4
Total energy [kNm/m <sup>3</sup> ]	17.96	9.06

## 6.1 Correlations to other parameters

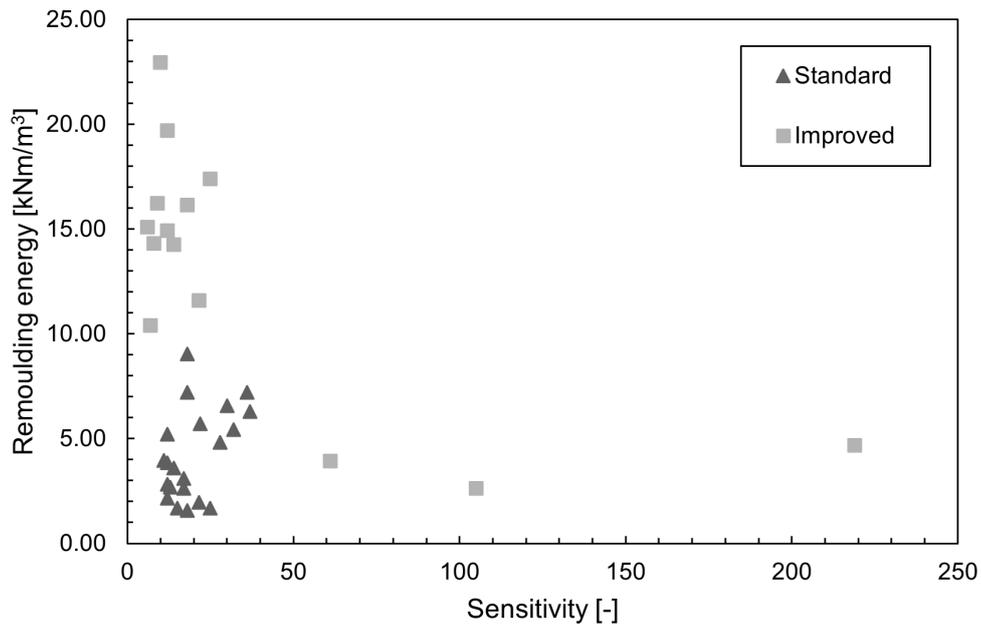
After the calculation of energies from the vane tests, a statistical analysis was performed, using IBM SPSS Statistics, to find correlations to the clay parameters. All results and parameters were correlated using Pearson correlation. Correlation values for all investigated parameters can be found in Appendix A. Some of the correlations are self-evident and will therefore not be evaluated further.

Figure 6.2 shows the relationship between the normalized energy and sensitivity of the clay, along with the associated sensitivity classification. A weak correlation was observed between these two parameters, with a correlation coefficient of -0.21. The plot reveals that quick clay or clay with very high sensitivity generated low normalized energy in comparison to clay with low sensitivity. This may indicate that clay with a higher sensitivity requires almost equal energy to reach failure as to fully remould. Since sensitivity could not be retrieved for all clays from the field vane tests, the used correlated sensitivity is the one determined from the fall cone test.



**Figure 6.2:** Normalized energy versus sensitivity determined with fall cone test, correlation value -0.21

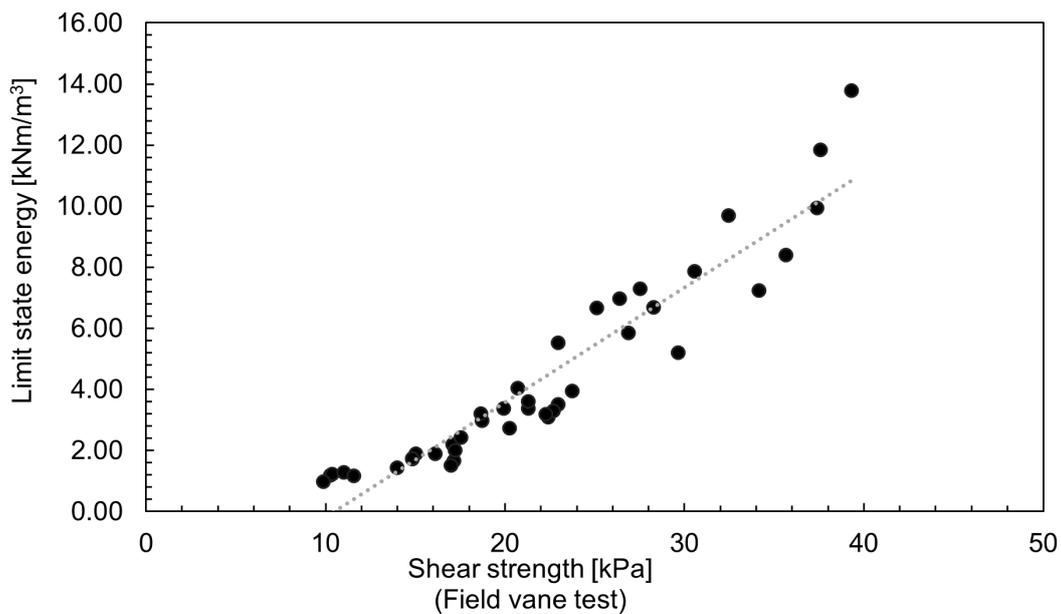
Similarly as normalized energy versus sensitivity, a weak correlation was found for the remoulding energy with sensitivity. However, from figure 6.3 it is clear that the improved test results show a more distinct negative trend than the results from the standard approach. The figure also presents that the remoulding energies from the improved approach are larger than the standard remoulding energies.



**Figure 6.3:** Remoulding energy from standard and improved approach versus sensitivity, correlation value -0.21

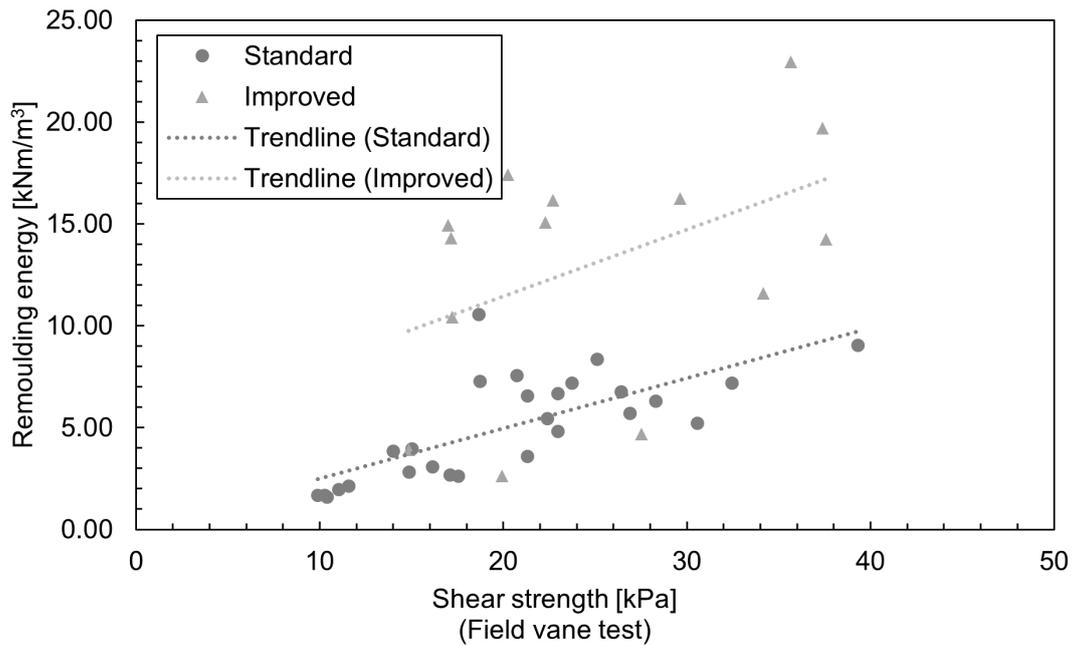
### 6.1.1 Shear strength

In figure 6.4, the limit state energy is plotted against shear strength obtained from the field vane test. These two parameters show a strong positive correlation. The higher the clay shear strength, the higher the energy level needed to reach failure.



**Figure 6.4:** Limit state energy plotted versus shear strength obtained from field vane test, correlation value 0.94

The remoulding energy results were also plotted against the shear strength obtained from the field vane test, as illustrated in figure 6.5. However, it is worth noting that this correlation appears to be weaker compared to the correlation observed between the limit state energy and shear strength. The figure demonstrates the differences in outcomes between the standard and improved approaches, with the improved tests generating higher levels of remoulding energy. Furthermore, the results obtained from the standard approach exhibit a stronger correlation with shear strength and align more closely with the linear trendline.

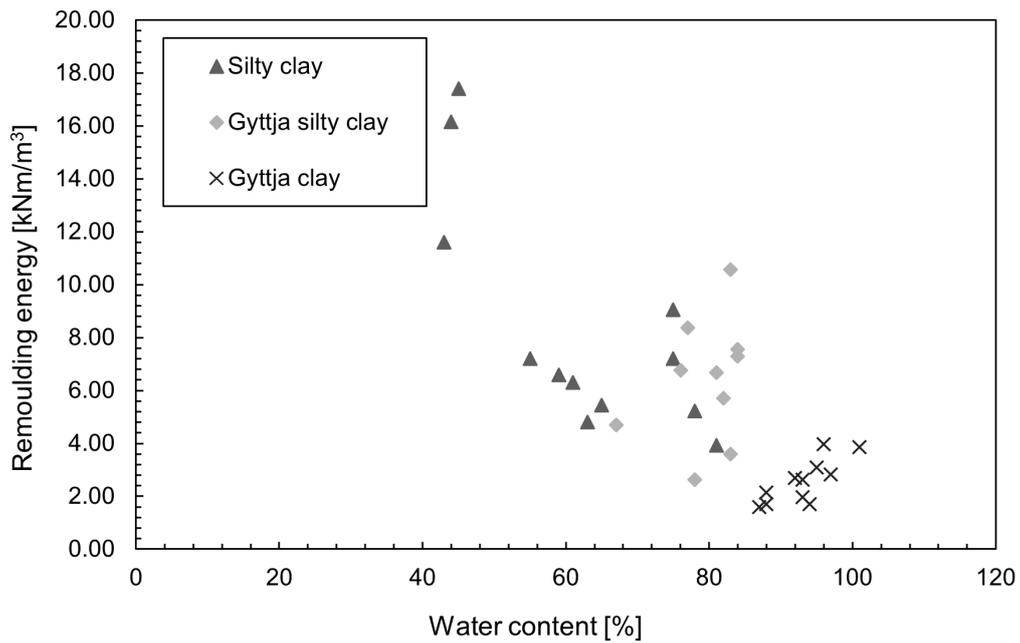


**Figure 6.5:** Remoulding energy from standard and improved approach plotted versus shear strength obtained from field vane test with associated linear trendlines, correlation value 0.57

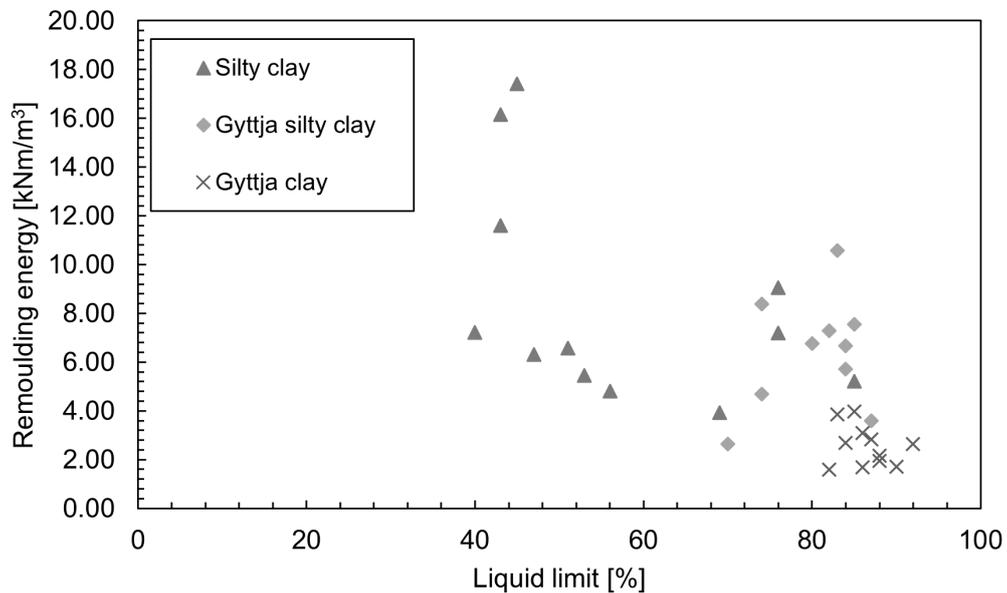
### 6.1.2 Water content and liquid limit

Figure 6.6 presents a negative correlation between remoulding energy and water content. It is clear that clay with a high water content, such as gyttja clay has a lower remoulding energy compared to clay with lower water content. Similarly, figure 6.7 presents a negative correlation between remoulding energy and liquid limit.

It should be noted that the results from Kärä have been excluded since no soil classifications were made for this study area. Therefore, the chosen data have also been re-correlated in SPSS and the new correlation values are presented in the caption of each figure.



**Figure 6.6:** Remoulding energy versus water content, correlation value -0.75



**Figure 6.7:** Remoulding energy versus liquid limit, correlation value -0.63

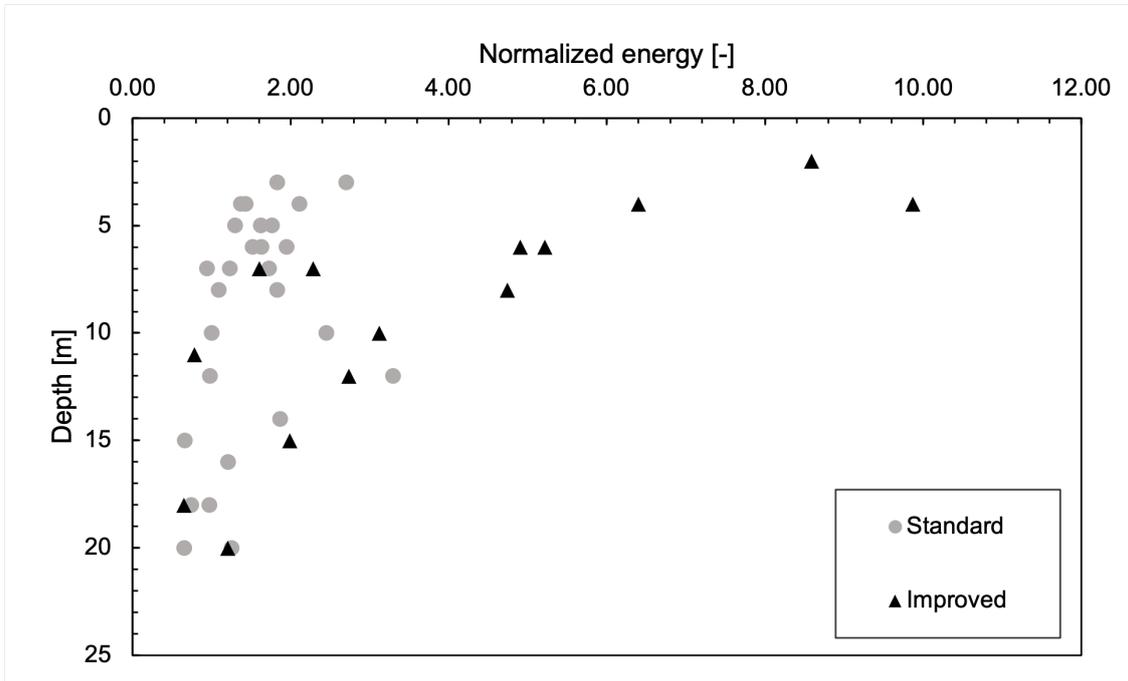
### 6.1.3 Energy in relation to depth

Figure 6.8 shows how the normalized energy varies over depth. It can be seen that the highest values for the normalized values are from the improved field vane test.

## 6. Results

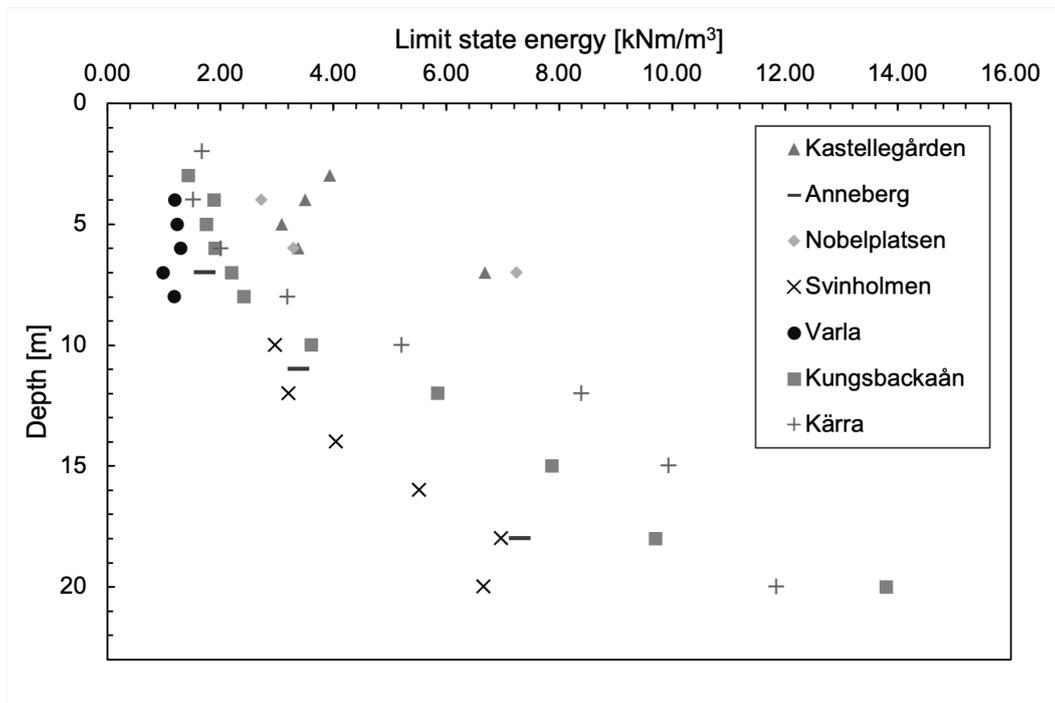
---

The normalized energy is the highest and closest to the surface and decreases with depth.



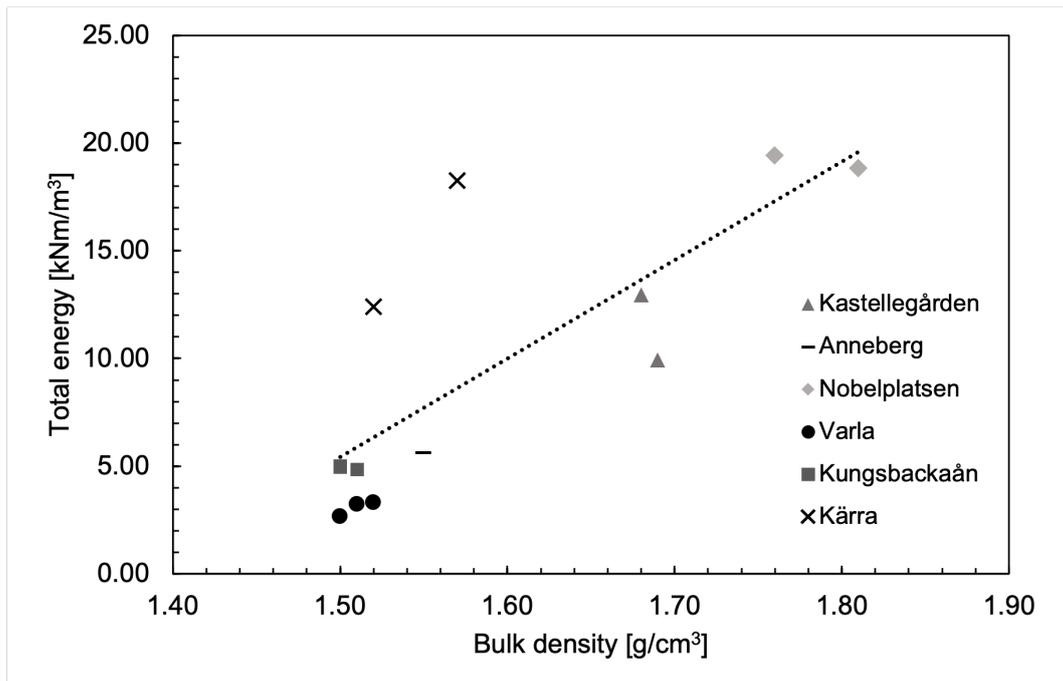
**Figure 6.8:** Normalized energy plotted against depth, correlation value -0.44, with a linear trendline fitted to the standard and improved data points

In figure 6.9 it can be seen that the majority of the study areas have an increase of the limit state energy with increasing depth. However, there are exceptions, such as Kastellegården, which exhibits a decrease over depth, and Varla, which remains relatively consistent over depth.



**Figure 6.9:** Plot of the limit state energy versus depth, for the different study areas

Figure 6.10 shows a positive trend between bulk density and total energy, for values from 6, 7 and 8 meters depth. It can be seen that the highest-located area, Nobelplatsen, results in the highest total energy and highest bulk density. As seen, Varla, Kungsbackaån and Anneberg, are located close to each other, resulting in very similar total energy and bulk density.



**Figure 6.10:** Total energy versus bulk density, for 6, 7 and 8 meters depth, with a correlation value of 0.790

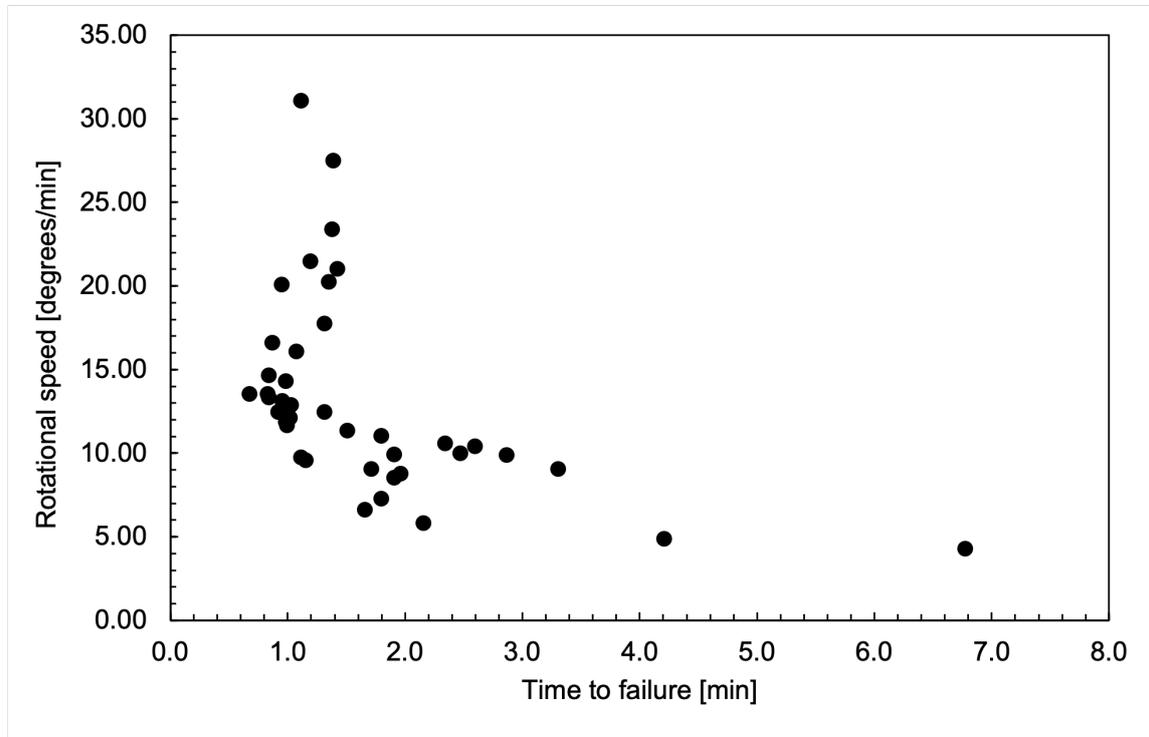
## 6.2 Time and speed dependency

During the tests, different speeds has been used when conducting the vane shear tests. These rotational speeds are varying from approximately 0.07 to 0.46 degrees/s, as seen in table 6.3.

**Table 6.3:** Used rotational speeds for the field vane tests for each site and depth together with time to failure

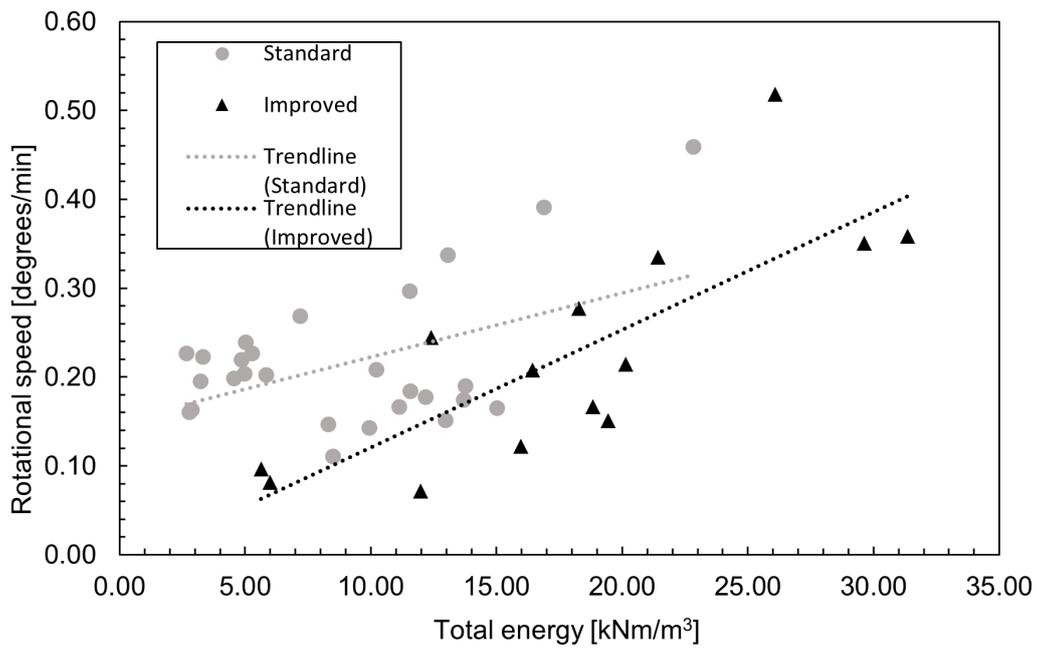
Site	Depth [m]	Rotational speed [degrees/s]	Time to failure [min]
Kastellegården	3	0.17	1.9
Kastellegården	4	0.15	2.0
Kastellegården	5	0.11	1.7
Kastellegården	6	0.14	1.9
Kastellegården	7	0.15	3.3
Nobelplatsen	4	0.21	1.0
Nobelplatsen	6	0.15	1.7
Nobelplatsen	7	0.17	2.5
Kärra	2	0.12	1.8
Kärra	4	0.21	0.9
Kärra	6	0.24	0.8
Kärra	8	0.28	0.9
Kärra	10	0.33	0.9
Kärra	12	0.36	1.2
Kärra	15	0.35	1.4
Kärra	20	0.52	1.1
Anneberg	7	0.10	2.2
Anneberg	11	0.08	4.2
Anneberg	18	0.07	6.8
Varla	4	0.16	1.1
Varla	5	0.16	1.2
Varla	6	0.19	1.0
Varla	7	0.23	0.7
Varla	8	0.22	0.8
Kungsbackaån	3	0.23	0.8
Kungsbackaån	4	0.20	1.0
Kungsbackaån	5	0.20	1.0
Kungsbackaån	6	0.20	1.0
Kungsbackaån	7	0.22	1.0
Kungsbackaån	8	0.24	1.0
Kungsbackaån	10	0.27	1.1
Kungsbackaån	12	0.30	1.3
Kungsbackaån	15	0.34	1.4
Kungsbackaån	18	0.39	1.4
Kungsbackaån	20	0.46	1.4
Svinholmen	10	0.21	1.3
Svinholmen	12	0.19	1.5
Svinholmen	14	0.18	1.8
Svinholmen	16	0.18	2.3
Svinholmen	18	0.17	2.6
Svinholmen	20	0.16	2.9

Figure 6.11 presents the rotational speed during the field vane test versus the time to failure reached during the field vane tests. A negative trend can be seen and from the correlation analysis, a correlation value of -0.48 was retrieved.



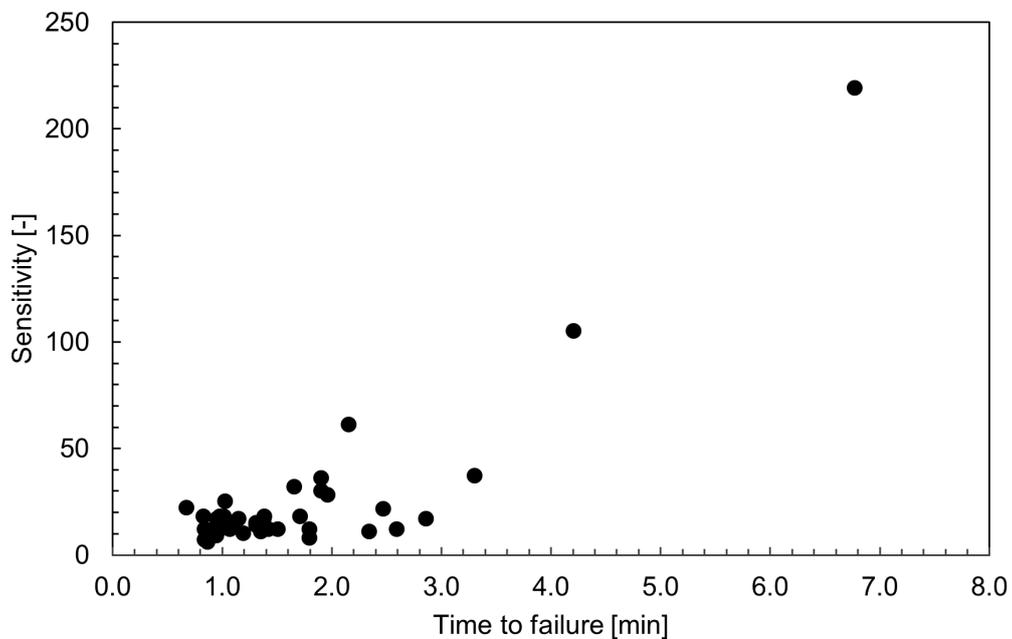
**Figure 6.11:** Plot of the rotational speed versus the time to failure, with a correlation value of -0.48

Figure 6.12 presents the rotational speed during the vane shear test versus the total energy, which was extrapolated from the vane shear test. A positive trend can be seen for both standard and improved tests. The inclination for the trendline from standard tests is lower than the improved one.



**Figure 6.12:** Plot of the rotational speed versus the total energy, for both improved and standard tests, correlation value 0.56

Figure 6.13 presents the time to failure versus sensitivity. There is a weak trend that with increasing sensitivity the time to failure is increasing.



**Figure 6.13:** Plot of the sensitivity versus the time to failure is reached, correlation value 0.87

Figure 6.14 shows how the rotational speed varies over depth, for the seven different study areas. It is clear that Kungsbackaån and Kärra has an increase of rotational speed with increasing depth. Svinholmen has a steady rotational speed, with a slight decrease over depth.

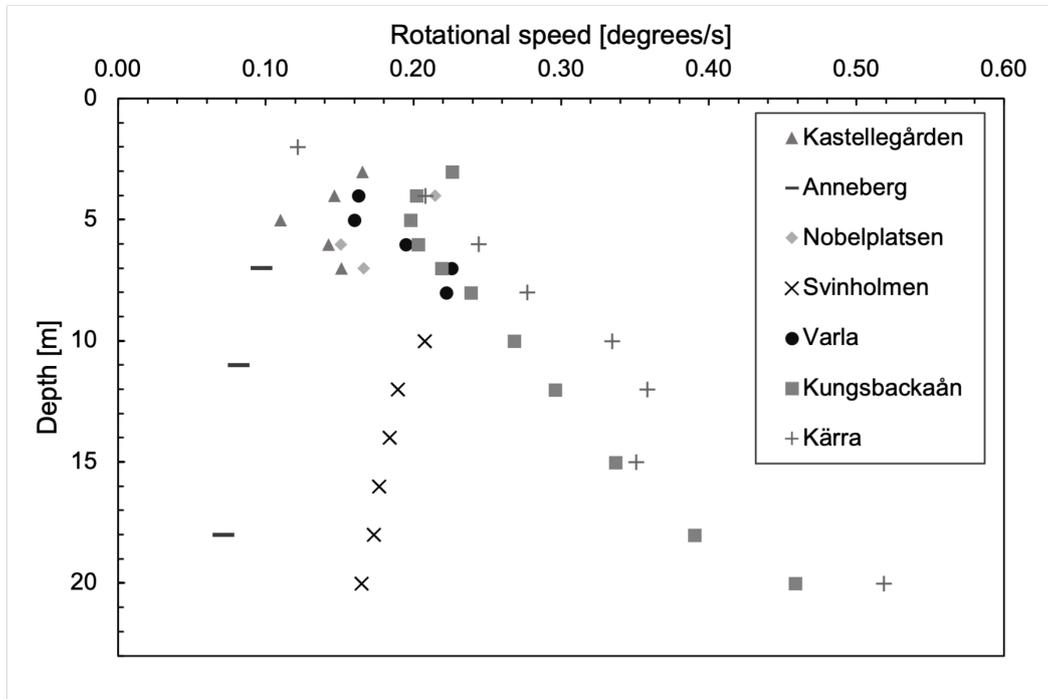
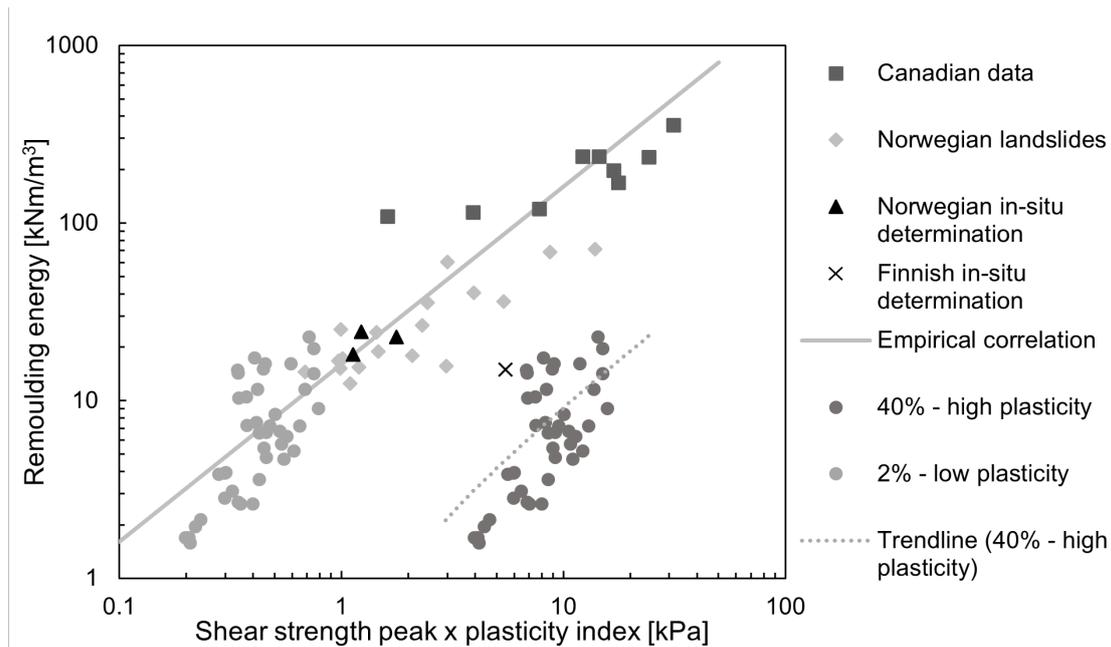


Figure 6.14: Plot of the rotational speed versus depth, for the different study areas

### 6.3 Comparison with previous findings

The obtained results were then compared to previous findings of remoulding energy, presented in chapter 3.2.3. Since most of the calculated energies are missing corresponding plastic limits, the results have been plotted with estimated plasticities, see figure 6.15. Two plasticity indices have been assumed, 2% representing very low plasticity and 40% representing high plasticity. These assumptions is assuming that all clay has the same plasticity index, which is not the real case. However, this is done to test if the results are in line with previous findings. It is also important to highlight, as figure 6.1 presents, that only a small fraction of this thesis' investigated samples are defined as quick clay. For the previous findings, the majority of the clay has been classified as quick clay, but not according to Swedish definitions. This is yet another difference between the results.



**Figure 6.15:** Remoulding energy estimated with 2 % and 40 % plasticity index plotted with previous findings

From the plot, one can see that the calculated values with 2% plasticity are in the same agreement as the other findings. However, most of the results for the remoulding energy are of a smaller magnitude than the other findings.

In one of the study areas the plastic limit was obtained and the plasticity index could be calculated. The values for Kärä were then plotted along with previous findings in figure 6.16. The results for the remoulding energy are in the same range as the other results. However, the products of the shear strength and plasticity index are higher. The clay in Kärä, Gothenburg has higher plasticity which causes a rightward shift along the x-axis. The clay in Kärä also has a lower sensitivity, with a range of low to medium sensitivity. As mentioned, the majority of the other research findings are classified as quick clay, which could be another reason for the differences.

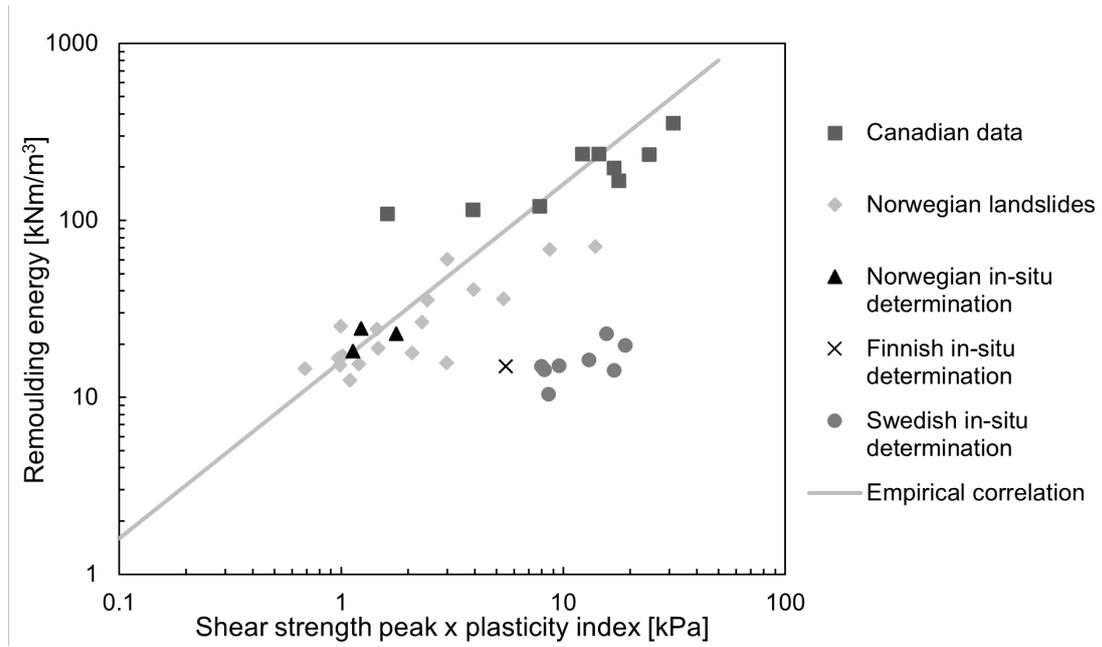


Figure 6.16: Results for Kärä plotted with previous findings

# 7

## Discussion

Findings from the remoulding-energy investigation are discussed in the following chapter. The correlations identified between remoulding energy and investigated parameters are discussed. The chapter also covers the time dependency of field vane tests along with advantages, disadvantages and differences between the standard and improved methodologies. Finally, previous research is compared with the findings from Kärä.

Presented in figure 6.1, only three of the investigated clay classifies as quick clay according to the fall cone test. The other clay ranges from low to very high sensitivity. Since most of the stability problems in clay are connected to quick clay, it would have been more representative to investigate a broader set of quick-clay data. To further evaluate and draw conclusions about remoulding energy in quick clay, more field vane tests should be performed.

The field vane tests have been conducted either according to the standard or as an improved. The improved one refers to the rotation of the vane where this one has been rotated further. The comparison between these two can be seen in table 6.2 where the improved results in higher energy. This indicates that the standard test might underestimate the remoulding energy, but without these the data set would be inadequate. Due to this some of the results present the difference in results between standard and improved. Since the energies is varying both between study areas and also between depths, as seen in table 6.1, all of them will be compared further. To estimate the energy as precise as possible it is suggested to implement a longer rotation of the vane during field vane tests.

### 7.1 Correlations

Based on the analysis of figures 6.4 and 6.5, it becomes evident that there exists a strong positive correlation not only between limit state energy and shear strength but also between remoulding energy and shear strength. Both figures demonstrate that higher shear strength in the clay corresponds to an increased requirement for energy, both to reach failure and to fully remould. This is partly due to the strong bonds between clay particles and the clay being more resistant to disturbances, which thus results in the need for more energy to be disturbed. A stronger correlation was found for limit state energy, which implies that when knowing the shear strength it

is more certain to determine the energy level needed to reach failure, than the energy level needed to fully remould. The results for remoulding energy are depending on the extrapolation. The limit state energy retrieved from the field vane test are not depending on extrapolation but on other factors such as time and speed for the test.

According to figure 6.8 the normalized energy decreases with increasing depth. The ratio of limit state energy and remoulding energy approaches 0 at deeper depths. Thus, it requires equal or more energy to reach failure than to fully remould the clay at deeper depths. This is in line with figure 6.9 which presents a strong positive correlation between depth and limit state energy.

Figure 6.8 also presents the difference between the improved and standard approaches, with the highest values for the normalized values from the improved vane shear test. Since the calculations from the improved tests have generated a larger magnitude of remoulding energies, the normalized energies will also be much higher than for the standard approach. However, the improved results show a clearer correlation over depth, with decreasing normalized energy over depth. The standard results are probably an underestimate of remoulding energy and therefore do not result in higher normalized energy than about 3.

As mentioned, the normalized energy versus depth is connected to figure 6.9, which presents that the majority of the study areas have an increase of the limit state energy with increasing depth. Clay at larger depths, defined as glacial clay, has been exposed to more erosion which causes a higher degree of consolidation. The consolidation reduces the natural water content in the clay (Larsson, 2008). This is in line with the correlation values for water content and shear strength over depth, according to Appendix B. The correlation values present that the shear strength is increasing over depth, but also that the shear strength is negatively correlated to water content. Over depth, the consolidation has contributed to a lower water content in the clay and a higher shear strength which results in the need for more energy to reach failure. A limit state energy as large or larger than the remoulding energy is then also generating a normalized energy of 1 or below 1.

However, figure 6.9 presents some exceptions, such as for Kastellegården, which exhibits a decrease in limit state energy over depth, and Varla, which remains relatively consistent over depth. From these two study areas, there is only data until a depth of 8 meters which means that it might not be representative when comparing energy over depth. The results might have been similar to the other study areas if these also would have been investigated deeper. The results from Kastellegården do, however, show a different trend with decreasing energy for the three first depths. From the laboratory results, presented in table 5.2, the clay showed a decrease in shear strength for the same depths. Also, the shear strength obtained from the field vane tests showed similar results, as presented in Appendix A. This explains the deviations found in Kastellegården's results since the limit state energy is strongly positively correlated to shear strength as presented in figure 6.4.

Figure 6.2 indicates that clay with a higher sensitivity requires almost the same amount of energy to reach failure as it does to be fully remoulded. This finding is

consistent with the fact that high-sensitive clay can undergo significant deformation even under very small changes in stress (Khalidoun et al., 2009). This deformation may cause a significant reduction in the shear strength of the clay.

Figure 6.3 presents the relationship between remoulding energy and sensitivity which presents a weak negative correlation. This indicates that clays with high sensitivity tend to have low remoulding energies and therefore also more easily remoulded. This weak negative correlation has also been identified by Thakur and Degago (2013). By the correlation values presented in Appendix B, it can be seen that the correlation value for remoulding energy versus the remoulded shear strength obtained from the fall cone test is 0.47. The correlation value for remoulding energy and undrained shear strength from the fall cone test is 0.12. This implies that the energy in correlation to sensitivity, with a correlation value of -0.21, is most dependent on the remoulded shear strength. Therefore, sensitivity might not be the most interesting parameter to evaluate when comparing remoulding energy. Instead, the remoulded shear strength could be more representative of the clay's behaviour.

Some of the clays have the same sensitivity but varying remoulding energy, and according to Dehlbom and Lundström (2020) is it possible for clays with the same sensitivity to require different remoulding energy. The results clearly show that clay with the same sensitivity can result in varying remoulding energy. From figure 6.3, it is clear that the improved results support this correlation more than the standard results. However, the overall correlation is weak and a greater set of data with larger variation of sensitivities would be needed to establish this correlation.

Figure 6.6 presents a strong negative correlation between remoulding energy and water content. The correlation value of -0.75 shows that a higher water content indicates that the clay needs less energy to fully remould. Appendix B presents that the correlation value of water content and shear strength from the field vane tests is -0.55. This means that a higher water content also indicates a lower shear strength.

Similar to the correlation to water content, remoulding energy shows a weak negative correlation to the liquid limit, as figure 6.7 presents. It can be seen that the plot of remoulding energy versus water content and the plot of remoulding energy and liquid limit are very similar. The findings in figure 6.6 and 6.7 require more tests to draw any actual conclusions. Those figures indicate that there is a negative trend between remoulding energy versus water content and remoulding energy versus liquid limit. With more samples, it could be possible to determine some relationships. The determination of what type of clay the site consists of is a subjective assessment which makes these results uncertain.

## 7.2 Time and speed dependency

Since the rotational speed is varying, as table 6.3 presents, the peaks have been affected. According to Torstensson (1973) the speed of rotation is something that affects the peak of the curve during vane shear tests. The peak shear strength gets less defined and thereby lower with a decrease in the rotational speed. The rotational

speed is affecting the outcome of the curve. Therefore the speed during the different vane shear tests has affected the graphs and thereby the extrapolation. Figure 6.11 shows a strong correlation that with increasing rotational speed the time to failure is decreasing. This is also affected by the shear strength in the clay. This would explain the inconsistent variations for the highest rotational speeds. During the tests from Thakur et al. (2015) the same constant speed has been used. The varying rotational speeds result in variation of the time to failure which affects the limit state energy, remoulding energy, normalized energy and total energy is affected. This implies that the comparisons also are affected. It is difficult to estimate the effect the variation has had for these tests. But since there are positive trends between rotational speed and remoulding energy, as figure 6.12 shows, the rotational speed has had an impact on our results. It is hard to determine to what extent those are affected, therefore further research is suggested.

The rotational speeds presented in table 6.3 are assumed to be constant throughout the test. This does not reflect the real case. In situ, the rotational speed is affected by the conditions in the soil. According to SiS (2020) rocks or shells at the shear level can affect the measurement. The rotational speed is measured at the drilling rig. It does not measure the actual rotational speed at the vane. SiS (2020) states that the vane rotation rate could vary from the uphole rotation rate. This implies that the rotational speed might vary more than what is actually measured. As seen in figure 6.14, the rotational speed is increasing with increasing depth for several of the tests. It is difficult to determine how this actually affects the results but a varying speed from the same site might make it more difficult to find trends from the same site.

Figure 6.13 requires a larger variation in sensitivity before any actual conclusions can be drawn. But there is a trend that a higher sensitivity results in a higher time to failure, with a correlation value of 0.87. It should be noted that this result is dependent on how the tests were conducted. Since the Swedish standard states that the time from vane engagement to failure should be 2 minutes this trend cannot be developed further if this standard were followed. If the standard used a rotational speed instead, this correlation could be investigated further.

### **7.3 Advantages and disadvantages of field vane test**

In-situ determination of remoulding energy is a better approach compared to laboratory tests since laboratory tests require sampling of the undisturbed clay. The sampling of sensitive clay can be complicated since the clay is sensitive to disturbances. For instance, the sampling needs to be performed in a correct way to enable laboratory tests to deform the clay to its residual strain level. Moreover, in-situ tests circumvent additional challenges associated with the transportation of samples to the laboratory. Challenges such as quick transportation, without any disturbances and correct storage of the clay samples.

According to the results the mean time to failure is 1.6 minutes, see table 6.3. The recommended time to failure according to SiS (2020) is 2 minutes. Torstensson (1973) has shown that with a higher rotation speed the time until failure is decreasing. This trend is also seen in figure 6.11. Table 6.3 shows a great variation in rotational speed for the different tests. The rotational speed is an interesting parameter to evaluate since there is no recommended rotational speed in Sweden, it is just recommended that it should be constant (SiS, 2020).

One uncertainty is that the recommendation from SiS (2020) is what time the failure should be reached during the tests since this is affected by many conditions. The results indicate that this time is hard to reach during the vane shear testing since it is difficult to estimate how fast the failure will be reached. An improvement to consider would be a span or a specific rotational speed. It is shown that almost all of the investigated field vane tests are reaching failure before 2 minutes, as seen in figure 6.11. As mentioned the mean value is 1.6 minutes which indicates that the tests are performed on the limit of the standard. Although this study does not investigate how well the tests are performed there is an indication that the standard does not suit the actual performance of the test. Therefore the Swedish standard should be revised and improved.

Another difficulty with the field vane test is that the accuracy of measuring the remoulded shear strength is limited. Due to this the result for sensitivity evaluated from the field vane test results in large variation, compared to those evaluated from the fall cone test. The remoulded shear strength from field vane test should be carefully considered and the actual measuring needs development and therefore further studies is suggested. According to Dehlbom and Lundström (2020) the field vane test should be developed to measure low shear strength.

Torstensson (1973) has shown that the time from when the vane is pushed down to the time for rotation is affecting the shear strength. Torstensson (1973) showed that an increased time increases the shear strength, although it is also affected by the soil conditions. Additionally SiS (2020) states that a longer waiting may increase the measured vane strength. A suggested improvement would be to measure the time from when the vane is pushed down to the start of the vane shear test. This would result in easier comparisons between tests.

## 7.4 Comparison with previous findings

From the comparison of the findings with previous research, one can see that the results are similar according to figure 6.15. Since no plasticity index was determined for most of the investigated clays, the comparison was based on two assumptions. Given the results assumed plasticity indices 2 % and 40 %, to see how they fit the other findings. When assuming a plasticity index of 2%, the results are in good agreement with the other findings but with smaller magnitudes of remoulding energy. This could be due to differences between Canadian, Norwegian and Swedish clays. This is expected since the Canadian clay undergoes cementation effects which result in having higher undrained shear strength in relation to vertical effective

stress than Norwegian clay (Karlsruud et al., 1985). Canadian clay is also generally more plastic and more over-consolidated than Norwegian clay. This is shown in figure 6.15, presenting Canadian data with higher levels of remoulding energy and a bigger product of shear strength and plasticity indices. It is important to note that previous Canadian data and results from the Norwegian landslides are determined with other approaches than this thesis. The plotted results from this thesis are in line with the in-situ determination results from Thakur et al. (2015). Therefore the estimated energies in this thesis are reasonable, with regard to the fact that there are no previous results on Swedish clay.

Swedish clay is similar to Norwegian clay but differs in terms of relief, clay mineralogy, source material and deposition environment. From figure 6.15 it is clear that Swedish clay results in a smaller magnitude of remoulding energy than both Norwegian and Canadian clay. A reason why the Swedish results are of a smaller magnitude than the Norwegian results could be due to the different natural water contents. As presented in figure 6.6 there is a negative correlation between remoulding energy and water content. According to Thakur et al. (2015) the Norwegian in-situ determined clays had a water content between 33-40 %. The Swedish clays vary between 43-101 % with a mean of 78 % which could explain the lower levels of remoulding energies.

The results from Kärä are in the same magnitude as the other in-situ determination results as presented in figure 6.16. The clay in Kärä has a higher plasticity index compared to the other clays in figure 6.16, which is why the results are shifted to the right in the diagram, in a similar range as for the Canadian clay. The results for Kärä are also similar to the result from the Finnish clay. Finnish clay is usually characterized by higher water content, clay fraction and plasticity than Norwegian clay which also agrees with the results for Kärä (Di Buò et al., 2019). The Norwegian in-situ determined clay had a plasticity index between 5-7 % which is lower than for the ones in Kärä, 43-51 %, (Thakur et al., 2015). However, the Finnish result is based on one dataset and therefore no further conclusion can be drawn. The results from Kärä are based on the improved field vane tests, which is why they are higher than most of the other results from this thesis. For further comparisons, it is of interest to cover a broader range of clay properties, such as shear strength, plasticity and sensitivity to fully determine the relationship to remoulding energy. From the two figures 6.15 and 6.16, it can be concluded that using the field vane test to determine the remoulding energy of Swedish clay is a promising approach.

### 7.5 Variation between study areas

The soil material distribution varies stratigraphically and laterally which could affect the remoulding energies. But from the routine analysis, the fractions of organic matter and grain size are not evaluated for all sites. Therefore it is hard to draw any conclusions in relation to the grain-size fractions. Additionally, the deglaciation and the marine limit have affected the soil layers. Due to the deglaciation of various

sedimentary environments, erosion, transport and deposition have occurred in the study areas. One thing which could affect the clay is the underlying layers of sand. If there is a permeable layer of sand below the clay it could affect the consolidation of the clay.

Figure 6.9 shows that the majority of the study areas have an increased limit state energy with depth. This is reasonable since the consolidation is higher with increasing depth. It is also some indications that the time above the marine limit is resulting in higher remoulding energy. A reason for this could be due to the higher possibility of consolidation. Further research regarding how the remoulding energy is related to consolidation is therefore suggested.

As figure 6.10 shows, Nobelplatsen requires the highest remoulding energy, compared to the other study areas at the same depths. This could be explained by the fact that Nobelplatsen has been the longest time above the marine limit. As the figures presenting the marine limit show, Nobelplatsen is above the marine limit at 7000 cal. years BP. The clay at Nobelplatsen has thereby had the possibility for the highest consolidation. The deglaciation and the isostatic land uplift has according to Stevens et al. (1991) driven the consolidation and thereby improved the clay strength. This could explain why Nobelplatsen requires the highest amount of remoulding energy. In addition, it also has the highest bulk density. This could also be due to the possibility of consolidation. Figure 6.10 shows that with increasing bulk density, the remoulding energy increases. This is in line with the correlation between elevation, marine limit, bulk density and consolidation versus remoulding energy.

Figure 6.10 presents results from 6, 7 and 8 meters depth and since these are from similar depths they should have a comparable degree of consolidation. The density from the different sites has varying bulk density. The bulk density is dependent on the grain size distribution which is related to the depositional environment and has affected the organic content. It is therefore required with further research regarding the density and correlating parameters before any clear conclusions can be drawn. As figure 6.10 presents, Varla, Kungsbackaån and Anneberg are locations which are all in Kungsbacka municipality and have resulted in very similar total energies. They have probably been deposited at similar times in similar conditions. According to Stevens et al. (1991) it is most likely that the shear strength of the clay is primarily dependent on the original floc bonds formed during deposition, which could explain their similar result. The other areas are located north of Kungsbacka and have had different depositional environments and a larger variation in bulk density and remoulding energy. It is hard to determine exactly what the major reason for the variation in the needed remoulding energy between the study areas is. A possible explanation could be the time and manner of clay deposition. But it can be concluded that it is several factors that affect the variation. How these interact and their individual significance requires extensive research. But it is clear that the deposition of clay in a similar environment is resulting in comparable total energy.

In general, the bulk density of clay increases as the water content decreases. This is because as the water content decreases, the void ratio decreases and the volume of

solids increases, leading to a higher bulk density. Conversely, as the water content increases, the void ratio increases and the volume of solids decreases, leading to a lower bulk density. However, this relationship between bulk density and water content is not always straightforward for clay, as other factors such as the type of clay, mineralogy, and compaction history can also influence the relationship. Therefore, it is important to consider these factors when interpreting the relationship between bulk density and water content for a specific type of clay. This relationship can also be found for remoulding energy versus bulk density and remoulding energy versus water content. Both higher density and lower water content in the clay result in increased remoulding energy.

### 7.6 Areas of improvement

As this study has compared vane shear test results from both standard and improved it can be concluded that the improved one is easier to compare and evaluate. Therefore an area of improvement is to rotate the vane further during field vane tests. This would result in a more comparable graph, an example can be seen in figure 3.5. By a more comparable graph, the tests could be evaluated and used in more studies. For a field technician, it does not require any more work.

A weakness of this study is that it is dependent on the Swedish standard for the vane shear tests since it does not suggest any rotational speed (SiS, 2020). Additionally, it cannot be assured that the tests were conducted according to the standard. As seen in figure 6.3 the rotational speed and time to failure is varying between the tests. According to the Swedish standard, the time to failure should be 2 minutes, where 1-3 minutes is acceptable (SiS, 2020). An improvement would be to make the Swedish standard more precise. A suggestion is to add a recommended rotational speed, which would make comparisons easier, both between tests in Sweden, but also internationally. It would be more useful to compare the occurrence of the peak by using a constant speed for all tests, rather than aiming for the peak to occur at the same time for all tests. Additionally, Dehlbom and Lundström (2020) suggests that field vane tests should be developed to measure low shear strengths. Also that the Norwegian method for the determination of remoulding energy with field vane tests should also be further investigated, for Swedish clays.

Another addition would be a more precise recommendation for how long the vane is set at the level before conducting the measurement. As for now, the recommendation is a maximum of 5 minutes (SiS, 2020). It could also be useful to measure the time from when the vane has reached the desired depth until the measurements start. This is a way to ensure that the tests are conducted more similarly and make them more comparable. It could also be useful to educate the field technicians further to assure that the tests will be conducted according to the standard. These suggestions go hand in hand since a more clear standard would be easier to follow. More knowledge among the field technicians would make more tests conducted in the same way, according to the standard. Thereby the variation in how the tests were conducted an important aspect that has the potential for improvement.

The field vane test only measures the rod friction at the beginning of the test, before the actual test is performed. This means that the rod friction is assumed to be constant during the whole test, which is probably not the case. This source of error is probably increasing at deeper depths since the rod is extended and the mantle area becomes larger. This has affected our results, but it is not possible to determine to what extent. More uncertainties are determined in SiS (2020) together with guidance on uncertainty minimisation.

## 7.7 Further research

Further research regarding the variation of the soil characteristics and how these relate to energy is of interest. The amount of information regarding these is limited in this thesis as well as in the Swedish literature. This development together with field vane tests from more locations is possible for further research. When considering further research the extrapolation should be another refinement area. By investigating and evaluating the extrapolation the actual relationship could be obtained.

Since, as mentioned, the rotational speed and time until failure is affecting the results a correlation which has not been evaluated is the inclination of the curve from field vane tests. More specifically to investigate if there is some correlation between remoulding energy and how fast the shear strength decreases after the peak. This comparison would require that all tests are conducted the same way.

The energies estimated from this thesis have the potential to be applicable in real-life scenarios involving clay disturbances. Therefore, a suggested area for further research is to evaluate how the estimated energy can be applied and compared to the energies generated by disturbances. It is stated by Larsson and Åhnberg (2011) that there is a need to evaluate landslides in conjunction with loads such as construction work and blasting. Further Larsson and Åhnberg (2011) means that there is a great need for determination of the parameter first introduced as rapidity. Additionally, the risk of landslides dependent on the remoulding energy is an area for further research. This has been applied for Norwegian and Candian clays by Thakur et al. (2015) and could potentially be applied for Swedish clays as well.

Another aspect for future work is to map larger areas of Sweden, which would allow this thesis' findings to be applied in a broader context and compared to more areas where similar tests have been conducted. Using the improved method is preferable as it reduces uncertainties and provides a more reliable characterization of the behavior compared to the standard method. This would enhance the understanding of soils, reduce uncertainties and thereby reduce the required safety factors. According to Dehlbom and Lundström (2020) could an improved understanding of breakdown in clay shear strength could result in a better basis when assessing areas that can be affected by a retrogressive or progressive landslide.



# 8

## Conclusion

The energy needed to disturb or fully break down the shear strength of the clay estimated from field vane tests varies. It can be concluded that similar sensitivity results in varying remoulding energy. The remoulding energy shows correlations to several parameters but further research is suggested to develop the method and correlations. To further utilize the method it is essential to conduct the field vane tests in a consistent manner. This is necessary to enable reliable comparisons of the results. The rotation of the field vane tests should be conducted until the undrained shear strength remains relatively constant.

The results for southwest-Swedish clay are of a smaller magnitude compared to Canadian and Norwegian clays. When considering the varying soil parameters the estimated remoulding energy is in line with previous research. The locations with the most similar depositional environment have resulted in similar remoulding energy. There is a possible trend for the remoulding energy geographically. It is also some indications that the time above the marine limit results in higher remoulding energy.

The energies and correlations lead to an increased understanding of the behaviour of clay during remoulding. This can in the future reduce uncertainties and lower the required safety factors for geotechnical engineering. Using the field vane tests to determine the remoulding energy shows promising results.



# Bibliography

- Aas, G. (1975). Skred som følge peleramming i bløt leire.
- Bergström, U., Pile, O., Curtis, P., & Eliasson, T. (2022). Göteborgsområdets berggrund, jordarter och geologiska utveckling. [www.sgu.se](http://www.sgu.se)
- Bernander, S. (2011). *Progressive Landslides in Long Natural Slopes* (Doctoral dissertation). Luleå University of Technology. Luleå.
- Brenner, R. P., Nutalaya, P., Chilingarian, G. V., & O. Robertson Jr, J. (1981). Engineering Geology on Soft Clay. In E. W. Brand & R. P. Brenner (Eds.), *Soft clay engineering* (pp. 159–238). Elsevier Scientific Publishing Company.
- Cadling, L., & Odenstad, S. (1950). The vane borer - An apparatus for determining the shear strength of clay soils directly in the ground.
- Callander, P. F., & Smalley, I. J. (1984). An application of Soderblom's rapidity test to Canadian soils. *Engineering Geology*, *20*(3), 235–240. [https://doi.org/10.1016/0013-7952\(84\)90003-6](https://doi.org/10.1016/0013-7952(84)90003-6)
- Dehlbom, B., & Lundström, K. (2020). Högsensitiv lera i Västernorrlands län, Bildning, förekomst och egenskaper.
- Di Buò, B., D'Ignazio, M., Selänpää, J., Haikola, M., Länsivaara, T., & Di Sante, M. (2019). Investigation and geotechnical characterization of Perniö clay, Finland. *AIMS Geosciences*, *5*(3), 591–616. <https://doi.org/10.3934/GEOSCI.2019.3.591/FULLTEXT.HTML>
- Eden, W., & Kubota, J. (1961). Some observations on the Measurement of Sensitivity of Clay. *Proceeding of the American Society for Testing and Materials*, 1239–1249.
- Johansson, J., Bouchard, S., & L'Heureux, J.-S. (2017). Vibratory Roller Influence Zone Near Slopes with Vibration Susceptible Soils. In V. Thakur, J.-S. L'Heureux, & A. Locat (Eds.), *Landslides in sensitive clays - from research to implementation* (1st ed., pp. 191–201). Springer.
- Karlsrud, K., Aas, G., & Gregersen, O. (1985). Can We Predict Landslide Hazards in Soft Sensitive Clays? Summary of Norwegian Practice and Experiences.
- Kenney, T. (1976). Formation and geotechnical characteristics of glacial-lake varved soils.
- Khaldoun, A., Møller, P., Fall, A., Wegdam, G., Leeuw, B., Méheust, Y., Fossum, J., & Bonn, D. (2009). Quick Clay and Landslides of Clayey Soils. *Physical review letters*, *103*, 188301. <https://doi.org/10.1103/PhysRevLett.103.188301>
- Larsson, R. (2008). Jords egenskaper.

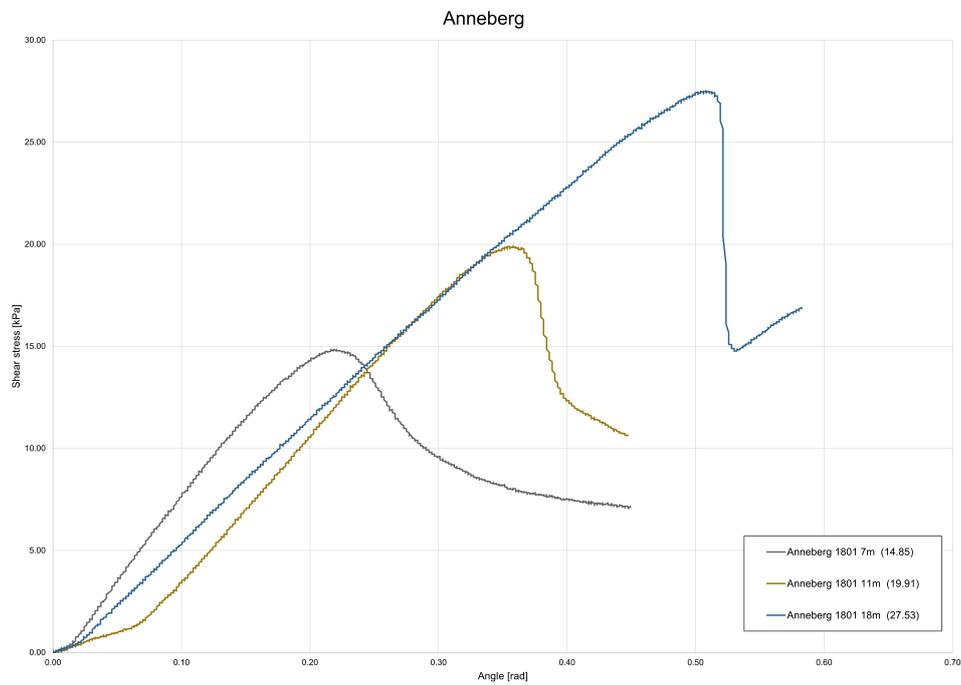
- Larsson, R., & Åhnberg, H. (2011). Nedbrytning av odränerad skjuvhållfasthet i lera på grund av cyklisk belastning och deformationer.
- Larsson, R., & Åhnberg, H. (2012). Strength degradation of clay due to cyclic loadings and enforced deformations.
- Larsson, R., & Sällfors, G. (1995). Sättningsgenskaper i lös lera på grund av geologisk avsättning och "åldring" Statens geotekniska institut Swedish Geotechnical Institute.
- Leroueil, S., Vaunat, J., Picarelli, L., Locat, J., Faure, R., & Lee, H. (1996). Geotechnical characterization of slope movements. In K. Senneset (Ed.), *Proceedings of 7th international symposium on landslides* (pp. 53–74). Balkema, Rotterdam. <https://www.tib.eu/de/suchen/id/BLCP%3ACN017761982>
- L'Heureux, J.-S. (2012). Natural Hazards project.
- L'Heureux, J., Høydal, Ø., Lopez, P., & Lacasse, S. (2018). Impact of climate change and human activity on quick clay landslide occurrence in Norway. In K. Ho, A. Leung, J. Kwan, R. Koo, & R. Law (Eds.), *Proceedings of the second jtc1 workshop triggering and propagation of rapid flow-like landslides* (pp. 65–68). The Hong Kong Geotechnical Society.
- Locat, P., Leroueil, S., & Locat, J. (2008). Remanement et mobilité des débris de glissements de terrain dans les argiles sensibles de l'est du Canada. *Proceedings of the 4th Canadian conference on geohazards: from causes to management*, 97–106.
- NGI. (2022). Store kvikkleireskred i Norge. <https://www.ngi.no/forskning-og-radgivning/naturfare-container/skred-og-ras/kvikkleireskred/store-kvikkleireskred-i-norge/>
- Norwegian Water Resources and Energy Directorate. (2014). The landslide at Nord-Statland. Investigation of technical causes.
- Olje- og energidepartementet. (2021). Årsakene til kvikkleireskredet i Gjerdrum 2020.
- Rankka, K. (2003). Kvikklera- bildning och egenskaper.
- Rankka, K., Andersson-Sköld, Y., Hulten, C., Larsson, R., Leroux, V., & Dahlin, T. (2004). Quick clay in Sweden.
- Rosenqvist, I. T. (1946). Om Leires Kvikaktighet. *Meddelelser fra Vegdirektören*, 3.
- Roy, M., Blanchet, R., Tavenas, F., & Rochelle, P. L. (1981). Behaviour of a sensitive clay during pile driving. *Canadian Geotechnical Journal*, 18(1), 67–85.
- SGI. (2020). Surte. <https://www.sgi.se/sv/kunskapscentrum/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/ras-och-skred/fakta-om-svenska-skred-och-ras/surte/>
- SGI. (2022a). Framtida kostnader till följd av ras, skred och erosion, Fördjupning av klimateffekter.
- SGI. (2022b). Jordarter. <https://www.sgi.se/sv/Forskning--larande/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/jordmateriallara/lera-och-kvikklera/>
- SGI. (2022c). Svenska skred och ras. <https://www.sgi.se/sv/kunskapscentrum/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/ras-och-skred/fakta-om-svenska-skred-och-ras/>

- SGI. (2022d). Tuve. <https://www.sgi.se/sv/kunskapscentrum/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/ras-och-skred/fakta-om-svenska-skred-och-ras/tuve/>
- SGI. (2022e). Småröd 2006. <https://www.sgi.se/sv/kunskapscentrum/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/ras-och-skred/fakta-om-svenska-skred-och-ras/smarod-2006/>
- SGI & MSB. (2021). Riskområden för ras, skred, erosion och översvämning.
- SGU. (2020a). Från istid till nutid. <https://www.sgu.se/om-geologi/jord/fran-istid-till-nutid/>
- SGU. (2020b). Riksöversikt över finkorniga jordars skredbenägenhet. <https://www.sgu.se/samhallsplanering/risker/skred-och-ras/riksoversikt-over-finkorniga-jordars-skredbenagenhet/>
- SGU. (2020c). Klimatets förändringar över tiden. <https://www.sgu.se/om-geologi/ett-klimat-i-standig-forandring/klimatets-forandringar-over-tiden/>
- SGU. (2020d). Kartvisaren Jordarter 1:25 000-1:100 000. <https://www.sgu.se/produkter-och-tjanster/kartor/kartvisaren/jordkartvisare/jordarter-125-000-1100-000/>
- SGU. (2020e). Postglaciala finkorniga sediment. <https://www.sgu.se/om-geologi/jord/fran-istid-till-nutid/landhojning-fran-havsbottnen-till-lerslatt/postglaciala-finkorniga-sediment/>
- SGU. (2022a). Strandförskjutningsmodell. <https://www.sgu.se/produkter-och-tjanster/geologiska-data/oppna-data/jordarter-oppna-data/>
- SGU. (2022b). Kartvisare Geologiskt intressanta platser. <https://www.sgu.se/produkter-och-tjanster/kartor/kartvisaren/geologisk-mangfald/kartvisare-geologiskt-intressanta-platser/>
- SiS. (2014a). Geoteknisk undersökning och provning - Laboratorieundersökning av jord - Del 1: Bestämning av vattenkvot (ISO 17892-1:2014).
- SiS. (2014b). Geoteknisk undersökning och provning - Laboratorieundersökning av jord - Del 2: Bestämning av skrymdensiteten hos finkornig jord (ISO 17892-2:2014).
- SiS. (2017). Geoteknisk undersökning och provning - Laboratorieundersökning av jord - Del 6: Provning med fallkon (ISO 17892-6:2017).
- SiS. (2018a). Geoteknisk undersökning och provning - Benämning och indelning av jord - Del 1: Benämning och beskrivning (ISO 14688-1:2017).
- SiS. (2018b). Geoteknisk undersökning och provning - Laboratorieundersökning av jord - Del 12: Bestämning av flytgräns och plasticitetsgräns (ISO 17892-12:2018).
- SiS. (2020). Geotechnical investigation and testing – Field testing – Part 9: Field vane test (FVT and FVT-F) (ISO 22476 9:2020).
- Söderblom, R. (1969). Salt in Swedish Clays and its Importance for Quick Clay Formation. *Swedish Geotechnical Institute Proceedings*, 22.
- Söderblom, R. (1974). New Lines in Quick Clay Research.
- Söderblom, R. (1983). Studies of the Rapidity Number. In *Symposium on slopes on soft clay* (pp. 381–395). Swedish Geotechnical Institute.
- Statens vegvesen. (2021). Feltundersøkelser Håndbok R211. [www.vegvesen.no](http://www.vegvesen.no)

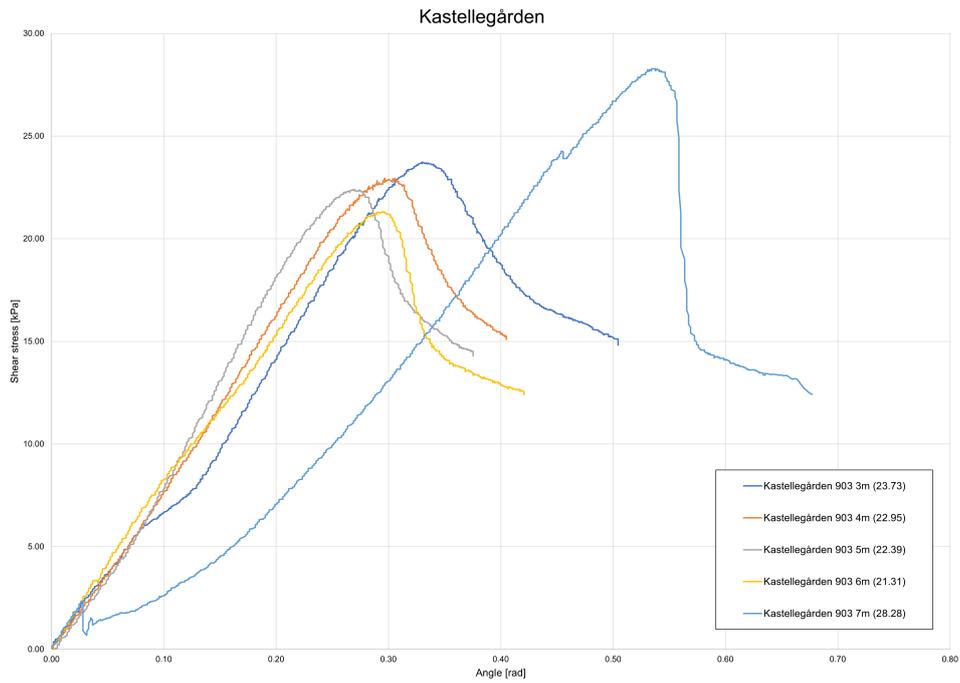
- Stevens, R. L., Rosenbaum, M. S., & Hellgren, L. G. (1991). Origins and engineering hazards of Swedish glaciomarine and marine clays. *Geological Society, London, Engineering Geology Special Publications*, 7(1), 257–264. <https://doi.org/10.1144/GSL.ENG.1991.007.01.24>
- Sundström, L., & Waerme, A. (2022). *Alternative Methods for Quick-Clay Mapping*. [www.chalmers.se](http://www.chalmers.se)
- Talme, O. (1968). Clay Sensitivity and Chemical Stabilization.
- Tavenas, F., Flon, P., Leroueil, S., & Leblais, J. (1983). Remolding energy and risk of slide retrogression in sensitive clays. In *Symposium on slopes on soft clays* (pp. 423–454). Swedish Geotechnical Institute.
- Thakur, V., & Degago, S. A. (2013). Disintegration energy of sensitive clays. *Géotechnique Letters*, 3(1), 20–25. <https://doi.org/10.1680/geolett.12.00062>
- Thakur, V., Gylland, A., Degago, S., Oset, F., & Sandven, R. (2015). In-situ determination of disintegration energy for soft sensitive clays. *Proceedings of GEOQuébec – challenges from North to South*.
- Thakur, V. (2017). Role of remolding energy in the post-failure movements of landslides. *19th International Conference on Soil Mechanics and Geotechnical Engineering*, 3525–3528. <https://www.issmge.org/publications/online-library>
- Thakur, V., Abate Degago, S., Selänpää, J., & Länsivaara, T. (2017). Determination of remoulding energy of sensitive clays. In V. Thakur, J.-S. L’Heureux, & A. Locat (Eds.), *Landslides in sensitive clays - from research to implementation* (1st ed., pp. 97–107). Springer.
- Torrance, J. K. (2013). Landslides in quick clay. In *Landslides* (pp. 83–94). Cambridge University Press. <https://doi.org/10.1017/cbo9780511740367.009>
- Torstensson, B.-A. (1973). Kohesionspålar i lös lera. En fältstudie i modellskala.
- Yafrate, N., DeJong, J., DeGroot, D., & Randolph, M. (2009). Evaluation of Remolded Shear Strength and Sensitivity of Soft Clay Using Full-Flow Penetrometers. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(9), 1179–1189. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000037](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000037)
- Zhu, G., Zhu, L., & Yu, C. (2017). Rheological properties of soil: a review. *IOP Conference Series: Earth and Environmental Science*, 64. <https://doi.org/10.1088/1755-1315/64/1/012011>

# Appendices

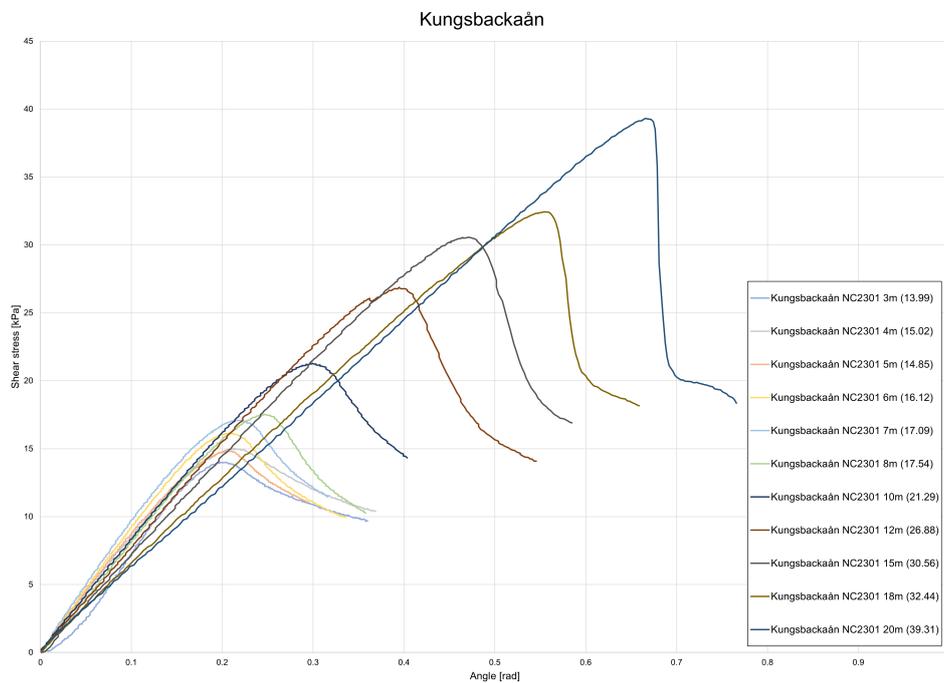
## A Field vane test results



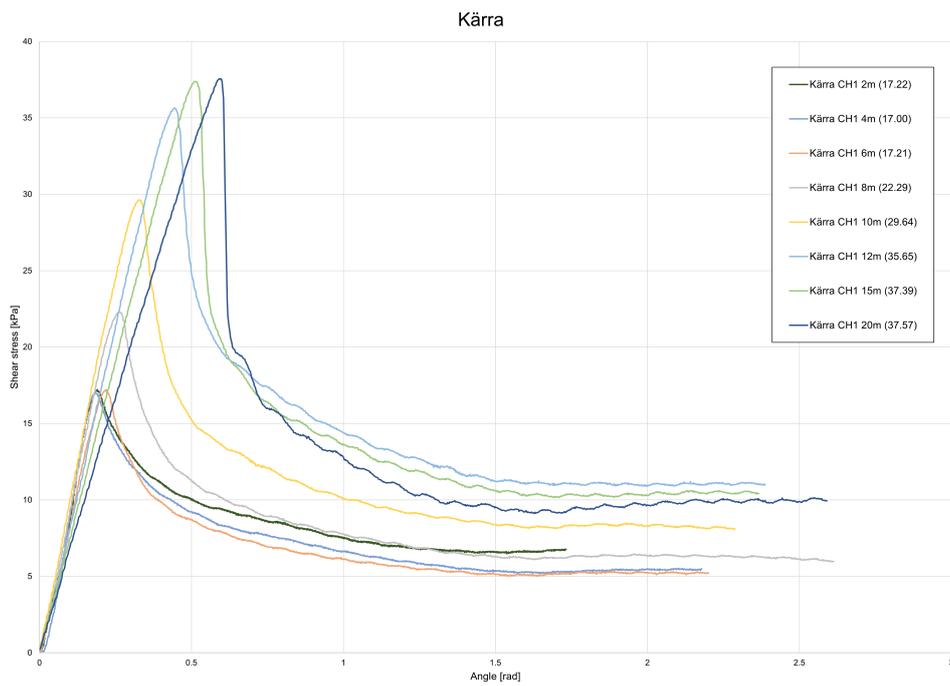
**Figure A1:** Obtained field vane test results from Anneberg, without rod friction, peak shear strength marked in parentheses



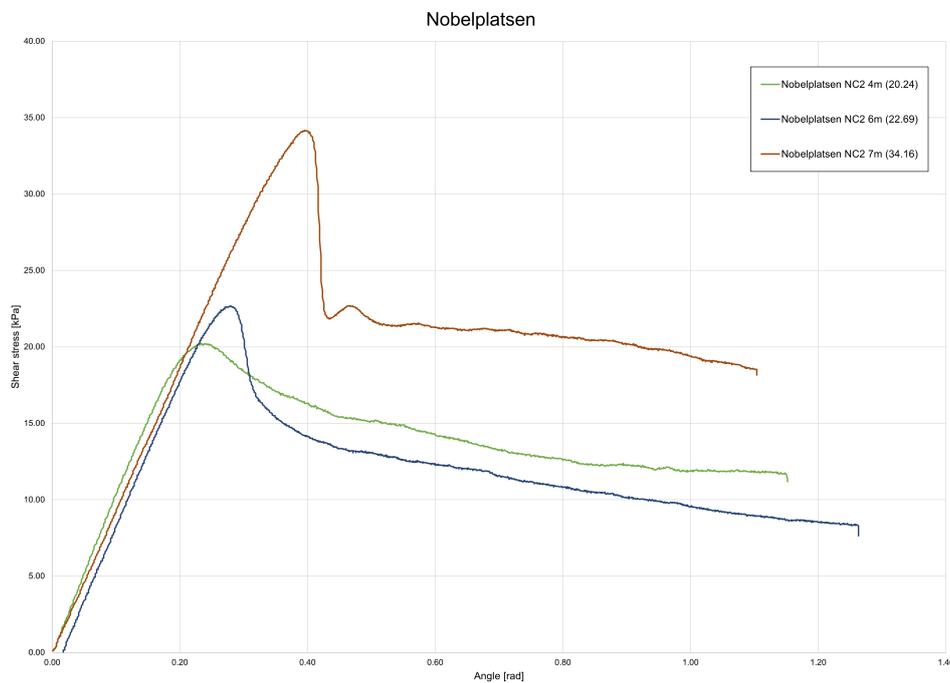
**Figure A2:** Obtained field vane test results from Kastellegården, without rod friction, peak shear strength marked in parentheses



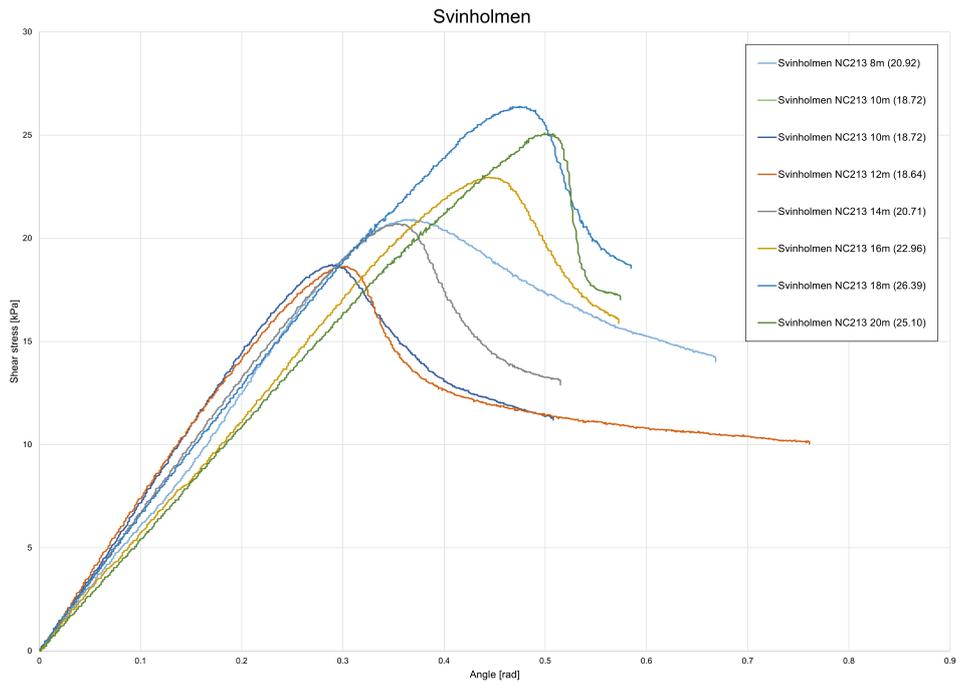
**Figure A3:** Obtained field vane test results from Kungsbackaån, without rod friction, peak shear strength marked in parentheses



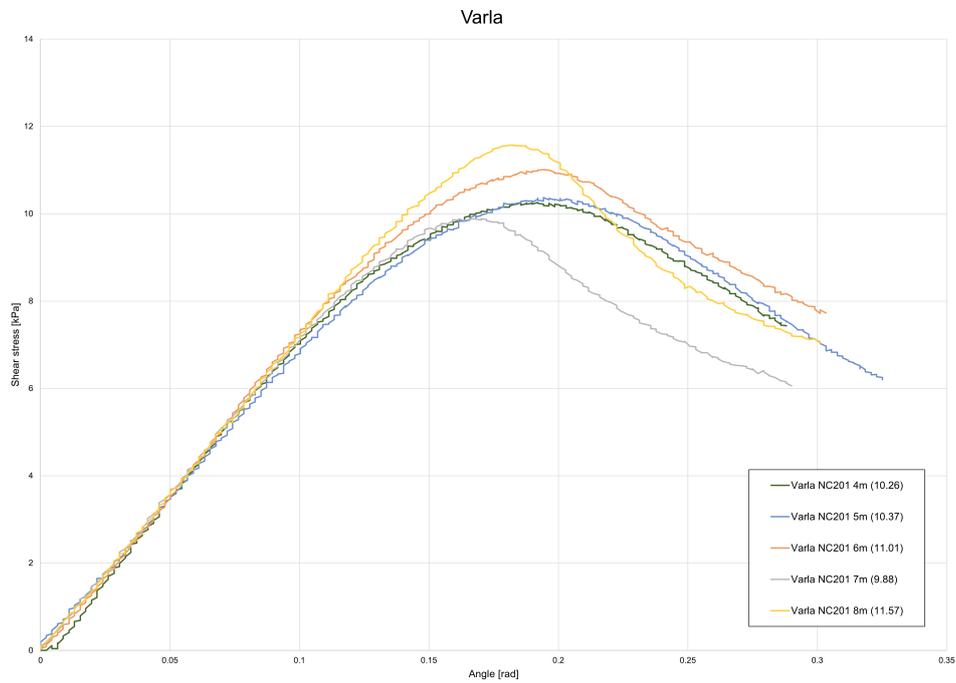
**Figure A4:** Obtained field vane test results from Kärä, without rod friction, peak shear strength marked in parentheses



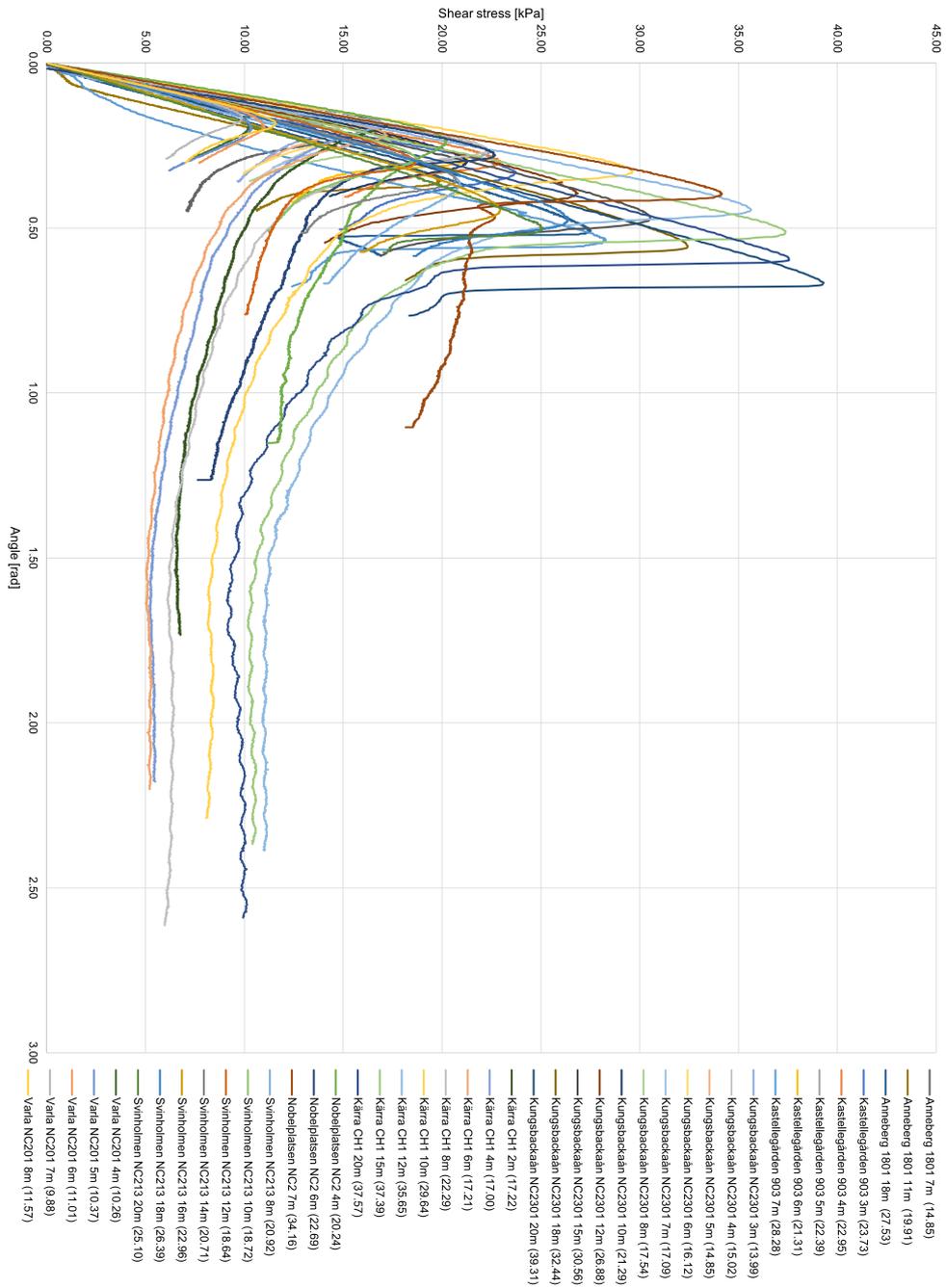
**Figure A5:** Obtained field vane test results from Nobelplatsen, without rod friction, peak shear strength marked in parentheses



**Figure A6:** Obtained field vane test results from Svinholmen, without rod friction, peak shear strength marked in parentheses



**Figure A7:** Obtained field vane test results from Varla, without rod friction, peak shear strength marked in parentheses



**Figure A8:** All obtained field vane test results without rod friction, peak shear strength marked in parentheses

**Table A1:** Summary of the obtained field vane test results

Site	Borehole ID	Depth [m]	Max. torque [Nm]	Rod friction [Nm]
Anneberg	1801M	7	22.41	7.56
Anneberg	1801M	11	30.66	10.75
Anneberg	1801M	18	44.06	16.53
Kastellegården	NC903	3	24.89	1.16
Kastellegården	NC903	4	24.63	1.68
Kastellegården	NC903	5	23.68	1.29
Kastellegården	NC903	6	23.29	1.98
Kastellegården	NC903	7	32.36	4.08
Kungsbackaån	NC2301	3	15.54	1.55
Kungsbackaån	NC2301	4	17.42	2.40
Kungsbackaån	NC2301	5	18.00	3.15
Kungsbackaån	NC2301	6	19.95	3.83
Kungsbackaån	NC2301	7	21.70	4.61
Kungsbackaån	NC2301	8	24.25	6.71
Kungsbackaån	NC2301	10	28.29	7.00
Kungsbackaån	NC2301	12	36.27	9.39
Kungsbackaån	NC2301	15	41.12	10.56
Kungsbackaån	NC2301	18	44.62	12.18
Kungsbackaån	NC2301	20	56.77	17.56
Kärra	CH1	2	19.06	1.84
Kärra	CH1	4	21.14	4.14
Kärra	CH1	6	21.98	4.77
Kärra	CH1	8	28.48	6.19
Kärra	CH1	10	37.46	7.82
Kärra	CH1	12	43.49	7.84
Kärra	CH1	15	49.91	12.52
Kärra	CH1	20	54.25	16.68
Nobelplatsen	NC2	4	22.31	2.07
Nobelplatsen	NC2	6	25.16	2.47
Nobelplatsen	NC2	7	37.09	2.93
Svinholmen	NC213	10	22.95	4.23
Svinholmen	NC213	12	23.79	5.15
Svinholmen	NC213	14	27.49	6.78
Svinholmen	NC213	16	31.52	8.56
Svinholmen	NC213	18	38.39	12.00
Svinholmen	NC213	20	37.88	12.28
Varla	NC201	4	12.82	2.56
Varla	NC201	5	13.06	2.69
Varla	NC201	6	13.06	2.05
Varla	NC201	7	13.17	3.29
Varla	NC201	8	14.91	3.34

## B Correlation values

	Depth (Level) [m]	Depth [m]	Total energy [kJ/m <sup>3</sup> ]	Limit state energy [kJ/m <sup>3</sup> ]	Remoulding energy [kJ/m <sup>3</sup> ]	Normalized energy [kJ/m <sup>3</sup> ]	Speed [degrees/minute]	Time to failure [min]	Bulk density [g/cm <sup>3</sup> ]	w [%]	w <sub>l</sub> [%]	Sensitivity	C <sub>u</sub> [kPa] (fall cone test - not corrected)	C <sub>u</sub> [kPa] (field vane test - not corrected)	C <sub>u</sub> [kPa] (field vane test - not corrected)	C <sub>u</sub> [kPa] (field vane test)	Sensitivity (field vane test)	w <sub>v</sub> [%]	Organic content [%]	Plasticity index
Depth (Level) [m]	1.00	-0.78	-0.20	-0.57	0.08	0.43	-0.49	-0.11	0.43	-0.31	-0.48	0.00	-0.46	-0.37	-0.41	0.42	-0.62	0.71	0.26	0.157
Depth [m]	-0.78	1.00	0.46	0.81	0.15	-0.44	0.48	0.35	-0.06	-0.10	0.20	0.18	0.48	0.72	0.66	0.19	0.22	-0.71	-0.26	-0.157
Total energy [kJ/m <sup>3</sup> ]	-0.20	0.46	1.00	0.73	0.92	0.27	0.56	0.03	0.41	-0.51	-0.38	-0.12	0.55	0.42	0.42	0.29	0.01	-0.56	0.03	-0.181
Limit state energy [kJ/m <sup>3</sup> ]	-0.57	0.81	0.73	1.00	0.40	-0.35	0.64	0.27	0.27	-0.40	-0.19	0.09	0.46	0.79	0.83	0.31	0.25	-0.73	-0.28	-0.093
Remoulding energy [kJ/m <sup>3</sup> ]	0.08	0.15	0.92	0.40	1.00	0.56	0.39	-0.11	0.40	-0.45	-0.40	-0.21	0.47	0.12	0.94	0.19	0.36	0.24	0.36	-0.229
Normalized energy [kJ/m <sup>3</sup> ]	0.43	-0.44	0.27	-0.35	0.56	1.00	-0.11	-0.26	0.08	0.00	-0.16	-0.21	0.03	-0.50	-0.21	-0.17	-0.07	-0.20	-0.07	0.184
Speed [degrees/minute]	-0.49	0.48	0.56	0.64	0.39	-0.11	1.00	0.46	-0.13	0.28	0.16	0.41	0.70	0.32	0.58	-0.17	0.57	-0.20	-0.20	-0.307
Time to failure [min]	-0.11	0.35	0.03	0.27	-0.11	-0.26	0.46	1.00	0.30	-0.33	0.90	0.19	-0.15	0.38	0.25	0.37	0.05	-0.38	-0.38	0.353
Bulk density [g/cm <sup>3</sup> ]	0.43	-0.06	0.41	0.27	0.40	-0.13	-0.48	0.30	1.00	-0.96	-0.93	0.19	-0.39	0.38	0.43	0.54	0.20	-0.72	0.27	-0.782
w [%]	-0.31	-0.10	-0.51	-0.40	-0.45	0.00	0.02	-0.33	-0.96	1.00	0.90	0.20	0.02	-0.50	-0.55	-0.42	0.23	0.64	0.21	0.627
w <sub>l</sub> [%]	-0.48	0.20	-0.38	-0.19	-0.40	-0.16	-0.42	0.87	0.90	0.90	1.00	-0.17	-0.54	-0.21	-0.37	-0.28	0.57	0.67	0.05	0.699
Sensitivity	0.00	0.18	-0.12	0.09	-0.21	-0.21	0.87	-0.39	-0.20	-0.17	1.00	0.44	0.44	0.44	0.06	0.32	-0.28	0.32	0.17	0.122
C <sub>u</sub> [kPa] (fall cone test - not corrected)	-0.46	0.48	0.55	0.46	0.47	0.01	0.70	0.32	-0.15	-0.15	-0.15	1.00	0.26	1.00	0.73	0.47	-0.08	0.26	0.17	-0.644
C <sub>u</sub> [kPa] (field vane test - not corrected)	-0.41	0.66	0.83	0.94	0.57	-0.21	0.58	0.52	-0.50	-0.50	-0.21	0.44	0.28	1.00	0.73	0.39	-0.08	0.47	0.47	-0.419
C <sub>u</sub> [kPa] (field vane test)	0.42	0.19	0.29	0.31	0.19	-0.17	-0.17	0.37	-0.59	-0.42	0.32	-0.03	0.63	0.39	1.00	0.79	0.02	0.21	0.21	0.178
Sensitivity (field vane test)	-0.62	0.22	-0.01	0.25	-0.14	-0.21	0.48	-0.28	-0.26	0.27	0.23	-0.28	0.17	0.16	0.39	1.00	-0.68	-0.46	0.02	-0.215
w <sub>v</sub> [%]	0.71	-0.71	-0.56	-0.73	0.61	-0.73	-0.73	0.05	-0.49	0.64	0.67	-0.58	-0.37	-0.65	-0.64	0.92	1.00	0.33	0.02	-0.098
Organic content [%]	0.26	-0.26	0.03	-0.28	0.36	-0.07	-0.20	-0.38	0.20	-0.21	-0.05	-0.66	0.47	-0.13	-0.08	0.21	-0.46	1.00	0.21	0.382
Plasticity index	0.157	-0.157	-0.181	-0.093	-0.229	0.184	-0.307	0.353	-0.782	0.627	0.699	0.122	-0.644	-0.419	-0.178	0.127	-0.215	0.098	0.382	1

Figure B1: Correlation values for all investigated study areas and depths

	Depth [m]	Total area (energy)	Limit state energy [kJNm/m <sup>3</sup> ]	Disintegration energy [kJNm/m <sup>3</sup> ]	Normalized energy [kJNm/m <sup>3</sup> ]	Speed [degrees/minute]	Time to failure [min]	Bulk density [g/cm <sup>3</sup> ]	w [%]	w [%]	Sensitivity	C <sub>u</sub> [kPa]	C <sub>u</sub> [kPa] (fall cone test - not corrected)	C <sub>u</sub> [kPa] (field vane test - not corrected)	C <sub>u</sub> [kPa] (field vane test)
Depth [m]	1	-0.077	0.036	-0.108	-0.195	0.396	-0.114	-0.207	0.213	0.292	-0.095	0.398	0.075	0.099	-0.095
Total energy [kJNm/m <sup>3</sup> ]	-0.077	1	0.705	0.962	0.599	-0.094	0.447	0.780	-0.849	-0.783	-0.101	0.330	0.341	0.824	0.739
Limit state energy [kJNm/m <sup>3</sup> ]	0.036	0.705	1	0.485	-0.111	-0.326	0.816	0.819	-0.782	-0.797	0.388	0.341	0.704	0.964	0.561
Remoulding energy [kJNm/m <sup>3</sup> ]	-0.108	0.962	0.485	1	0.781	0.010	0.238	0.660	-0.746	-0.659	-0.085	0.009	0.824	0.964	0.561
Normalized energy [kJNm/m <sup>3</sup> ]	-0.195	0.599	-0.111	0.781	1	0.233	-0.232	0.142	-0.287	-0.208	-0.306	-0.113	-0.396	0.074	-0.113
Speed [degrees/minute]	0.396	-0.094	-0.326	0.010	0.233	1	-0.758	-0.534	0.507	0.626	-0.855	0.825	-0.358	0.074	-0.113
Time to failure [min]	-0.114	0.447	0.816	0.238	-0.232	-0.758	1	0.734	-0.710	-0.818	0.669	0.559	-0.273	0.728	0.176
Bulk density [g/cm <sup>3</sup> ]	0.207	0.790	0.819	0.660	0.142	-0.534	0.734	1	-0.985	-0.956	-0.104	0.750	0.848	0.897	0.897
w [%]	0.213	-0.849	-0.782	-0.746	-0.287	0.507	-0.710	-0.985	1	0.970	-0.215	-0.644	-0.834	-0.820	-0.820
w [%]	0.292	-0.783	-0.797	-0.659	-0.208	0.626	-0.818	0.970	0.970	1	-0.384	0.259	-0.605	-0.820	-0.820
Sensitivity	-0.085	-0.101	0.188	-0.195	-0.306	-0.855	0.669	-0.215	-0.384	-0.384	1	-0.869	0.137	0.103	-0.267
C <sub>u</sub> [kPa] (fall cone test - not corrected)	0.388	0.330	-0.052	0.426	0.480	-0.855	-0.545	0.059	-0.644	0.259	-0.869	1	-0.129	0.062	0.825
C <sub>u</sub> [kPa] (field vane test - not corrected)	0.009	0.824	0.964	0.647	0.074	-0.358	0.559	-0.605	-0.834	-0.605	0.137	-0.129	1	0.620	0.825
C <sub>u</sub> [kPa] (field vane test)	-0.095	0.739	0.561	0.545	-0.113	-0.123	0.176	0.897	-0.895	-0.725	-0.267	0.257	0.825	0.726	1

Figure B2: Correlation values for 6, 7 and 8 meters

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING  
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden

[www.chalmers.se](http://www.chalmers.se)



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY