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Correlation of Properties in Geotechnical Engineering

The impact of Index parameters on Mechanical Properties of Soil

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Abstract:
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This thesis starts out by defining basic soil properties. Formation of soil by weathering is covered, along with clay mineralogy. The mineral structure of some of the most common clay minerals, as well as some defining characteristics that they possess is discussed. Basic soil properties and mineralogy is then tied up to mechanical properties of the soil.

The correlations between the soil parameters that are discussed is based on literature as well as analyzes of data from GEODIP's high quality database for clay materials (SP8). Comparing correlations found in literature with correlations from SP8 provide insight in the mechanical behavior that can be expected for Norwegian soil. It is clear that the water content is especially influential of the mechanical behavior. Results indicate that stiffness and compressibility properties of Norwegian soil is less dependent on plasticity than suggested by theory. This is likely a result of Norwegian soil having a generally low plasticity.

Keywords:

1. Clay
2. Mineralogy
3. Stiffness
4. Strength

(sign.)

Preface

This Master Thesis was written as a conclusion to the MSc in Geotechnical Engineering at the Department of Civil and Transport Engineering AT NTNU. The thesis was carried out during the spring and summer of 2018, under the supervision of Professor Steinar Nordal. Steinar Nordal is also the person who came up with the topic of this thesis.

Trondheim, 2018-07-26

Marie Monsen Londalen

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My most sincere gratitude goes out to the Norwegian Geotchnical Institue, and especially Jean-Sebastien L'Heureux for allowing me access to the GEODIP SP8 database which has been used to find correlations in this thesis. The database made it possible to find experimental results, which are a major part of this thesis.

I would also like to thank all my fellow master students for making the process of writing the thesis an overall more enjoyable experience. A special thanks also goes to Sofie Steinkjer for allowing me to stay in her place while finishing up the thesis.

M.M.L.

Summary

In order to effectively use the mechanical parameters of a soil as a tool in soil mechanics, insight about basic properties is necessary. Index properties of soil, such as the water content and the plasticity index influence the mechanical behavior. Thus, awareness about how various properties correlate is an asset which is valuable when making predictions about soil behavior, as well as in validating results of soil tests. The topic of this thesis is correlations between soil properties, with a focus on Norwegian clay. The mechanical parameters have been limited to basic strength, stiffness and compressibility properties.

This thesis starts out by defining basic soil properties. Formation of soil by weathering is covered, along with clay mineralogy. The mineral structure of some of the most common clay minerals, as well as some defining characteristics that they possess is discussed. Basic soil properties and mineralogy is then tied up to mechanical properties of the soil.

The correlations between the soil parameters that are discussed is based on literature as well as analyzes of data from GEODIP's high quality database for clay materials (SP8). Comparing correlations found in literature with correlations from SP8 provide insight in the mechanical behavior that can be expected for Norwegian soil. It is clear that the water content is especially influential of the mechanical behavior. Results indicate that stiffness and compressibility properties of Norwegian soil is less dependent on plasticity than suggested by theory. This is likely a result of Norwegian soil having a generally low plasticity.

Sammendrag

For å kunne benytte mekaniske parametere for jord mest mulig effektivt i geotekniske beregninger er det nødvendig å kjenne til grunnleggende egenskaper for jorden. Indeksparametere for jord, slik som vanninnhold og plastisitetsindeksen påvirker den mekaniske oppførselen. På bakgrunn av dette er det nyttig å kjenne til hvordan ulike parametere for jord korrelerer. Kjennskap til slike forhold bistår i å forutsi oppførselen, i tillegg til å validere resultater fra tester på jord. Tema for denne avhandlingen er korrelasjoner mellom parametere for jord, med et spesielt fokus på norsk leire. De mekaniske egenskapene som dekkes er begrenset til de som omhandler styrke, stivhet og kompressibilitet.

Avhandlingen åpner med å definere grunnleggende jordparametere. Dannelsesprosesser i form av forvitring er dekket, i tillegg til leirmineralogi. Egenskaper og struktur for noen vanlige leirmineraler er diskutert. Grunnleggende jordegenskaper samt mineralogi er så knyttet opp mot mekanisk oppførsel.

Korrelasjonene mellom indeksparametere og mekaniske egenskaper som dekkes baserer seg på allerede eksisterende litteratur, samt korrelasjoner funnet ved hjelp av GEODIP sin høykvalitets-database for leirmaterialer (SP8). Sammenligninger mellom korrelasjoner gir innsikt i den mekaniske oppførselen som kan forventes for norsk leire. Det er tydelig at vanninnhold er spesielt innflytelsesrik på de mekaniske egenskapene. Resultatene i avhandlingen tyder på at stivheten og kompressibiliteten til norsk leire er mindre avhengig av jordens plastisitet enn forventet. Dette er sannsynligvis et resultat av at norsk leire generelt har lav plastisitet.

Contents

List of Symbols

A Activity

C Clay content

$\mathbf{C}_c$ Compression index

$\mathbf{C}_u$ Coefficient of uniformity

CEC Cation Exchange Capacity

$\mathbf{E}_{10}$ Stiffness modulus at 10% mobilized shear strength

$\mathbf{E}_{50}$ Stiffness modulus at 50% mobilized shear strength

$\mathbf{E}_u$ Undrained stiffness modulus

$\mathbf{E}_{oed}$ Stiffness modulus

$\mathbf{E}_{oed}^{ref}$ Tangential oedometer stiffness at $p_{ref} = 100$ kPa

e Void ratio

$\mathbf{G}_s$ Specific gravity

$\mathbf{I}_L$ Liquidity index

$\mathbf{I}_P$ Plasticity index

$\mathbf{K}_0$ At rest earth pressure ratio

M Stiffness modulus or critical state slope

$\mathbf{m}$ Modulus number

$\mathbf{m}_0$ Modulus number through origin

$\mathbf{m}_s$ Mass of solid particles

$\mathbf{m}_w$ Mass of water

$\mathbf{n}$ Porosity

OCR Overconsolidation ratio

$\mathbf{S}_r$ Degree of saturation

$\mathbf{S}_t$ Sensitivity

$\mathbf{s}_r$ Remolded shear strength

$\mathbf{s}_u$ Undrained shear strength

$\mathbf{u}$ Pore pressure

$\mathbf{V}$ Volume

$\mathbf{V}_s$ Volume of solids

$\mathbf{V}_p$ Volume of pores

$\mathbf{w}$ Natural water content

$\mathbf{w}_L$ Liquid limit

$\mathbf{w}_P$ Plastic limit

$\mathbf{w}_S$ Shrinkage limit

ϵ Strain

γ Unit weight

γ_w Unit weight of water

λ Compression index

λ^* Modified compression index

ϕ Friction angle

ϕ'_{crit} Critical state friction angle

ψ Dilatancy angle

σ Total stress

σ' Effective stress

σ'_c Preconsolidation stress

σ'_r Reference pressure

σ'_v Vertical effective stress

Chapter 1

Introduction

1.1 Background

In geotechnical engineering, mechanical properties of soil are used to perform evaluations and calculations of different types. Since soil is such a diverse medium, several factors contribute to the mechanical properties. The relationship between a soils geological origin and its mechanical properties is an area of soil mechanics which may provide insight in the expected behavior of soil.

Evaluation of the importance of the composition and structure of a soil, as well as the effect of these factors on the mechanical properties is of interest. Relating this to geological factors such as the mineralogy may also give an explanation of why mechanical properties vary with location. Awareness in this area may lead to a greater understanding of soil behavior. Basic index parameters and soil mineralogy may provide a basis for the expected behavior of soil in engineering work. Such insight can be an asset in geotechnical work, as it may validate or invalidate calculations when comparing results to known empirical relationships.

Most mechanical properties of a soil have some known or unexplored relationship to the composition. Some of these are more apparent than others, however, it is fair to assume that all mechanical properties of a soil can be traced back to the origin of the soil in some manner.

1.2 Problem Definition

The purpose of this thesis is to find correlations between soil parameters, with a special focus on Norwegian soil. Mechanical parameters will be discussed in accordance to basic index properties, as well as the mineralogy of clay minerals. The effect of the low plasticity which is common for Norwegian soil is of special interest. An important part of this thesis is to find out if the low plasticity affects the behavior of the soil, and which aspects that are affected.

Awareness of how different soil parameters correlate is advantageous in geotechnical engineering as it provides a framework for the type of behavior one can expect of various soils. This is an asset when performing calculations and estimations, as it may validate or invalidate the results that are achieved.

As this is a topic which may potentially be very large, the mechanical parameters that will be examined are limited to the ones related to stiffness, strength and compressibility. In addition, correlations will be limited to those regarding clay, while correlations for coarse grained materials will be excluded.

Already existing correlations from literature will be discussed and compared to correlations in Norwegian soil. The correlations for Norwegian soil will be found by analyzing data from GEODIP SP8, which is a database containing high quality soil parameters for clay (access granted to the database by NGI).

Literature Survey

Large parts of this thesis is based on *Grunnlag i Geoteknikk* by Janbu (1989). Chapter 2 from Janbu (1989) deals with the classification and identification of soil, and this forms the basis of chapters 2 and 4 of this thesis. In addition to this, material from other sources have provided a broader outline for the text. In particular, these sources include

Fundamentals of Soil Behaviour by Mitchell and Soga (2005), as well as *Correlations of Soil Properties* by Carter and Bentley (1990), *The Mechanics of Soils and Foundations* by Atkinson (1993) and *Manual of Mineralogy* by Klein and Hurlbut (1993).
Chapter 9 in *Soil Behaviour and Critical State Soil Mechanics* by Wood (1990) have been used considerably in finding correlations between soil properties.

1.3 Limitations

Large parts of this thesis is based on already existing literature, which means that one of the major limitations of this thesis is linked to the availability of data, and especially site specific data. Another limitation in finding experimental correlations is related to the available data used for plotting. Some parameters have been found only for a limited amount of sites, which limits the validity of the results.

Chapter 2

Basic Knowledge about Soil

This chapter will cover basic definitions and knowledge about soil from a geotechnical perspective. Large parts of the material is based on chapter 2 of *Grunnlag i Geoteknikk* by Janbu (1989).

2.1 Importance of Geological Factors

Knowledge about soil is the basis of all geotechnical work. The geological state of soil is an important aspect in understanding soil behavior, as well as how the behavior varies with respect to location. For engineering purposes, the mechanical properties of the soil is most relevant. While geologists examine several factors in order to understand earth formations, geotechnical engineers are most concerned with how these factors affect the mechanical properties of the soil. To geotechnical engineers, the most interesting relationships regarding geology are the geological formation and deposition of the soil, as well as well as its mineralogy. Knowledge about the stress history of the soil is also beneficial. In Scandinavia in particular, previous ice ages have had a huge impact on the soil in many aspects (Mitchell and Soga, 2005).

Due to a variation in geological processes throughout the world, geotechnical parameters tend to differ in accordance with location. As will be seen in this thesis, basic properties of soil influence the mechanical properties. Since soil is such a diverse medium, awareness about previous geological processes can be a helpful aid in geotechnical work, as it may indicate which characteristics one should expect.

Excessive geological history will not be covered in this thesis. Weathering processes, which play an important role in the formation of soil, will be covered briefly, along with mineralogy of clay in chapter 3.

2.2 Classification of Soil

Soil may be regarded as a three-phase system, with a solid, liquid and gaseous phase. By that definition, the solid phase consists of grain particles, the liquid is most often water, and the gaseous phase is generally air. The liquid and gas is found in the voids between the grains. The grains that make up the soil are typically fragments of rocks or clay particles, and the type of grain present tend to have a large impact on the mechanical properties of the soil, which will be discussed further. The soil will act in accordance to its composition, and soil may be classified with basis in several characteristics. Grain structure of the soil deposits, as well as shape and size of the grains are of special interest for geotechnical purposed, as these factors all affects mechanical properties (Janbu, 1989). The mineralogy of the particles are also crucial to some important mechanical properties. The following sections will cover the topics of classification in accordance to size, shape and surface of the grains, as well as the grain structure of some typical soils skeletons. Soil mineralogy will be covered more extensively in chapter 3.

2.2.1 Grain Size and Grain Size Distribution

Figure 2.1 illustrates the limits that define the different grain sizes, collected from Atkinson (1993). The figure also describes the type of medium used to see the grains. Clay particles are too small to be seen with a microscope, and an electron microscope is necessary. The classification of soil based on grain size is useful, as the mechanical properties of coarse grained materials varies largely from those of fine grained materials (Atkinson, 1993). Note that the illustrated limits between each grain type may vary in definition for different places in the world. However, the limits which are illustrated are the ones most commonly used according to Norwegian standards, where the upper limit of clay is typically 0.002 mm (Janbu, 1989). This limit is used to define clay in this thesis.

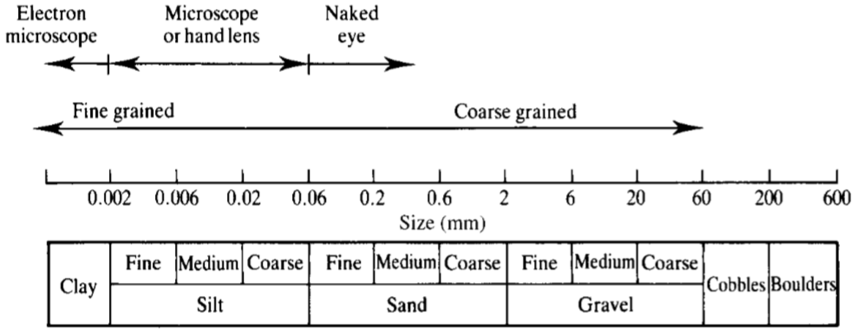

Figure 2.1: Soil particle sizes with classification (Atkinson, 1993)

The relative weight of each grain size fraction in a soil sample can be found and plotted against grain size. The plot formed is denoted a grain size distribution curve, and an example may be seen in figure 2.2. A soil is classified as a clay if the clay content is above 30% (Mitchell and Soga, 2005). This is due to the large impact that clay particles have on the soils mechanical properties, which will be discussed further in later chapters.

The slope of the different materials plotted in figure 2.2 represents the gradation of the material, which is a an indicator of how much the grain sizes of a material differs from each other. The gradation can be expressed through the coefficient of uniformity, C_u, as seen in expression 2.1 (Janbu, 1989).

$$C_u = \frac{d_60}{d_10} \tag{2.1}$$

where

d_{60}: the diameter for 60% of the material passing through

d_{10}: the diameter for 10% of the material passing through

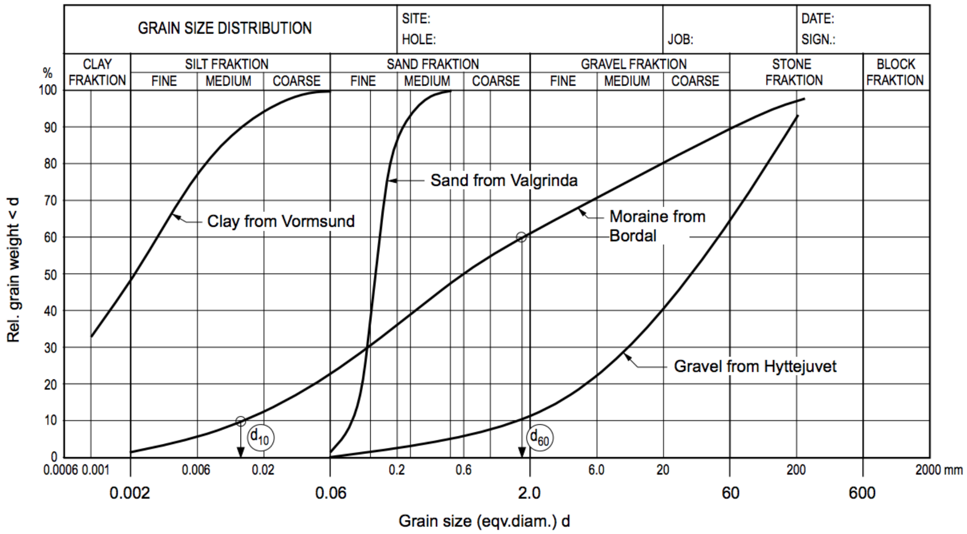

Figure 2.2: Grain Size Distribution Curve, with examples (Janbu (1989) as translated in (Emdal et al., 2017))

Table 2.1 illustrates how to classify a material in accordance with the coefficient of uniformity. A low value of C_u for a material implies that the grains in said material is of similar sizes. The gradation of soil is an indicator of other properties of the soil, such as the compressibility of the soil, as it dictates how tightly packed the grain particles can be. A material with a low coefficient of uniformity is packed looser than one with a high value, and vice versa (Janbu, 1989). Although the gradation number will not be explored further in this thesis, it is a valuable parameter in soil classification.

Table 2.1: Description of Soil, According to the Coefficient of Uniformity (Janbu, 1989)

C_u	Description
< 5	Uniformly graded
5-15	Medium graded
> 15	Well-graded

2.2.2 Shape and Surface of Grains

Soils may also be classified based on the shape of its grains. The difference in the shape of sand and clay particles is a more crucial difference than the size. Clay particles tend to be elongated or platy, and each mineral particle is very small (Mitchell and Soga, 2005). The shape will affect the structure of the soil, and in turn the material properties, such as the strength, compressibility and permeability(Mitchell and Soga, 2005). The shape and structure of clay particles, as well as the importance of this, will be covered more extensively in chapter 3.

2.2.3 Structure of Soil Skeleton

The structure of a soil skeleton is dependent on the type of sediment present. For soils with clay particles, the sustainability of the structure depends more on the bindings between the particles rather than the gradation of the soil (Mitchell and Soga, 2005).

Coarse Grained and Morainic Material

The structure of coarse grained material, such as coarse silt, sand and gravel, can in large parts be described in terms of its gradation. Morainic materials deposited by glaciers tend to be unsorted, well-graded and densely packed. This type of material may vary both in characteristics and density depending on where in the glacier it was transported and deposited. Morainic material is typically very dense (Janbu, 1989).

Clays

Soils with a clay content larger than 30% is classified as being a clay (Janbu, 1989). For clays, the structure of the sediment is affected by the means of deposition as well as the bonds between clay particles. Most clays have been deposited in flowing or still water.

Marine clays are clays that have been deposited in saltwater, which by definition contains charged ions. As will be discussed in section 3.8 clay particles typically have a negative surface charge, which is cancelled out by cations in the saltwater it is deposited in. The positive to negative attraction that is created between the clay particles and the pore water creates bonds throughout the clay, which makes up its structure (Mitchell and Soga, 2005). These attractive forces are of van der Waals-character (Carter and Bentley, 1990). The structure of marine clays is often compared to that of a card house (Emdal, 2014), which means that it is typically open and porous, with relatively large voids.

Lacustrine clays, or clays deposited in fresh water, tend to have a denser structure than marine clay. Due to the lack of salt in the water, the bonds between particles is not built up in a network of attractive forces, such as in the marine clay (Janbu, 1989). This means that the clay particles in a lacustrine clay is typically oriented in a more parallel manner than in marine clays, leading to a structure which is more dense (Janbu, 1989).

2.3 Phase Relationships of Soil

Some basic soil properties needs to be defined. Identifying properties in terms of relationships between weight and volume of soil is common. Such definitions are advantageous in exploring empirical correlations to strength and stiffness parameters. In this section, some properties of such character will be defined.

2.3.1 Weight Volume Relationships

Figure 2.3 illustrates the phases a soil is typically divided into (see section 2.2), as well as the relationship between the weight and volume of the different phases.

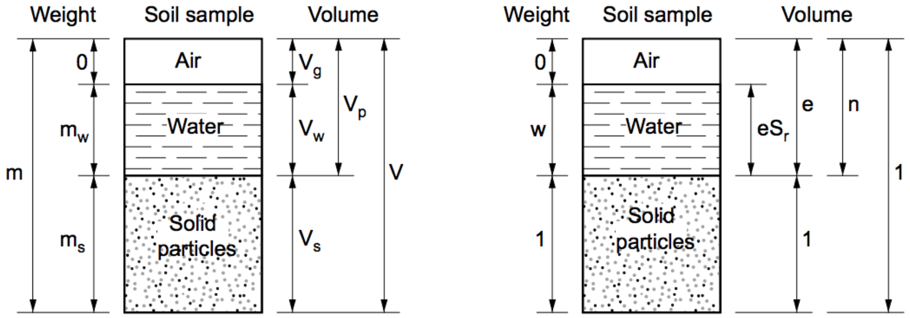

Figure 2.3: Weight-Volume Relationships of Soil (from Janbu (1989) as translated in Emdal et al. (2017))

The illustrated relationships are helpful in deriving basic properties of soil, which serves as important constituents for further soil mechanics.

Unit Weight and Specific Gravity

The unit weigh, γ, defined as in expression 2.2, is one of the most basic properties of soil. It is used in deriving several other properties of soil, as well as being crucial in determining stresses in the soil.

$$\gamma = \frac{(m_s + m_w)g}{V} = \frac{m * g}{V} \tag{2.2}$$

where
m$_s$: mass of solid particles [g]
m$_w$: mass of water [g]
V: total volume of sample [m^3]
g: gravity, 9.81 m^3/s

The specific gravity (G$_s$) of soils is sometimes useful in deriving other expressions. G$_s$ is defined as the ratio between the unit weight of the material in question and the unit weight of water($\gamma_w = 10\ \frac{kN}{m^3}$), see expression 2.3. The value of G$_s$ varies in accordance with the material present in the soil. Table 2.2 shows typical values for selected minerals, with values collected from Mitchell and Soga (2005).

$$G_s = \frac{\gamma}{\gamma_w} \tag{2.3}$$

Table 2.2: Specific gravity values for different soil minerals, values from Mitchell and Soga (2005)

Mineral	Specific gravity (G$_s$)
Montmorillonite	2.35-2.7
Illite	2.6-3.0
Kaolinite	2.60-2.68
Quartz	2.65

2.3.2 Porosity, Void Ratio and Degree of Saturation

The relationships described in this section are found in Janbu (1989).

Figure 2.3 illustrates the porosity (n) of a sample. The porosity is defined as the relationship between the volume of the pores and the total volume, see expression 2.4.

$$n = \frac{V_p}{V} \tag{2.4}$$

The void ratio (e) is the relationship between the volume of pores and the volume of solids. It can be found by expression 2.5.

$$e = \frac{V_p}{V_s} \tag{2.5}$$

The void ratio is especially important in regard to clay. It is a useful measure in determining volume changes. The specific volume can be found directly by expression 2.6 (Atkinson, 1993).

$$V = e + 1 \tag{2.6}$$

The degree of saturation (S_r) of a soil is defined as the relationship between the volume of water and the volume of pores, as seen in expression 2.7. It describes how much of the pores are filled with water.

$$S_r = \frac{V_w}{V_p} \tag{2.7}$$

For all soils under the ground water table, and most clays in general, S_r is equal to, or close to, 100 percent ($S_r = 1$). Soils with a saturation of 100 percent are said to be fully saturated. In this thesis, all clays are assumed to be fully saturated unless otherwise stated.

2.3.3 Natural Water Content

The natural water content (w) of a soil (sometimes referred to as the in situ water content) is defined as the relationship between the weight of water and the solid matter of a sample, see expression 2.8.

$$w = \frac{m_w}{m_s} \tag{2.8}$$

The void ratio of a soil and the natural water content are highly connected, as suggested by figure 2.3. The relationship between the two is derived in expression 2.9.

$$w = \frac{m_w}{m_s} = \frac{\gamma_w \cdot V_w}{\gamma_s \cdot V_s} = \frac{\gamma_w \cdot e \cdot S_r}{G_s \cdot \gamma_s} = \frac{e \cdot S_r}{G_s} \tag{2.9}$$

For fully saturated soils (S_r = 1), the air-phase is negligible. This means that the expressions of water content and void ratio expresses the same relationship (expression 2.10).

$$w = \frac{e \cdot \gamma_w}{\gamma} = \frac{e}{G_s} \tag{2.10}$$

The natural water content of a soil depends on factors such as the amount of clay minerals present in the soil and the type of clay minerals. This will be discussed further in chapter 3. The impact of water content on mechanical properties of clays will be discussed further in later chapters.

2.4 Stress History

The stress history of a soil describes the stresses that the soil has been subjected to over the course of time. This gives insight into the type of geological landscape that might have existed at a location in previous times. A soil that has been subjected to large loads over a period of time which has then been removed, will still show signs of this load. A soil skeleton which has been compressed and lost its original structure will not typically regain it when the load is removed. These types of events affects the mechanical properties of a soil significantly, particularly properties describing the stiffness and compressibility of a soil (Mitchell and Soga, 2005).

For Scandinavian soils in particular, the stress history is largely defined by previous ice ages. Huge glaciers which pressed down the land, and compressed large soil masses, lead to a change in volume and compaction of soil in many places. The result is a soil which is denser than originally (Emdal, 2014). This is one of the geological factors which may affect the behaviour of Norwegian and Scandinavian soil.

2.4.1 Overconsolidation Ratio

The phenomenon of consolidation, where the volume of the soil is decreased by pore water being pressed out, is highly linked to the stress history of soil(Carter and Bentley, 1990). Geological processes which have occured may have led to a variaton in stress states over time. The highest stress state a soil has experienced is described as the preconsolidation stress, which may be denoted σ'_c (or p'$_c$). A soil can be described as being normally consolidated (NC) or overconsolidated (OC), depending on the current stress state in accordance to the preconsolidation stress (Janbu, 1989). One may say that the soil remembers the highest stress state that it has been subjected to. This phenomenon is largely represented by changes in the soil structure.

The ratio between the current stress state and the preconsolidation stress is given by the overconsolidation ratio (OCR), which is defined by expression 2.11.

$$OCR = \frac{\sigma'_c}{\sigma'_v} \tag{2.11}$$

A normally consolidated soil is defined by having an effective stress equal to the preconsolidation stress (note that it can not be higher, as this indicates that the current stress is the preconsolidation stress), while an overconsolidated soil has a current stress level which is lower than the preconsolidation stress.

An overconsolidated soil is typically classified by OCR ≥ 2 (Emdal et al., 2017).

Chapter 3

Weathering and Mineralogy

In this chapter, physical and chemical weathering will be covered, as well as the importance of clay mineralogy. Some of the most common clay minerals will be discussed in depth, with regard to structure and characteristics.

3.1 Weathering

Weathering of rocks and soil is the driving force behind soil formation. Knowledge about weathering processes is an asset in understanding the structure and composition of a soil, which in turn is fundamental to the understanding of soil behavior. Various clay minerals with distinct properties may form as a result of weathering of rocks and soils with different compositions and in varying environments.

Mitchell and Soga (2005) defines weathering as *"all of the destructive mechanical and chemical processes that break down existing rock masses in situ"*. Erosion agents such as wind and running water transports the weathered product to locations with a different environment than the origin. Weathering may occur as a reaction to the environmental factors of the new location. Soil is formed by transformation of rocks into sediments by weathering and erosion. The weathering product is determined by the minerals present as well as the environment in which the weathering occurs(Helle, 2013).

In this section, the two main types of weathering will be covered briefly. Physical weathering describes mechanical processes of weathering, while chemical weathering describes processes in which the minerals are transformed or completely dissolved (Mitchell and Soga, 2005). Of the two, chemical weathering is the most crucial in the formation of clay minerals.

3.1.1 Physical weathering

Several processes of physical weathering are relevant for the formation of soil. These processes are a result of changes in environmental factors such as temperature and pressure. Examples of physical weathering includes unloading, thermal expansion and contraction, crystal growth, colloid plucking and organic activity (Mitchell and Soga, 2005). The elementary process of physical weathering is mechanical abrasion, which leads to soil being broken down into smaller fragments. Physical weathering may be seen as the initiator of chemical weathering, as it leads to an increase in surface area while breaking down the material(Schulze, 2002).

3.1.2 Chemical weathering

Chemical weathering processes are ones in which the minerals are transformed or even completely dissolved. The different environmental conditions at a new location means that the minerals in rocks or soils may react with the new environment and produce new minerals which are more stable at the new conditions.

The presence of water is essential to most chemical weathering processes. In many cases, weak acids formed in water (such as carbonic acid produced in rain water) lead to chemical weathering (Schulze, 2002). The initiation of most chemical weathering processes is hydration which describes the adsorption of water to the surface of minerals (Mitchell and Soga, 2005).

Hydrolysis is perhaps the most vital weathering process with respect to the formation of clay. The process of hydrolysis describes reactions between the clay mineral and the and H^+ and $(OH)^-$ ions of water (Helle, 2013). These replace ions in the mineral, which sometimes leads to the formation of new minerals.

Leaching is another example of a chemical weathering process. Leaching describes the process of ions being removed from the parent rock or soil by dissolution into water (Klein and Hurlbut, 1993).

Chemical weathering may also occur by oxidation, in which minerals react with free oxygen and the oxidation state of an ion is changed. This is most common for minerals that contain iron, as iron has several oxidation states (Schulze, 2002).

Other important chemical weathering processes include dehydration and complete dissolution. Dehydration describes the process where H_2O or OH^- is removed from the ion. Complete dissolution means that all of the mineral is completely dissolved by water (Schulze, 2002).

3.1.3 Mineral Stability

Different minerals have a varying degree of stability. The stability of minerals varies in accordance with environmental factors, such as temperature, pressure and access to water and oxygen. A minerals stability is determined by its resistance to chemical weathering. Close to the surface of the earth, where soil is found, the most stable minerals are iron oxides, aluminum oxides(such as hematite) and gibbsite, followed by quartz which is followed by clay minerals (Klein and Hurlbut, 1993). This means that clay minerals are among the most stable minerals.

3.2 Mineralogy

Klein and Hurlbut (1993) defines a mineral as *"A naturally occurring homogeneous solid with a definite (but generally not fixed) chemical composition and a highly ordered atomic arrangement. It is usually formed by inorganic processes"*. Paraphrased, minerals are compositions of different atoms, arranged in specific ways.

The mineralogy of soil particles are a major contributor in determining the shape and size of the particles, as well as the engineering properties of the soil. A large variation of minerals exist, and the different minerals can be identified by their physical and chemical properties. In the following sections, clay mineralogy will be explored, with examples of some of the most common minerals in soil, as well as some of their characteristic traits.

Note that mineralogy is a very wide topic. The purpose of this chapter is to function as a background for the later topics of this thesis. Thus, for the purpose of this thesis, the minerals of interest are the ones that make up clay, and hence the focus will be on these.

3.3 Silicate Minerals

Elements that are most abundant in the earth's crust can be seen in table 3.1. As illustrated, oxygen and silicon are the most abundant, and these go together to form the base of silicate minerals. More than 90% of the earth's crust are thought to be silicates, and almost 40% of common minerals can be classified as silicates(Schulze, 2002). This amount include most of the minerals in igneous rocks, as well as the bulk of most soils. Primary minerals that are inherited from igneous and metamorphic rocks, as well as secondary minerals formed by weathering products of primary minerals make up silicate minerals (Schulze, 2002).

Table 3.1: Elemental composition of the whole Earth and the crust(percentage by weight) (data from Press and Siever, collected from figure 2.1 in Mitchell and Soga (2005))

Element	Earth's crust [%]
Oxygen (O)	46
Silicon (Si)	28
Aluminum (Al)	8
Iron (Fe)	6
Magnesium (Mg)	4
Calcium (Ca)	2.4
Potassium (K)	2.3
Sodium (Na)	2.1
Other	<1

3.3.1 The Silicon Tetrahedron

Silicate structures are based around a fundamental unit, which is the SiO_4 tetrahedron. The SiO_4 tetrahedron is made up by four O^{2-} ions, located at the tips of a common tetrahedron coordinated to one Si^{4+} at the center. As illustrated in figure 3.1, the three "bottom" oxygens are referred to as the basal oxygens, while the oxygen on top is referred to as the apical oxygen. The tetrahedron has a net charge of -4 (SiO_4^{-4}).

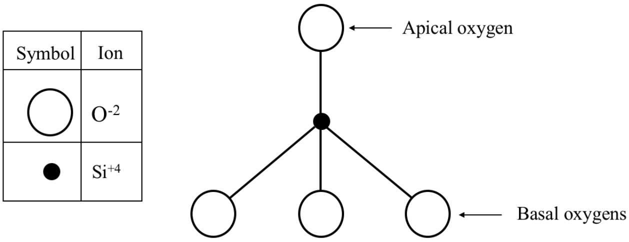

Figure 3.1: Silicon tetrahedron (redrawn from Mitchell and Soga (2005))

Complex structures are formed by tetrahedrons linked together by sharing O^{2-} ions. Various classes of silicate minerals exist, and these classes are distinguished by the arrangement of the SiO_4 tetrahedrons in relation to one another. Neosilicates (single tetrahedra), sorosilicates (double tetrahedra), cyclosilicates (rings), inosilicates (single or double chains), phyllosilicates (sheets) and tectosilicates (three-dimensional frameworks) are among the most common silicate classes(Schulze, 2002). The phyllosilicates includes several of the most common clay minerals, and will be discussed further.

3.4 Phyllosilicates

The phyllosilicates, also denoted sheet silicates, includes minerals like micas, chlorite, talc, serpentine, and clay minerals. This group is known for having a generally small particle size and large surface area, in addition to unique cation exchange rates. This which will be discussed in sections 3.6 and 3.8. Due to the special properties, minerals of this group are highly influential of both chemical and physical properties of soil.

The basic structure of the phyllosilicates consists of rings of six interconnected SiO_4^{4-} in a hexagonal arrangement (see figure 3.2). The rings are connected to other rings, which extends into infinite sheets. Each tetrahedron shares its three basal oxygens with other tetrahedra, keeping the apical oxygen unshared (leading to a basic structural unit of $(Si_2O_5)^{-2}$). This leaves the apical oxygen free to bond with cations.

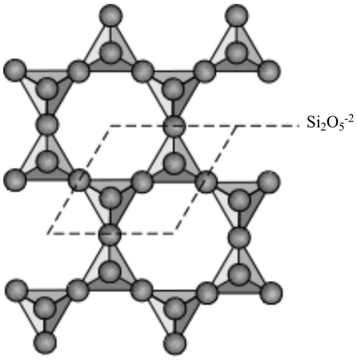

Figure 3.2: Structure of phyllosilicates (Klein and Hurlbut, 1993)

Most of the phyllosilicates members contain hydroxyl, with the (OH) group located at the center of the rings, at the same height as the apical oxygens. Ions from external sources may connect to the sheets, by coordination to two apical oxygens and one (OH). This forms a new sheet structure, which usually consist of magnesium or aluminum in octahedral coordination with the hydroxyls and oxygens (Mitchell and Soga, 2005). The bonds that form between the octahedral and tetrahedra sheets are typically half covalent and half ionic, which makes them very strong(Klein and Hurlbut, 1993). The phyllosilicates can be conceptualized as silicate sheets stacked on magnesium or aluminum sheets. This is illustrated in figure 3.3.

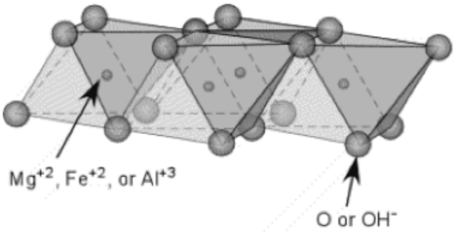

Figure 3.3: Structure of phyllosilicates, modified from Klein and Hurlbut (1993)

3.4.1 Dioctahedral and Trioctahedral Sheets

The octahedral sheets of the phyllosilicates can exist in two ways, depending on the valency of the cations present. In the case of divalent cations, such as Mg^{2+} or Fe^{2+}, each cation site is occupied. This means that each oxygen or (OH)-group is surrounded by 3 cations, which makes the sheet electrically neutral (Schulze, 2002). In this case, the structure is that of brucite ($Mg(OH)_3$). This type of structure is known as trioctahedral (Klein and Hurlbut, 1993).

If the cations are trivalent, such as Al^{3+}, charge balance is achieved by every third cation site being left unoccupied, which means that each oxygen or (OH) group is surrounded by two cations. In this case, the octahedral layer takes on the structure of gibbsite ($Al(OH)_3$), and is denoted as being dioctahedral(Klein and Hurlbut, 1993). Generally, dioctahedral sheets are more resistent to weathering than trioctahedral (Schulze, 2002), and is thus more stable.

A schematic illustration of how basic sheets may be depicted is seen in figure 3.4. These will be used to illustrate different clay minerals later in this chapter.

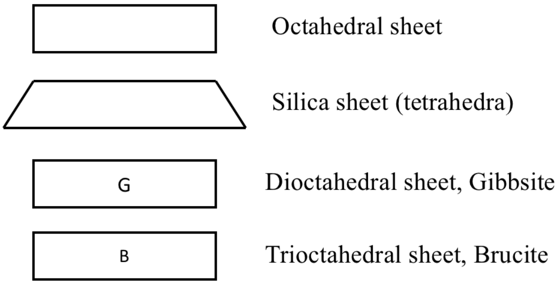

Figure 3.4: Idealized illustration of sheet minerals, redrawn from Mitchell and Soga (2005)

3.5 Clay Minerals

Phyllosilicates may be divided into groups based on the layering structure of the minerals. The most common clay minerals will be summed up in accordance to structure in this section. The minerals that have been chosen as examples are typical minerals in its respective group, and are among the most common clay minerals.

3.5.1 1:1 Minerals

1:1 minerals, or two-layered sheet minerals, have a basic structure which consists of one octahedral and one tetrahedral sheet bound together. The apical O^{2-} ions of the tetrahedra is shared with cations in the octahedra. Several such units are stacked together to form clay (Schulze, 2002).

Of the 1:1 minerals, there are two main subgroups, which are distinguished by the octahedral layer. Trioctahedral sheets leads to the serpentine subgroup, while dioctahedral sheets leads to clay minerals in the kaolinite subgroup. Trioctahedral 1:1 minerals are relatively rare, which means that clay with an abundance of 1:1 minerals is usually kaolinite (Mitchell and Soga, 2005).

Kaolinite

Kaolinite is the most commonly found 1:1 type mineral. The octahedral sheet is gibbsite, which indicates an abundance of aluminum. Figure 3.5 illustrates the structure of kaolinite.

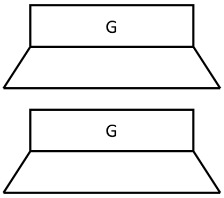

Figure 3.5: Idealized illustration of kaolinite, redrawn from Mitchell and Soga (2005)

The 1:1 layer in kaolinite has a low amount of substitution, and thus, it also has little or no permanent charge. This means kaolinite is close to electrically neutral, which in turn makes it a quite stable mineral. Gibbsite in the octahedra sheet is also an indication of its high stability. The high stability means that it is a quite abundant mineral (Schulze, 2002).

Successive layers of 1:1 minerals are bound together by hydrogen bonds or van der Waals forces. The hydrogen bonds occur between basal oxygens in the tetrahedral sheets and hydroxyls in the octahedra sheet in the adjacent layer (Mitchell and Soga, 2005). These bonds are strong enough that water molecules are prevented from entering between the sheets. In turn, this prevents interlayer swelling in the presence of water (Mitchell and Soga, 2005).

Kaolinite is usually formed by advanced weathering of granitic rocks that are rich in feldspar and mica. It is typically abundant in soils that have been highly weathered, and can form in soils where weathering of primary and secondary minerals leads to the release of Si and Al (Schulze, 2002).

Ions released during weathering, such as Na, K, Ca, Mg and Fe, is required to be leached from the system for kaolinite to form (Klein and Hurlbut, 1993). This leaching is favored by acidic environments with high precipitation and good drainage, which means that those are the typical environments where kaolinite is found (Helle, 2013).

3.5.2 2:1 Minerals

2:1 minerals, or three-layered sheet minerals, consist of two tetrahedra sheets and one octahedral, with one tetrahedra bound to each side of the octahedra sheet. This structure means that the faces of the unit-minerals consist merely of basal oxygens, and no hydroxyl groups. Thus, it is not possible for hydrogen bonds to occur between the successive layers (Schulze, 2002). Instead, bonds between layers are usually of van der Waals type, with cations that balance charge deficiencies in the structure (Mitchell and Soga, 2005). Such bonds are typically quite weak, and because of this, the successive layers can be separated quite easily by water or other polar liquids (Schulze, 2002).

Several groups of three-layered sheet minerals exists, but for the purpose of this thesis, only the illites and the smectites will be covered.

Illites

The clay mineral most commonly found in engineering contexts is illite (Mitchell and Soga, 2005). Illite, often referred to as hydrous mica, is a micalike clay mineral with a 2:1 layer structure. Mica minerals can exist in several variations, where the most common are muscovite (white mica), phlogopite (brown mica) and biotite (black mica) (Helle, 2013).

The structure of illite is most similar to that of muscovite, with some variations. Muscovite has a 2:1 structure with dioctahedral sheets of gibbsite. Typically, about one quarter of the silicon (Si^{+4}) is replaced by aluminum(Al^{+3}) (Klein and Hurlbut, 1993). The variation in valences leads to an excess negative charge. This charge is balanced by a monovalent cation in the interlayer, which is usually potassium (K^{+}) (Mitchell and Soga, 2005). This structure is the same as for illite, although illite typically have fewer substitutions of aluminum for silicon, as well as having less potassium in the interlayer than muscovite. The unit layer stacking is also more random than it is in muscovite, and the particles are significantly smaller (Helle, 2013). Figure 3.6 illustrates of the structure of muscovite and illite.

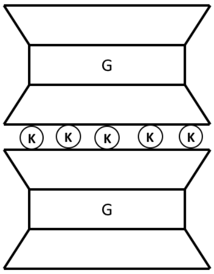

Figure 3.6: Idealized illustration of muscovite/illite, redrawn from Mitchell and Soga (2005)

Illites are formed by weathering of rocks that have high contents of potassium and aluminum in high pH-conditions (Klein and Hurlbut, 1993). Mica in soil is usually inherited from a parent rock. This is a result of weathering of igneous and metamorphic rocks, as well as their sediments. The different micas all have potassium in their interlayers, but muscovite, being the only dioctahedral mica, has the highest resistance to weathering, and is thus the most stable (Schulze, 2002). The presence of potassium in the interlayers prevents entrance of H_2O molecules entering the structure, which in turn makes this a non-expanding mineral (Klein and Hurlbut, 1993). Note that in some illites, the interlayer potassium may be substituted by other monovalent cations, such as Ca^+ or Mg^+ (Mitchell and Soga, 2005).

Smectites

Smectite is another 2:1 type mineral. Successive layers of smectites are held together by van der Waals forces and cations which balance the charge deficiencies (Mitchell and Soga, 2005). These bonds are relatively weak, and may be separated by cleavage or polar liquids entering (Schulze, 2002). Thus, the smectites have extensive adsorption properties. Exposure to water may lead to expansion several times its own size, which makes this a swelling mineral type (Mitchell and Soga, 2005). Swelling is the most important characteristic of the smectite group.

Isomorphous substitution by cations for Si^{4+} and Al^{3+} is comprehensive. Al^{3+} in the octahedral sheet may be replaced by either Mg^{2+}, Fe^{2+}, Zn^{2+}, Ni^{+}, Li^{+} or others, while Al^{3+} may replace Si^{4+} in the tetrahedra sheet by as much as 15% (Mitchell and Soga, 2005). Smectites can contain significant amounts of both magnesium and iron which substitutes into the octahedral layers. Thus, smectites may be both di- and trioctahedral, although it is most common that it is dioctahedral (Klein and Hurlbut, 1993). The most common mineral in the smectite group is montmorillonite, which has dioctahedral layers (Helle, 2013). Montmorillonite is known for being particularly prone to swelling. Figure 3.7 illustrates the structure of montmorillonite.

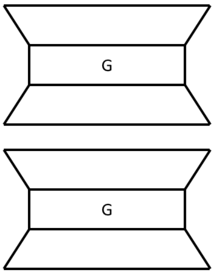

Figure 3.7: Idealized illustration of montmorillonite, redrawn from Mitchell and Soga (2005)

Typically, smectites occur in dry environments, where there is a higher rate of evaporation than precipitation. It is typically a result of weathering of basic and intermediate igneous rocks, as well as of volcanic ash and its derivatives. The concentration of magnesium and calcium needs to exceed the concentration of sodium and potassium, and the pH must be high in order for smectite to form (Helle, 2013).

3.5.3 Mixed Layer Clays

Most of the time, natural clay contains a mixture of different clay minerals, meaning that it is not purely one mineral affecting the properties of soil. In fact, second to illite, mixed layer clays are the most abundant type of clay found in nature (Mitchell and Soga, 2005). Common structure combinations include montmorillonite-illite, as well as chlorite-vermiculite and chlorite-montmorillonite (chlorite is another 2:1 mineral, which will not be covered further in this thesis) (Helle, 2013).

Mixed layer clays is mostly a result of minerals with similar crystal structures having the possibility of interstratification of two or more layer types. This may occur even within a single clay particle. The structure of the mixed layers can both be random and have a regularly repeating structure pattern (Mitchell and Soga, 2005).

Infinite variations of soils exist. Different means of weathering and transportation over a long period of time means that it is impossible to determine the composition of a soil without actually checking it. It is, however, useful to be aware of the characteristics associated with varying clay minerals.

3.6 Specific Surface Area

Due to the shape and size of clay minerals, the surface area is generally large relative to the size and mass of the material. The specific surface area is directly related to the clay minerals. The degree of structural order in a mineral, or its crystallinity, impacts the size of the surface area. Two-layered minerals usually have a smaller surface area than three-layered ones, indicating a difference in specific surface area. Table 3.2 gives an overview of typical values of specific surface areas for the minerals discussed in the previous sections. The typical value of the specific surface area of clean sand is included in the table. The structure of a typical grain of sand is significantly different from clay minerals, and this comparison illustrates the significance of crystallinity in clay.

Awareness of crystallinity and specific surface area of clay minerals is a key aspect in understanding the behaviors associated with clay. The surface area affects properties such as the ability to absorb water. Clay particles with a large specific surface tend to bind more water to its surface than those with a small surface area. These properties will be discussed in later chapters.

Kaolinites have a relatively small specific surface area compared to smectites and illites. This is largely due to the 1:1 sheet structure. Additionally, the strong interlayer bonds means that only the outer edges of the particle contributes to the surface area.

Particles with poor crystallization are smaller, and thus they have a smaller surface area (Helle, 2013).

Table 3.2: Specific surface of minerals (Mitchell and Soga, 2005)

Mineral	Specific surface area[m^2/g]
Montmorillonile	Up to 840
Illite	65 - 200
Kaolinite	10 - 20
Clean sand	~2 10^{-4}

Illites typically have somewhat larger specific surface areas than kaolinites, because of the 2:1 structure. However, the strong interlayer bonds limits the size (Helle, 2013).

The surface area of smectites are typically very large compared to other minerals, and this is especially true for montmorillonite. This is due to the 2:1 sheet structure, as well as the weak interlayer bonds. The specific surface area of smectites may be divided into the primary and secondary surface area. The primary one includes the outer edges of the mineral(excluding the interlayers), while the secondary surface is the area that is revealed in the case of expansion of the unit cell layer. This expansion enables polar molecules to penetrate the layers (Helle, 2013). The secondary surface area is much larger than the primary one. According to Mitchell and Soga (2005), the primary surface area of smectites range from 50 - 120 m^2 / g, while the secondary specific surface area can be as large as 840 m^2/g.

3.7 Pore Water Chemistry

The pore water chemistry influences the behaviour of clay particles in contact with water. It is vital to note the importance of the depositional environment of the soil, as this will affect the soil particles and the pore water composition.

3.7.1 Water Molecules and the Attraction to Clay Particles

The dipole nature of water molecules leads to attraction to dissolved ions, as well as strong attraction to the surface of clay minerals (Helle, 2013). There are several possible mechanisms of such an attraction. Commonly, the water molecule form a hydrogen bonding with the clay particle, as the clay minerals often expose either oxygen (silicon tetrahedron attracts the positive end of water molecules) or hydroxyls (octahedra attracts the negative end of water molecules) (Klein and Hurlbut, 1993).

Water molecules may also be attracted to the clay particles by other mechanisms, such as the hydration of exchangeable ions, osmosis, charged surface-dipole attraction, London dispersion forces or by capillary condensation (Klein and Hurlbut, 1993).

Water present in a soil is either adsorbed onto the clay minerals, or it exist freely as water in the pores. The water which is adsorbed onto the clay minerals tend to be strongly attached and may in some sense be viewed as an extension of the clay particle itself, although it is not completely fixed to one spot. Most of the water present in a soil may be said to be associated with the clay fraction of the soil (Mitchell and Soga, 2005).

Cations in the pore water is attracted to the adsorbed water. In soils of low saturation, the cations will be fighting to be attached to the water molecules, while for highly saturated soils, the cations have more water molecules to attach to. In such cases, some of the cations may even move away from the particle surface by diffusion (Helle, 2013).

3.7.2 Pore Water Composition

The composition of pore water depends on several factors. Such factors include chemical weathering processes which have occurred, the dissolution of minerals, redox reactions, and ion exchange reactions etc. The pore water composition is another important factor that affects the behavior of clays. Some of the things that are affected by it includes the ability of flocculation, the ability to form quick clay, and the bonding between minerals (Helle, 2013).

The pore water consists of ions, and the composition of these is mainly a result of the depositional environment. Marine clays will have an abundance of Na^+ as the adsorbed cations, while lacustrine clays tend to have different cations in the adsorbed places (in decreasing order: Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}). The anions most common in the pore water of marine clays are SO_4^{2-}, Cl^{-}, PO_4^{3-} and NO_3^{-}, while in fresh water sediments, the most common anion is HCO_3^{-} (Helle, 2013).

3.7.3 The Diffuse Double Layer

A saturated clay may be seen as a two-phase system, in which particles and water with free ions interacts. One may view this system as two parallel layers of charge that surrounds the particle. The first layer consists of a surface charge of adsorbed water onto the particle surface, with strong forces keeping the water attached to the clay surface. The second layer is more loosely attached to the soil, and may be seen as free ions that move in the fluid under the influence of electric attraction (Klein and Hurlbut, 1993). Since the attraction is strongest closest to the particle, the concentration of free ions is highest closest to it, and dissipates with distance to the surface(see figure 3.8). This layer can be described as being diffuse, and thus it is called the diffuse double layer.

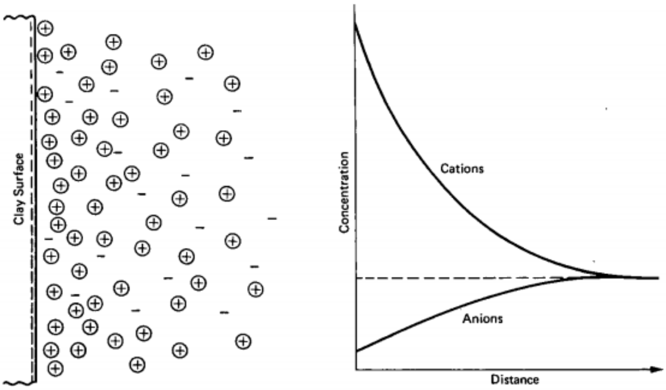

Figure 3.8: Ion distribution in the diffuse double layer surrounding the clay minerals surface (Mitchell and Soga, 2005)

The distance from the particle surface to where the ions are still affected by the electrical charge describes the thickness of the diffuse double layer(Helle, 2013). Due to the double layer, the surface charge on the clay particle is not evenly distributed (Klein and Hurlbut, 1993).

3.8 Cation Exchange

Cation exchange measures the amount of cations that can be retained on the surface of soil particles (Mitchell and Soga, 2005). Intuitively, this suggests that a large specific surface area leads to a large capacity of cation exchange. This is synonymous with a high capacity of adsorption. As clay minerals generally have large surface areas, they tend to have high capacities of cation exchange.

Since she surfaces of clay minerals are typically negatively charged, positively charged cations are attracted to the surface. As mentioned in section 3.7.2, cations exist in the pore water. This means that the composition of the pore water is a major influence on the clay composition. In addition to the chemical and biological composition of the pore water, the pH, temperature and pressure state in the natural environment all have significant effects on the adsorption of ions onto solid surfaces (Klein and Hurlbut, 1993).

3.8.1 Ion Exchange

While the natural environment of a soil is stable, the soil-water system is in equilibrium. Environmental changes in the water, such as in the pH, temperature, pressure and the biological and/or chemical composition, may induce changes in the type of ion which will be released and adsorbed from solid surfaces (Helle, 2013). The soil surface always strives to reach equilibrium, which means that the ion exchange will change in response to changes in the environment.

Exchange capacity describes how easily cations on mineral surfaces can be replaced when soil is leached with a solution that contains dissolved cations (Helle, 2013). The dissolved cations have a higher replacing power than the adsorbed cations, and can hence be exchanged. The exchange capacity is dependent on the ion size and the valence of the ions, as well as the relative abundance of the different types of ions (Helle, 2013). According to (Mitchell and Soga, 2005), the replacing power of ions is in the following order:

$Na^+ < Li^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}$

The type of ions adsorbed onto the mineral surface is influenced by changes in ion composition and ion concentration in the pore water (Mitchell and Soga, 2005). These changes may affect the physical and physicochemical properties of soil. Different sizes of various ions leads to a varying ability of adsorption(Helle, 2013). The amount of ions present may also affect the exchange capacity. Even though the solid surfaces tend to prefer ions with a high valence, a high concentration of ions with low valence may replace high valence ions that have a low concentration (Helle, 2013).

3.8.2 Cation Exchange Capacity (CEC) of Clay Minerals

The cation exchange capacity (CEC) for clay minerals will vary in accordance with the mineral. This is largely due to the crystal structure of the minerals, as well as the surface area and surface charge density of the particles. As discussed in section 3.6 the surface area varies for different minerals, meaning that the CEC does as well. It is also important to note that as soil usually consist of several types of clay minerals, the CEC will have contributions from several of these (Helle, 2013).

Kaolinite have strong bonds between the sheets, which leads to all the exchange occuring on the non-cleavage surface and along the particle edges. The CEC of kaolinite is pH-dependent, since the pH affects the surface charge. Acid environments leads to positive charge and basic environment leads to a negative charge.

Illites have extensive isomorphous substitution, primarily in the silica sheets. The mineral is non-expanding, but a CEC which exceeds 15 meq/100 g indicates that there is some expansion between the unit layers (Helle, 2013).

Smectites have isomorphous substitution in the silica and octahedral sheets, which results in a charge deficiency. This charge is then balanced by cation adsorption in the interlayers and on the particle surface(Helle, 2013). A high CEC is the result of large amounts of unbalanced substitution.

Illites and smectites have exchange sites between unit layers, which means that the exchange reactions take longer for these types of minerals than for minerals such as kaolinite (Mitchell and Soga, 2005). Table 3.3 lists typical values of the CEC of different minerals. Note that these values are not fixed, but typical approximate values.

Table 3.3: Cation exchange capacity of minerals, values from table 3.6 in Mitchell and Soga (2005)

Mineral	CEC [meq/100 g]
Montmorillonile	80 - 150
Illite	10 - 40
Kaolinite	3 - 15

Chapter 4

Properties of Clay

Clay is abundant in soils throughout the world. Large parts of the soil encountered in Scandinavia is clay or clayey material. The recognition of basic properties particular to clay is essential in understanding the behavior of clay and soils in general, as such properties are highly influential of several mechanical properties of soil. Clay properties will be discussed in this chapter. The material in this chapter is largely based on content from *"Grunnlag i Geoteknikk"* by (Janbu, 1989).

As described in section 2.2.1, the definition of clay most commonly used is particles with a diameter smaller than 0.002 mm. A soil is classified as a clay if the clay content is larger than 30 percent. The clay content have a larger impact on soil properties than the content of coarse grained materials (Mitchell and Soga, 2005), which is largely due to the distinct mineralogy of clay particles, as seen in chapter 3.

4.1 Atterberg Limits

The water content of a soil impacts its consistency. As illustrated in figure 4.1, soil can be defined as being in one of four distinct states in accordance with its water content. Large amounts of water present in a clay makes it resemble a liquid. This is largely due to decreased attraction between clay particles as a result of excessive amounts of water between the particles(Mitchell and Soga, 2005).

Early in the 1900s, Swedish agricultural engineer Albert Atterberg established a set of tests which could be used to determine water content at the limits between the four soil states (Wood, 1990). These limit values are denoted Atterberg limits, and the limits that are still in use includes the liquid limit, the plastic limit and the shrinkage limit. Natural water content in relation to Atterberg limits is an indication of a soils consistency and behavior. The Atterberg limits may also give an indication of the type of clay minerals that make up the soil (see table 4.3). The different Atterberg limits will be discussed in the following sections.

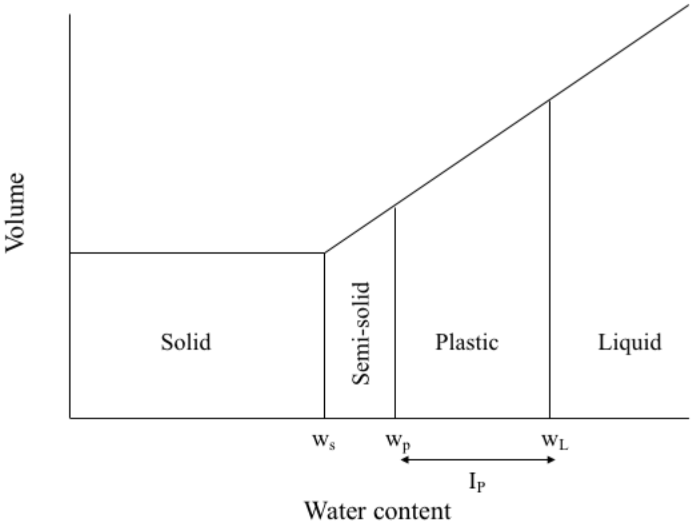

Figure 4.1: Volume and consistency changes with water content change, redrawn from Carter and Bentley (1990)

4.1.1 Liquid Limit

The liquid limit (w_L) of a soil describes the lowest water content at which the soil is considered to act as a liquid. The liquid limit of a soil is defined by Casagrande as the water content which corresponds to a shear strength of 2 kPa (sometimes denoted "c_L" or "s_L") (Wood, 1990).

At water contents higher than the liquid limit, the amount of water is large enough to break the attraction between clay particles (Mitchell and Soga, 2005). The clay gets approaches a liquid state as more water enters. An increase in volume without an increase in clay minerals indicates that the distance between the particles increases. The attraction is weakened, and thus, the material starts flowing (Carter and Bentley, 1990). This phenomena is illustrated in figure 4.1.

4.1.2 Plastic Limit

The plastic limit (w_P) of a clay is the lowest water content at which the soil can be plastically molded without yielding or crumbling (Carter and Bentley, 1990). The plastic limit is defined by Casagrande as the water content at approximately 100 times the strength at the liquid limit, which means it is close to 200 kPa (sometimes denoted "c_P" or "s_P") (Wood, 1990).
Plasticity will be discussed further in section 4.2.

4.1.3 Shrinkage Limit

The shrinkage limit (w_S) represents the highest water content a clay can have without any change in volume. Soils with a water content that is lower than the shrinkage limit is densely packed (Carter and Bentley, 1990). In modern geotechnical engineering, the shrinkage limit is not widely used, although one may argue it is useful in providing a basis for understanding soil behavior.

4.1.4 Dependency on Mineral

Table 4.1 lists typical values of the Atterberg limits for montmorillonite, illite and kaolinite. It is clear that the values of the different minerals correlates with the with specific surface area of the minerals(see table 3.2). This illustrates the significance of the minerals present in clay in relation to the soil behavior.

Table 4.1: Typical values of Atterberg limits for different minerals (values collected from Mitchell and Soga (2005))

Mineral	w_L [%]	w_P [%]	w_S [%]
Montmorillonite	100 - 900	50 - 100	8.5 - 15
Illite	60 - 120	35 - 60	15 - 17
Kaolinite	30 - 110	25 - 40	25 - 29

4.2 Properties Derived from the Atterberg Limits

The Atterberg limits of soils are important tools which can be used to describe a soils behavior and character. Comparing the Atterberg limits of the soil to its natural water content provides valuable information. Two important index properties can be derived from values of natural water content and the liquid and plastic limit of soil. These indices are the plasticity index (I_P) and the liquidity index (I_L).

4.2.1 Plasticity and the Plasticity Index

The most fundamental difference between clay and coarse-grained soil is the ability of clay to act plastically. Plasticity is one of the most important and defining characteristics of clay, and the crystallinity of clay minerals is the major cause of this plasticity (Carter and Bentley, 1990). Soil is said to be plastic when the water content is between the liquid and plastic limit, and the plastic range, which is the difference between these two limits is labeled the plasticity index, I_P (see expression 4.1). Figure 4.1 illustrates the plastic area in terms of the plasticity index.

$$I_P = w_L - w_P \tag{4.1}$$

The value of I_P varies with the soil content and the clay minerals present. I_P is dependent on w_P and w_L, which, as seen in table 4.1, both varies significantly in magnitude for the minerals represented. The plasticity index may be seen as an indicator of how much water a soil may contain without too much of an impact on its structure. The plasticity may also be linked to the specific surface area of the soil, as this impacts the potential water content. The specific surface area of clean sand (table 3.2) is minimal compared to that of clay minerals, and this supports the notion that coarse grained material have a minimal plasticity.

Norwegian clay can be described as having very low plasticities compared to international clays (Emdal et al., 2017). Table 4.2 shows how to classify Norwegian clays in accordance to plasticity.

Table 4.2: Classification of plasticity for Norwegian clays (Janbu, 1989)

Classification of Plasticity	I_p [%]
Low plasticity	< 10
Medium plasticity	10 - 20
High plasticity	> 20

There is a strong correlation between the plasticity index I_P, and the liquid limit, w_L. Figure 4.2, collected fromTomlinson (2001), illustrates this correlation. From the figure, it is also evident that clays have a higher range of plasticity than silts, while cohesionless soils is indicated as having a low or no plasticity.

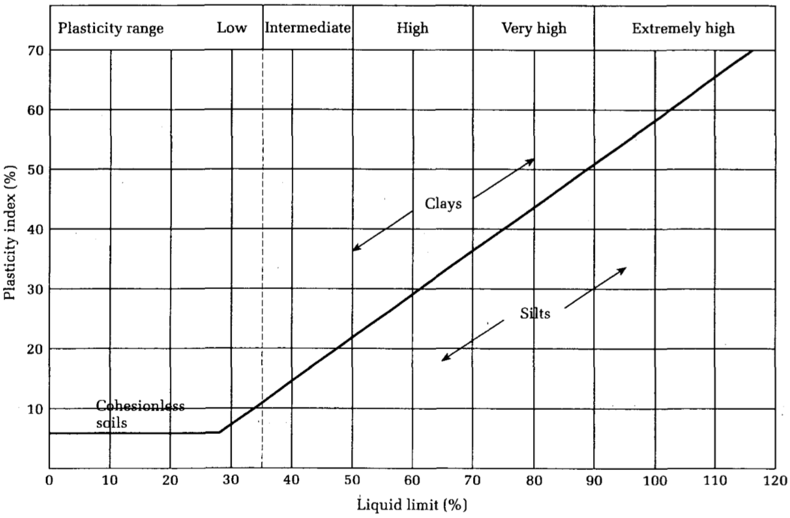

Figure 4.2: Relationship between liquid limit w_L and plasticity index I_P (Tomlinson, 2001)

The correlation between I$_P$ and w$_L$ was emphasized by experiments performed by geotechnical engineer Casagrande (Wood, 1990). The experiments performed led to the definition of a so-called A-line, which provides an empirical boundary between mainly organic and inorganic clays (Wood, 1990). The A-line is defined by expression 4.2, and may be seen in figure 4.3.

$$I_P = 0.73(w_L - 0.2) \tag{4.2}$$

For index tests of several clay samples of similar origin and composition, the values of w$_L$ and I$_P$ tends to form a plot which is close to parallel to the A-line. Tests on a group of similar soils will plot on a line on the form of expression 4.3. (Wood, 1990).

$$I_P = A(w_L - B) \tag{4.3}$$

Figure 4.3 illustrates this relationship with examples of different clays. Clays that plot above the A-line tend to be inorganic, while those that plot below it is generally plastic soils that contain organic colloids. Inorganic silts and silty clays are also mainly found below the A-line (Wood, 1990).

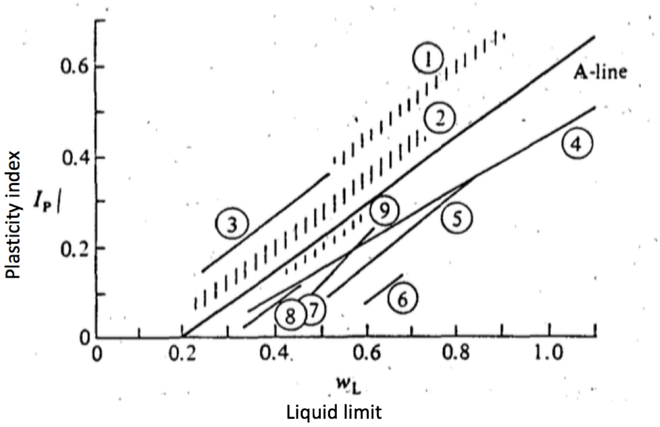

Figure 4.3: Relationship between liquid limit w$_L$ and plasticity index I$_P$ for soils, after Casagrande (1: Gumbo clays (Mississippi, Arkansas, Texas), 2: Glacial clays (Boston, Detroit, Chicago, Canada), 3: Clay (Venezuela), 4: Organic silt and clay (Flushing Meadows, Long Island), 5: Organic clay (New London, Connecticut), 6: Kaolin (Mica, Washington), 7: Organic silt and clay (Panama), 8: Micaecous sandy silt (Cartersville, Georgia), 9: Kaolin-Type clays (Vera, Washington, and South Carolina)) (Wood, 1990)

4.2.2 The Liquidity Index

The liquidity index, I_L, is defined by expression 4.4. I_L describes the natural water content in relation to the plastic area (Janbu, 1989). Hence, it describes the relative water content of the soil, making it a property which is easily comparable for different soils.

$$I_L = \frac{w - w_P}{w_L - w_P} \tag{4.4}$$

A value of the liquidity index higher than 1 indicates that the natural water content is in the liquid area, and a value between 0 and 1 indicates that w is between w_P and w_L, or the plastic area (Janbu, 1989).

4.3 Activity

The activity of a soil is defined as the plasticity of the clay fraction of the soil, as seen in expression 4.5. It describes the plasticity of pure clay minerals, or the ability of the clay mineral to bind water (Mitchell and Soga, 2005). The activity of a soil is therefore highly dependent on the clay minerals present.

$$Activity = \frac{I_P}{\%weight < 2\mu m} \tag{4.5}$$

The activity of different minerals may be seen in table 4.3, which is collected from Janbu (1989). Clays containing minerals that have a high activity will have a high ability to bind water, and consequently a high plasticity index (Mitchell and Soga, 2005). Figure 4.4 illustrates how to define soils in accordance to activity. Table 4.4 shows the classifi-

Table 4.3: Activity of Minerals (Janbu, 1989)

Mineral	Activity
Quartz	0
Calcite	0.18
Mica	0.23
Kaolinite	0.33-0.40
Illite	0.9
Montmorillonite, Ca	1.50
Montmorillonite, Na	7.20

cation of clay by activity, as suggested by Skempton (Janbu, 1989). The values in parentheses is the value used by Bjerrum to separate between active and medium active clay (Janbu, 1989). These values are illustrated as lines separating different activities in figure 4.4.

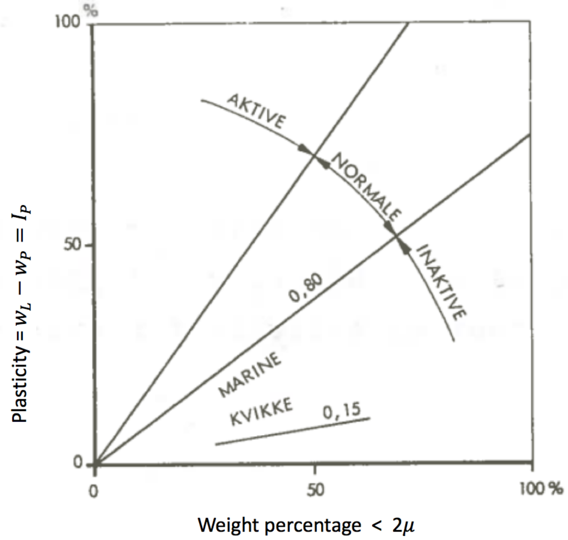

Figure 4.4: Classification of activity (Janbu, 1989)

Table 4.4: Classification of activity (Janbu, 1989)

Classification of Activity	A
Active	> 1.25 (1.4)
Medium activity	0.75 - 1.25 (1.4)
Low activity	< 0.75

The salt content may also have an effect on the activity of a soil. A high content of salt leads to stronger bonds between the clay particles, and a structure which may be described as being more crystalline (Mitchell and Soga, 2005). This relationship is illustrated in figure 4.5.

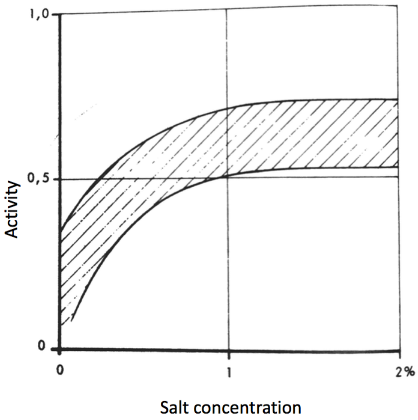

Figure 4.5: Relationship between salt concentration and activity (Janbu, 1989)

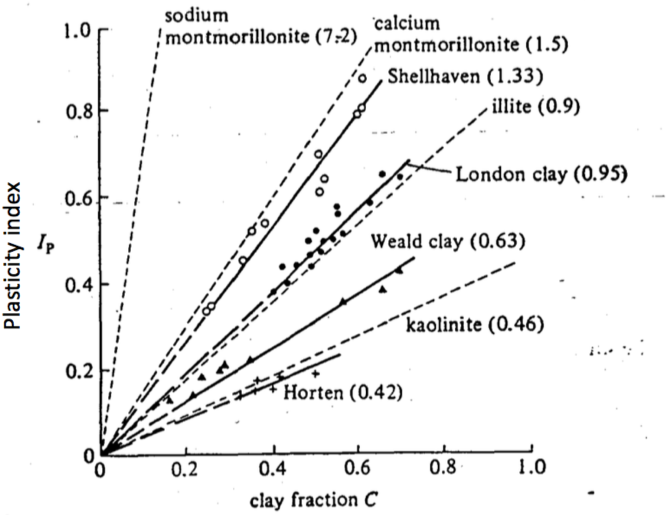

Figure 4.6: Relationship between plastic index and clay fraction for natural clays and clay minerals, with activity A indicated (Wood, 1990)

As mentioned in section 4.2.1, Norwegian clays usually have low plasticities, and this is reflected by low activities. Figure 4.6 from Wood (1990), illustrates the activity of a Norwegian clay from Horten compared to clays from other locations, as well as the activity of some clay minerals. In the figure, the clay from Horten plots very close to kaolinite in terms of activity. Comparing the position of the clay to the chart in figure 4.4 makes it evident that the soil may be defined as being inactive.

4.4 Sensitivity

The sensitivity of clay expresses the clays ability to resist shear stresses. It can be expressed as the ratio of undisturbed strength over remolded strength (expression 4.6) (Janbu, 1989).

$$S_t = \frac{s_u}{s_r} \tag{4.6}$$

where
s_u: undisturbed shear strength
s_r: remolded shear strength

Highly sensitive clays tend to be unstable, with a high risk of failure. In such soils, overloading may cause rapid loss of strength, which leads to failure occurring quickly and without warning (Emdal et al., 2017). Often there is no opportunity to improve the stability before failure occurs. In clays of low sensitivity, failure tends to occur slowly, which means that preventative work may be performed to avoid complete failure (Janbu, 1989). Table 4.5 shows how to classify clays in accordance to sensitivity.

Table 4.5: Classification of sensitivity (Janbu, 1989)

Classification of Sensitivity	S_t [%]
Low sensitivity	< 8
Medium sensitivity	8 - 30
High sensitivity	> 30

The sensitivity of clay is dependent on the concentration of salt in the soil. This is illustrated by figure 4.7. From this figure, it is evident that a high concentration of salt leads to a lower sensitivity. This is due to the fact that a higher salt content leads to stronger attraction between the clay particles, and a more stable material, which in turn gives a material of lower sensitivity(Mitchell and Soga, 2005).

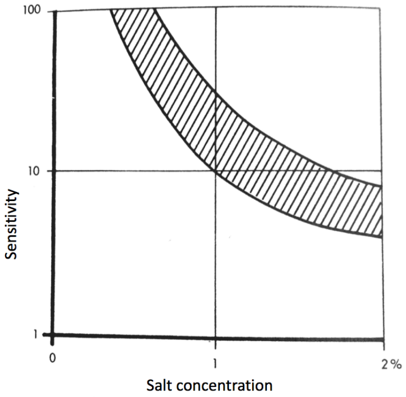

Figure 4.7: Relationship between sensitivity and salt concentration (Janbu, 1989)

A proven correlation between the sensitivity and the liquidity index exists. Related soils generally have an increase in sensitivity with increasing liquidity index (Carter and Bentley, 1990). This is illustrated in figure 4.8. From the figure, it is evident that clays with a water content within the plastic area ($I_L < 1$) have a lower sensitivity than clay in the liquid area.

$$S_t = \exp(kI_L) \tag{4.7}$$

where

k: material factor

k = 0 indicates an insensitive soil.

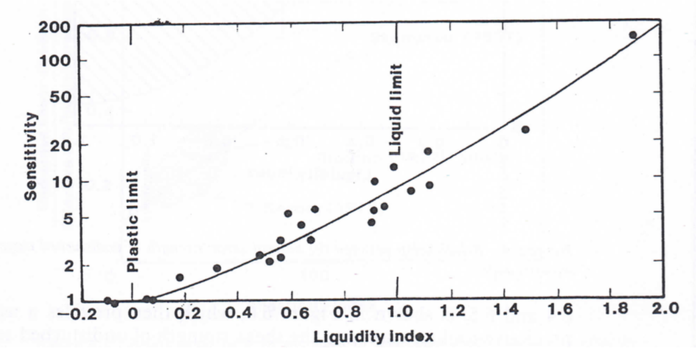

Figure 4.8: Relationship between liquidity index and sensitivity (Carter and Bentley, 1990)

The relationship described by expression 4.7 may be seen for different soils in figure 4.9, which illustrates an example for marine clays from Norway.

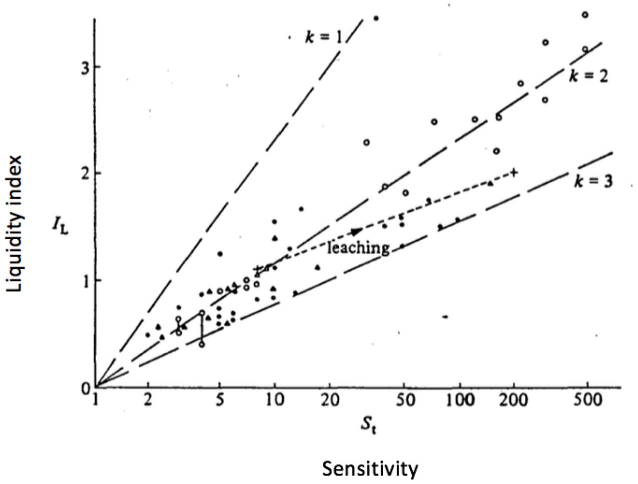

Figure 4.9: Relationship between sensitivity and liquidity index for marine clays from Norway (Wood, 1990)

4.4.1 Quick Clay

Quick clay is an example of a clay of very high sensitivity. The definition of a quick clay is a clay with remolded shear strength, $s_r < 0.5$ kPa. The exact value of s_r may be hard to determine, but the sensitivity may exceed 50(Emdal, 2014).

Quick clays have been formed by marine clays in which most of the salt has been leached over time, and as a result the attraction between the clay minerals have weakened considerably (Emdal et al., 2017). The salt concentration in quick clay is less than 0.5%, and as seen in figure 4.7, this indicates high sensitivity. A characteristic trait of quick clay is that it has a natural water content which is higher than the liquid limit (expression 4.8).

$$w > w_L, I_L > 1 \tag{4.8}$$

Due to the rise of land masses after the last glacial period, clays that have been deposited in a marine environment now exist in non-marine environments where the salt has been leached from the material. Because of this fact, quick clays are especially abundant in Scandinavia (Emdal, 2014). Hence, awareness of the issue is important. Due to its special nature, quick clays may correlate with mechanical parameters differently than non-quick clays.

Chapter 5

Correlations to Stiffness and Strength Parameters from Literature

In this chapter, correlations between index properties and mechanical parameters of soil is going to be examined, with a basis in correlations found in literature. Such correlations are beneficial, as they provide useful insight to the expected behavior of a soil. The correlations which will be explored in this thesis will predominantly focus on clay. Strength and stiffness parameters are highly connected, and thus, both will be explored in this chapter.

The crystallinity of clay minerals influences several of the relationships which will be examined. In section 4.2.1, it was described how the plastic behavior of clay can be largely credited to the structure of the minerals. As will be seen in this chapter, the plasticity of clay has an impact on several stiffness and strength parameters, and thus, so does the crystallinity. A soil with a large amount of clay minerals will have a higher degree of crystallinity and hence be more plastic (Schulze, 2002).

Some of the correlations explored is valid only for soils at critical state. This is a soil state in which the soil has lost its original structure as a result of large shear-induced volume change (Mitchell and Soga, 2005). In such cases, further shear strains may be applied without changes in the soils effective stress or volume (Nordal, 2017). Soils at critical state indicates that the material is remolded. Due to this, different factors than the structure tend to be of greater importance for such soils (Carter and Bentley, 1990). In other words, the correlations which are presented in this chapter is valid for soils at certain states, and awareness of the soil state in regard to the correlations is critical.

5.1 Stiffness

The stiffness of a soil describes its resistance towards deformation, and may be expressed by a stiffness modulus. Different soil conditions and different tests calls for a variation of stiffness moduli. Commonly, the stiffness of soils may be found through oedometer or triaxial testing. Stiffness moduli has several denotations, based on the conditions for its validity. It is crucial to be aware of this validity in terms of reviewing correlating properties.

Some common stiffness moduli for soil include M or E_{oed} which are stiffnesses found through oedometer testing. E_u describes the stiffness of an undrained soil, while E_{10} and E_{50} describes soil stiffness at 10 and 50 percent of the peak strength, respectively. The latter two is found mainly through triaxial testing. The stiffness of soil varies with whether the soil is being loaded or unloaded. In addition, it is necessary to note whether it is a drained or an undrained test which provides the stiffness, as these two stiffnesses are fundamentally different. Drained stiffness is typically lower than undrained, mainly due to the fact that drained stiffness depends on change in volume, while undrained stiffness can be related to changes in shape and structure (Nordal, 2017).

In this section, the effect of different index parameters on the stiffness of clay will be explored. This gives an indication of how certain parameters may suggest the behavior of clay in terms of stiffness and deformation.

5.1.1 The Modulus Number

In oedometer testing, the stiffness M describes the slope of the stress-strain curve. When plotting M against σ', a modulus number (m) is used to describe the slope of the curve, hence relating the stiffness to the stress level, see expression 5.1.

$$M = m \cdot f(\sigma') \tag{5.1}$$

It is assumed that the stiffness of OC-clay is approximately 5 times as much as that of NC-clay ($m_{OC} = 5 \cdot m_{NC}$ (Nordal, 2017).

5.1.2 Dependency on Natural Water Content

It is assumed that the amount of water present will affect the stiffness of the soil in some manner. Soils with a high water content that approaches the liquid limit resembles a liquid and easier to mold, and hence less stiff. Soils approaching a liquid state will be a great deal weaker than drier soils.

A correlation exist between the modulus number m and the natural water content w (sometimes denoted w_n) (Janbu, 1989). This statement is based on statistical correlations, an example of which can be seen in figure 5.1. The figure indicates that soils with a high water content has a low modulus number, and consequently the material has a lower stiffness. The lowest line in figure 5.1 is an indicator of the fact that Norwegian clays with a water content between 30 – 40% may have a lower modulus number than the average m. This is especially true for high sensitive clays (Janbu, 1989).

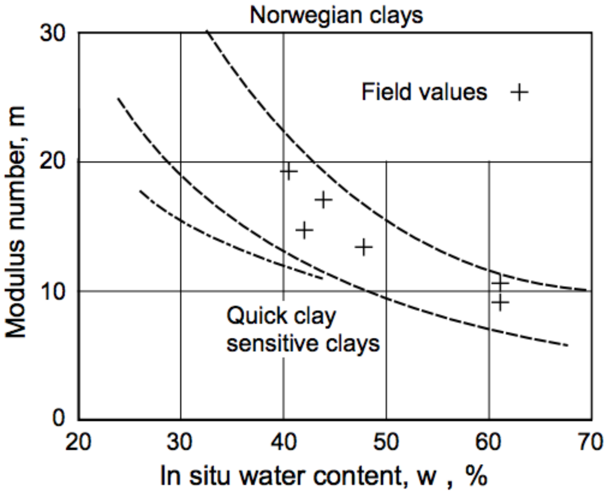

Figure 5.1: Empirical relationship between modulus number m, and natural water content w (Janbu, 1989) as modified in (Emdal et al., 2017)

Drained stiffness is often found through oedometer testing. The drained stiffness found from such tests can be expressed as in 5.2, proposed by Janbu. For NC-clays, m=1 is often used, which gives expression 5.3. p_{ref} = 100 kPa, and E_{oed}^{ref} is defined as the tangential oedometer stiffness at p_{ref}.

$$E_{oed} = E_{oed}^{ref}\left(\frac{\sigma'_y}{p_{ref}}\right)^m \tag{5.2}$$

$$E_{oed} = E_{oed}^{ref}\left(\frac{\sigma'_y}{p_{ref}}\right) \tag{5.3}$$

Expression 5.3 is a version of the oedometer stiffness, and the stiffness found is related to the modulus number m, in that they both express stiffness of clays of similar character. As such, E_{oed}^{ref} is also related to the natural water content of the soil, and this relationship may be seen in figure 5.2. The line drawn represents values of E_{oed}^{ref}, while the area marked shows where typical stiffness values of NC-clays tend to plot.

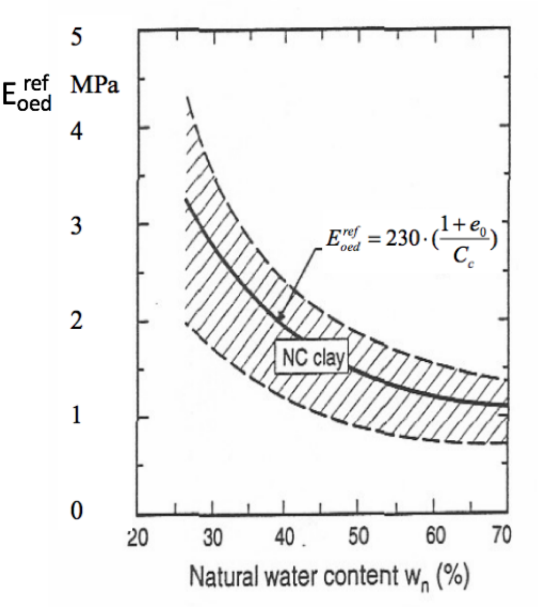

Figure 5.2: Relationship between natural water content and drained stiffness modulus (Nordal, 2017)

The relationships illustrated in this section suggests a strong correlation between the water content and the stiffness of clays.

5.1.3 Dependency on Plasticity

For short term loading, the soil is assumed to be in undrained condition (Carter and Bentley, 1990). It is thereby assumed that the volume does not change, as the pore water is thought to be incompressible. This insinuates that the deformations which arises are shear related. In these cases, one normally uses the stress-strain curves from undrained triaxial tests to find an average shear modulus, denoted G_u^{50}. This value is the slope of the tangential line through the 50% failure point, or half way to the critical undrained shear strength (Nordal, 2017). A simple relationship may be derived between G_u^{50} and the stiffness modulus at 50% of the failure strength (E_u^{50}), as seen in expression 5.4 (valid if E_u^{50} is defined in terms of total stresses $\Delta\sigma_y$, as $E_u^{50} = \frac{\Delta\sigma_y}{\Delta\epsilon_y}$ (Nordal, 2017)).

$$E_u^{50} = 3 \cdot G_u^{50} \tag{5.4}$$

A general relationship provided by Termat, Vermeer and Verger, as seen in Nordal (2017) relates the stiffness to the undrained shear strength and the plasticity index. This relationship is seen in expression 5.5, which is valid for NC-clays. Expression 5.5 indicates a correlation between the undrained stiffness and the plasticity of clays, which would make sense, as undrained deformation assumes change in shape and structure of the soil, and the plasticity of a soil is a direct result of the structure of the soil.

$$E_u^{50} = \frac{15000 \cdot s_u}{I_p} \tag{5.5}$$

Experiments performed by Duncan and Buchignani (1976) supported the relationship seen in expression 5.5 for NC-clays, while stiffer overconsolidated soils proved to have a lower factor in front of s$_u$ in the expression. Figure 5.3 illustrates how the stiffness of soils relate to the degree of overconsolidation and plasticity. As observed, the effect of the plasticity is more important for normally consolidated soils.

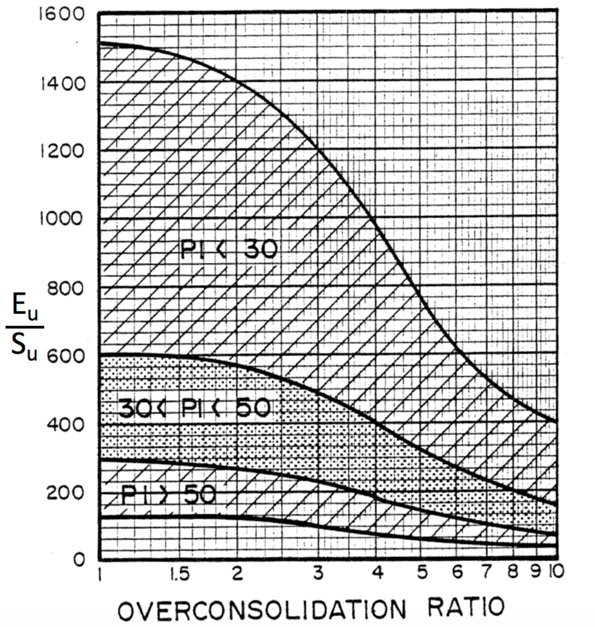

Figure 5.3: Relationship between E$_u$ normalized for S$_u$ and OCR in accordance with I$_P$ (Duncan and Buchignani, 1976)

5.1.4 Compressibility

The compressibility of a soil is the relationship between the effective stress applied to the soil and the volume change which is induced by the stress. It may be described as being the inverse of stiffness, as soils with a high stiffness generally have low compressibilites while soils with low values for the stiffness are generally highly compressible. This may also be seen directly from expression 5.6, in which the compressibility λ is defined as the inverse of the modulus number m(eq. 5.7) (Nordal, 2017).

$$\epsilon = \frac{1}{m} \ln\left(\frac{\sigma'}{\sigma'_c}\right) \tag{5.6}$$

$$\lambda = \frac{1}{m} \tag{5.7}$$

A compressibility index Cc can be found from λ as in expression 5.8.

$$Cc = \lambda \cdot \ln 10 \tag{5.8}$$

The compressibility of a soil is an important parameter in terms of determining the expected consolidation and settlements of the soil. As such, it is interesting to see how it relates to other properties of the soil.

In figure 5.4, which shows the sedimentation curves for several normally compressed sediments plotted as the vertical effective stress against the specific volume and water content of the sediments, the slope of each group of data gives the compressibility of that soil. The specific volume is found as in equation 2.6, and as discussed in section 2.3.3, the void ratio and water content expresses the same thing for fully saturated soils. As such, there is an evident relationship between the compressibility of a soil and its water content and void ratio. Changes in the void ratio can be found by the compressibility index C_c, which can be found for different soils through oedometer testing (Carter and Bentley, 1990).

A theoretical estimation of C_c, is expressed in 5.9. Here, the compression is expressed as a function of the liquid limit. Intuitively, it makes sense that a soil with a higher wa-

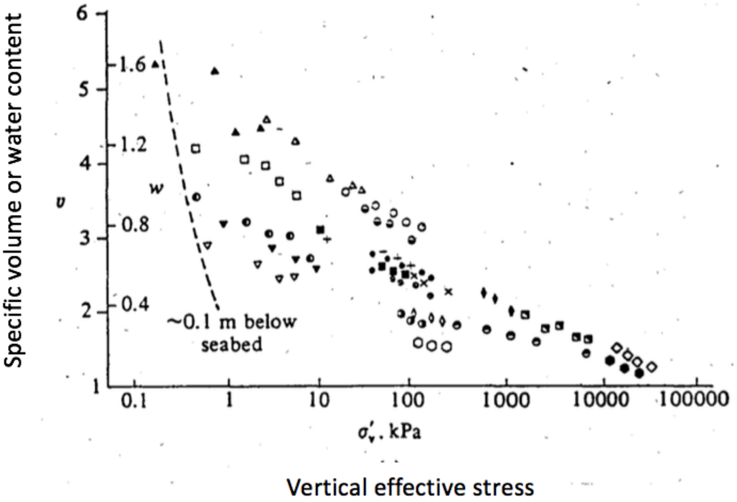

Figure 5.4: Data of specific volume v/water content w and vertical effective stress σ'_v (Wood, 1990)

ter content has a higher compressibility, as it indicates a larger void ratio. This also fits well with the information from section 5.1.2, in which it was established that soils with a high water content are less stiff than those with a low water content.

$$C_c = 0.9(w_L - 0.1) \tag{5.9}$$

Vermeer (2002) recommends an updated expression for C$_c$, as seen in expression 5.10. It is apparent that the compressibility is dependent on the liquid limit of the soil.

$$C_c \approx w_L - 0.1 \tag{5.10}$$

A correlation between the compressibility of a soil and its plasticity index also exist, as presented in eq. 5.11 and 5.12 (Wood, 1990).

$$\lambda = \frac{I_P G_S}{ln 10} \simeq 0.6 I_P \tag{5.11}$$

$$\lambda = 0.586 I_P \tag{5.12}$$

Combining expressions 5.12 with 5.8, an expression for the compressibility index in terms of the plasticity is found by eq. 5.13

$$C_c \approx 1.35 I_P \tag{5.13}$$

The relationship to plasticity seen in expressions 5.12 and 5.13 is illustrated in figure 5.5. It is evident that the values for the soils plotted in the chart typically falls around the relationship specified in the expressions.

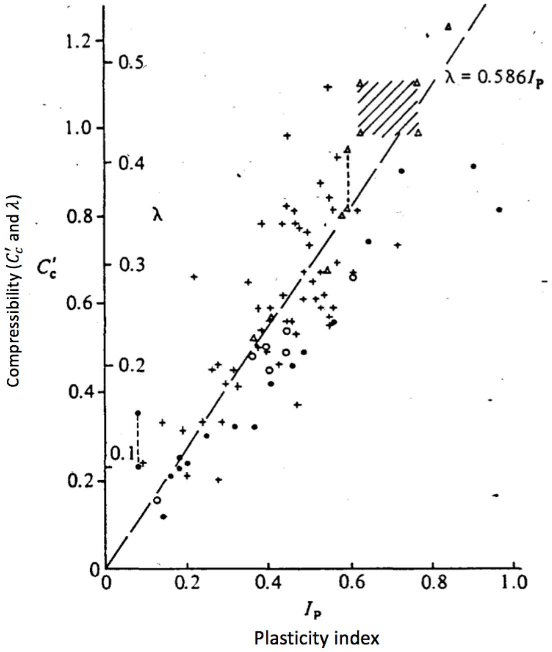

Figure 5.5: Empirical relationship between compressibility (Cc') and plasticity index (I_P) for soils: Mississippi delta and gulf of Mexico (+)(data from McClelland, 1967); Egyptian soils (○) (data from Youssef, el Ramli, and el Demery, 1965); scabed soils off Tel Aviv (△) (data from Almagor, 1967); soils from Britain and elsewhere (•) (Wood, 1990)

A modified compression index is introduced as λ^*, defined as in eq. 5.14. The modified index may be used to express the compression law, as seen in Vermeer (2002) (eq. 5.15).

$$\lambda^* = \frac{\lambda}{1+e} \tag{5.14}$$

$$\Delta\epsilon = \lambda^* \Delta \ln \sigma' \tag{5.15}$$

λ^* is found in terms of C$_c$ by expression 5.16, which uses the assumption of e ≈ 1 for soft soil (Vermeer, 2002).

$$\lambda^* = \frac{C_c}{(1+e)\ln 10} \approx \frac{C_c}{4.6} \tag{5.16}$$

λ^* can be found in terms of I$_P$ and w$_L$ by combining expression 5.16 with expressions 5.13 and 5.10, respectively. The relationships may be seen in eq. 5.17 and 5.18.

$$\lambda^* \approx 0.3 I_P \tag{5.17}$$

$$\lambda^* \approx 0.2(w_L - 0.1) \tag{5.18}$$

The relationships expressed in this section are all similar, and all indicate a strong correlation between the compressibility of a soil and the water content, plasticity and liquid limit of the soil.

5.2 Shear Strength

The shear strength describes the amount of shear stress a soil can take before failure. Primarily, the undrained shear strength (s$_u$) and the remolded shear strength (s$_r$) are of interest. As the undrained shear strength implies the strength of a soil which is structurally intact, while the remolded shear strength describes the strength of a clay in which the structure has to a large extent been broken, the two describe different soil states. Their dependencies on index parameters may therefore vary.

5.2.1 Undrained Shear Strength

Koumoto and Houlsby (2001) defined a relationship between the water content of a soil and its undrained shear strength (eq. 5.19). In the expression, *a* and *b* are parameters dependent on the soil. a is the water content in percent at s$_u$ = 1 kPa, while b is the slope of the linear function which gives the ratio between the natural logarithm of w and the natural logarithm of S$_u$ (a and b must be found experimentally).

$$w = a \cdot s_u^{-b} \tag{5.19}$$

As such, a relationship exists between the undrained shear strength and the water content of a soil. Figure 5.6 illustrates how the undrained shear strength changes with the water content of a soil.

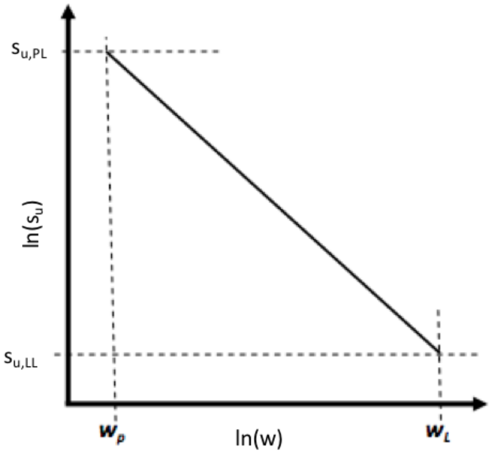

Figure 5.6: Relationship between undrained shear strength and water content, modified from Vardanega and Haigh (2014)

The shear strength is also dependent on the liquid limit of the soil, as seen in figure 5.7. This illustrates the importance of the relative water content, as the liquid limit of a soil is defined as the liquid limit at s_u = 2 kPa (see section 4.1.1).

Since the water in a soil is strongly attached to the clay minerals present, it is valid to assume that almost all of the water in the soil can be associated with the clay phase (Mitchell and Soga, 2005). As such, a correlation between the clay content of a soil and the undrained shear strength may also be found (Trauner et al., 2005). As seen in figure 5.6, a high water content indicates that the soil is weak. The fact that the shear strength is influenced by the liquid limit also indicates some mineral dependency, as the liquid limit varies for various minerals (see table 4.1), which means that there must be some

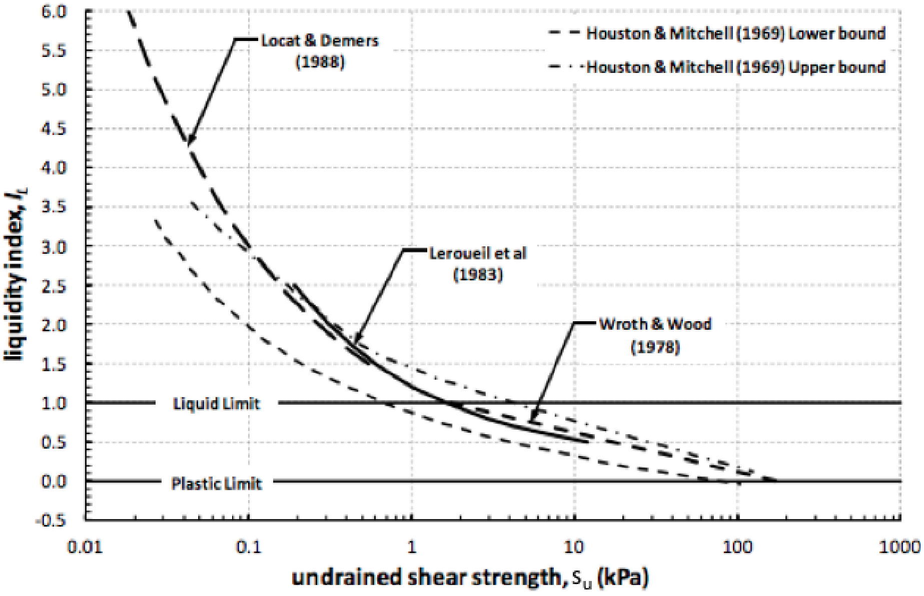

Figure 5.7: Relationship between undrained shear strength and liquid limit, modified from Vardanega and Haigh (2014)

correlation between the minerals present and the undrained shear strength. Note that it should be clarified that as most natural soils are highly complex materials with several minerals present in its composition, and thus, one can not tell which minerals are present simply by looking at results such as in figure 5.7. However, the relationships presented here indicates some correlation, which has also been discussed by Trauner et al. (2005).

5.2.2 Remolded Shear Strength

A relationship exists between the liquidity index and the remolded shear strength of soils as well. Experimental data forms the base of this correlation (expression 5.20), defined by Wood (1990). The relationship is illustrated graphically in figure 5.8.

$$s_r = 2 \cdot 100^{(1-I_L)} \tag{5.20}$$

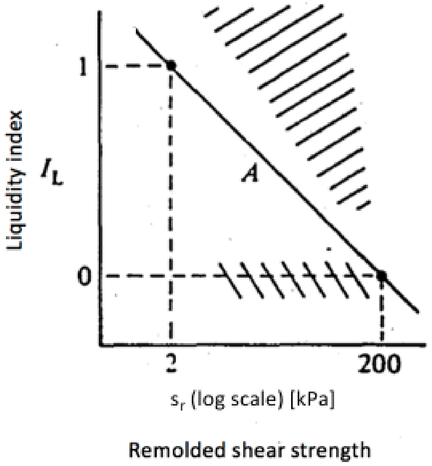

Figure 5.8: Relationship between liquidity index and remolded shear strength (Wood, 1990)

As illustrated in the figure, the correlation is strongest in the plastic area (s_r between 2 – 200 kPa). In figure 5.9, this relationship is plotted for actual soils. It is obvious that the relationship is similar for undrained and remolded shear strengths (see fig. 5.7).

The impact of clay minerals on the remolded shear strength may be seen in figure 5.10. K indicates kaolinite, while M indicates montmorillonite. The amount of the mineral present in the soil is marked in the parenthesis. The remaining soil consist of natural quartz, which has no plasticity. Data in figure 5.10 indicates that the remolded shear strength is higher for the soils containing minerals with a high plasticity (see table 4.1) (Wood, 1990).

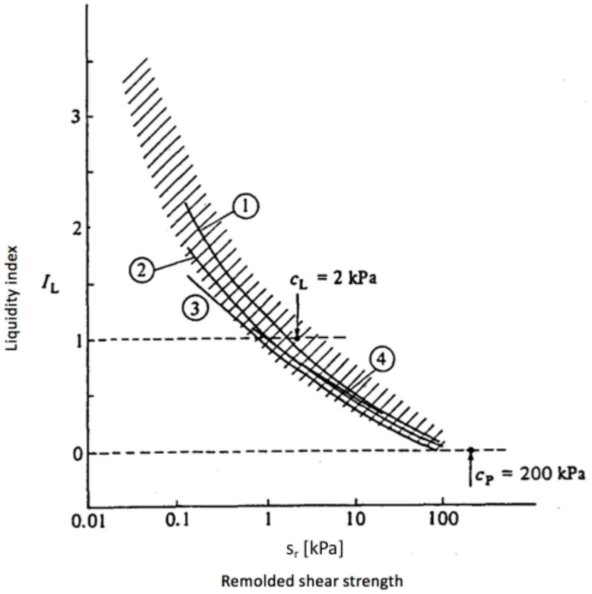

Figure 5.9: Variation of remolded undrained strength c$_u$ with liquidity inex I$_L$ for different clays (1: Horten clay (w$_L$ = 0.30, w$_P$ = 0.16); 2: London clay (w$_L$ = 0.73, w$_P$ = 0.25); 3: Shellhaven clay (w$_L$ = 0.97, w$_P$ = 0.32); 4: Gosport clay (w$_L$ = 0.80, w$_P$ = 0.30) (After Skempton and Northey, 1953) (Wood, 1990)

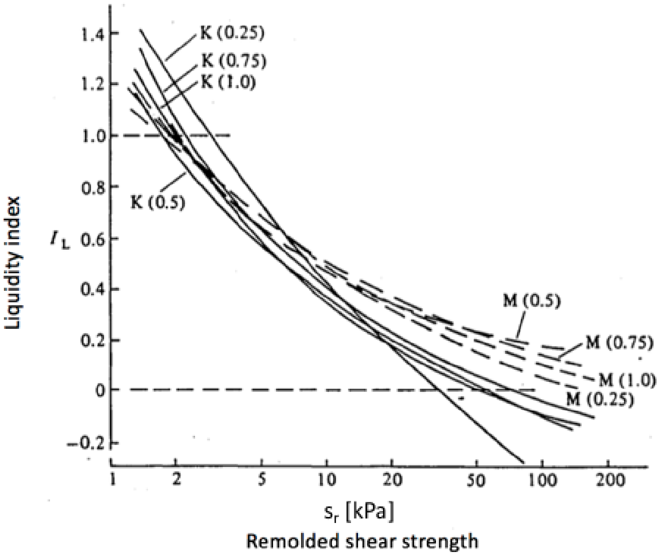

Figure 5.10: Variation of remolded shear strength c$_u$ with liquidity index I$_L$ for mixtures of kaolinite and montmorillonite with natural quartz sand (mineral content is marked for each curve) (Wood, 1990)

Different soil conditions leads to varying dependencies on the liquidity for the shear strength. This is illustrated in figure 5.11, which illustrates how different soils plots differently. Such charts may be used to indicate the consolidation history of a soil deposit (Wood, 1990). Line X represents expression 5.20, which is valid for remolded and disturbed soils which has lost its natural structure. The expected plotting area of different types of clay in regards to consolidation history (Wood, 1990) is indicated by letters A through D.

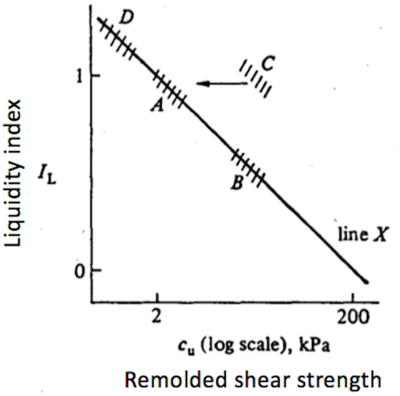

Figure 5.11: Soils of different consolidation state plotted in the I_L vs. c_u and I_L vs. σ'_v plots (Wood, 1990)

A illustrates normally consolidated insensitive soils, with strengths dependent on the liquidity of the soil. These soils are expected to plot around line X.

B indicates overconsolidated soils, in which strength is a function of the water content, or liquidity index. The liquidity is lower than for a normally compressed soil. Referring to section 2.4, the structure of a soil will be affected by its stress history, and the I_L of the soil tends to be lower than for a normally consolidated soil. Hence, the soil should be expected to plot on the X-line.

Naturally sensitive soils, which are denoted as C in the figure, have a peak strength which is higher than their remolded strength. Such soils, tend to have a structure which is more open than what the stress level implies, and there is more water present in the soil than normal. Thus, they tend to plot to the right of the X-line.

Underconsolidated soils are denoted D. These types of soils are normally compressed, but with a lower vertical effective stress than expected. This is due to an unknown, non-hydrostatic, pore pressure. It is important to be aware of a soil being underconsolidated, as large settlements may be induced as the pore pressures fall to hydrostatic levels. If the pore pressure is known, then the soil should plot on the X-line, but for unknown pore pressure, D tends to plot differently (Wood, 1990).

5.3 Friction Angle

The friction angle of soils, which is an important shear strength parameter, has a proven correlation with plasticity. The relationship between the friction angle and the plasticity may be explained by a conceptual comparison to the friction angle of sand. Figure 5.12, collected from Mitchell and Soga (2005), shows the variation of the friction angle with porosity for granular soils. The friction angle in sand can be found by expression 5.21 (Nordal, 2017). In the expression, ϕ is the friction angle, ϕ_i is the inner friction angle, and ψ is the dilatancy angle.

$$\phi = \phi_i + \psi \tag{5.21}$$

The inner friction angle is a constant material property, depending on the material, while the dilatancy angle may be seen as the resistance to shear strains. By definition, the dilatancy will be equal to zero at critical state. Thus, at critical state, the inner friction angle is equal to the total friction angle, and may be denoted as ϕ'_{cs}, or ϕ'_{crit}. The inner/critical state friction angle occurs at the critical void ratio, and depends on the material in question. Thus, one may use the friction angle to identify the soil composition. The value of ϕ'_{crit} for clays tends to be low, as there is not much friction between clay particles (Mitchell and Soga, 2005). Table 5.1 illustrates the critical state friction angles for some minerals compared to that of sand (quartz). Comparing the friction angles in table 5.1 to the specific surface seen in table 3.2 proves that the friction angle between clay particles will be less for minerals with a large specific surface area than those of a smaller specific surface area.

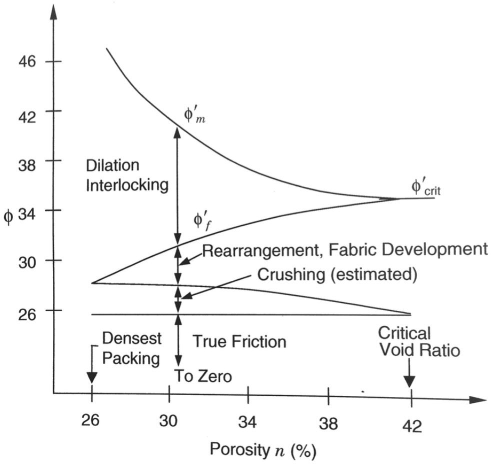

Figure 5.12: Relationship between friction angle and porosity for granular material (Mitchell and Soga, 2005)

Table 5.1: Friction angle of minerals, adapted from Mitchell and Soga (2005)

Mineral	ϕ'_{crit} [degrees] [%]
Quartz	35
Kaolinite	12
Illite	10.2
Montmorillonite	4-10

The critical state friction angle is related to the critical state slope value, M (as used in the cam-clay soil model (Nordal, 2017)) by expression 5.22, which is valid for the compression of soils. It describes the relationship between the mean effective stress applied to a soil and the shear stress which it invokes. Thus, M is also an expression of the strength.

$$M = \frac{6\sin\phi'}{3 - \sin\phi'} \tag{5.22}$$

Figure 5.13 illustrates a plot of the critical state friction angle, expressed in the figure as as sinϕ', and the plasticity index, I$_P$, with data assembled by Mitchell (1967) (Wood, 1990). In the figure, a clear correlation between plasticity index and the critical state friction angle may be seen. ϕ'_{crit} decreases as the plasticity increases. The relationship can be described by equation 5.23 (Wood, 1990).

$$sin\phi' = 0.35 - 0.1 I_P \tag{5.23}$$

Figure 5.13 also illustrates how the friction angle varies in accordance with the type of clay mineral present, which makes sense as this is largely what dictates the plasticity. From figure 5.13 and table 5.1, it is apparent that clays with a large amount of highly active minerals (see table 4.3) will have a lower friction angle than soils of lower activity.

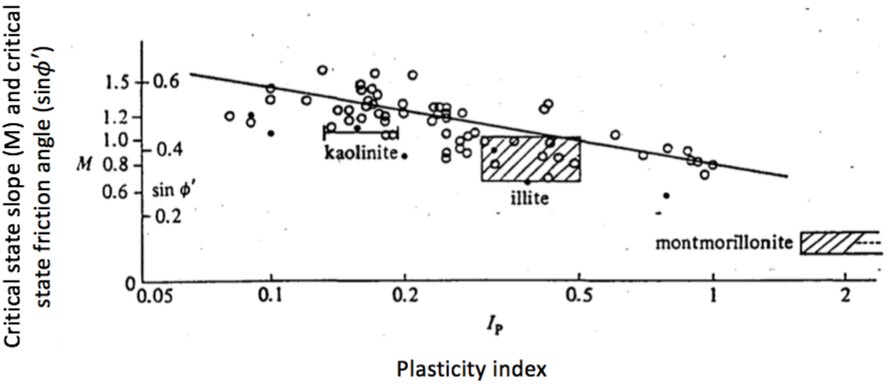

Figure 5.13: Relationship between plasticity index and critical state friction angle (Wood, 1990)

5.4 At Rest Earth Pressure Ratio

The coefficient of earth pressure at rest, K_0, defined as the ratio of horizontal to vertical effective stress (eq. 5.24), is an important parameter because it can give us information about a soils properties as well as the stress history of the soil.

$$K_0 = \frac{\sigma'_h}{\sigma'_v} \tag{5.24}$$

For one dimensional normally consolidated soils, an expression for K_0 that links it to the friction angle was presented by Jaky, as seen in expression 5.25. The expression provides a correlation between the plasticity index and K_0, obtained by Massarsch (1979)

(L'Heurex et al., 2017) as seen in figure 5.14 . This relationship has been obtained from laboratory tests, and is valid for NC-clay.

$$K_0 = 1 - \sin\phi' \tag{5.25}$$

A similar expression of K_0 as seen in eq. 5.25 may be seen in eq. 5.26. This relationship was developed by Brooker and Ireland (2017) based on laboratory tests on clays. The results that was obtained in laboratory testing led to the development of a plasticity chart, represented in figure 5.15, in which the value of K_0 was linked to the OCR and I_P of clay.

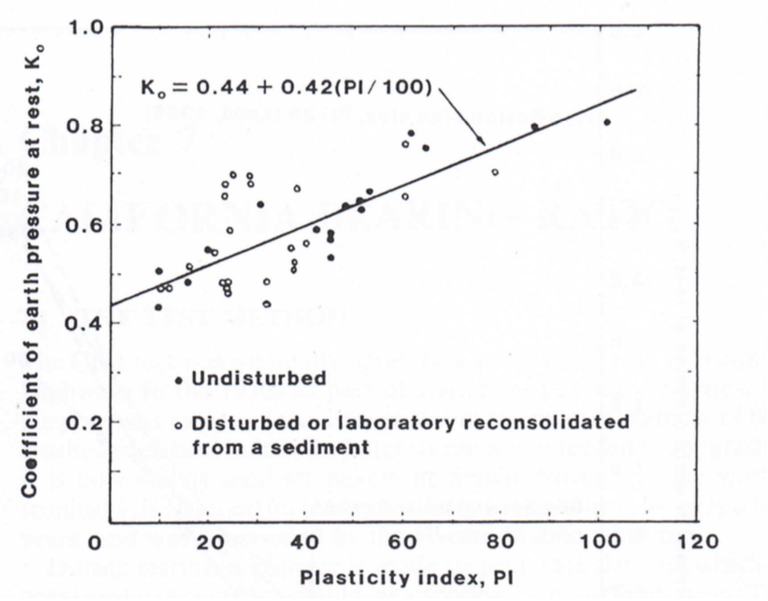

Figure 5.14: Relationship between K_0 and I_P (Carter and Bentley, 1990)

$$K_0 = 0.95 - \sin\phi' \tag{5.26}$$

However, analysis of data on Norwegian clays in comparison to expression 5.26 and figure 5.15 proved that K_0 calculated by expression 5.26 does not correlate well with Norwegian clays. From multivariable regression analyses (see L'Heurex et al. (2017) for the full procedure) it was found that the K_0 of low plasticity clays were underestimated by as much as 17%. For clays of high plasticity, K_0 was overestimated by the same amount for

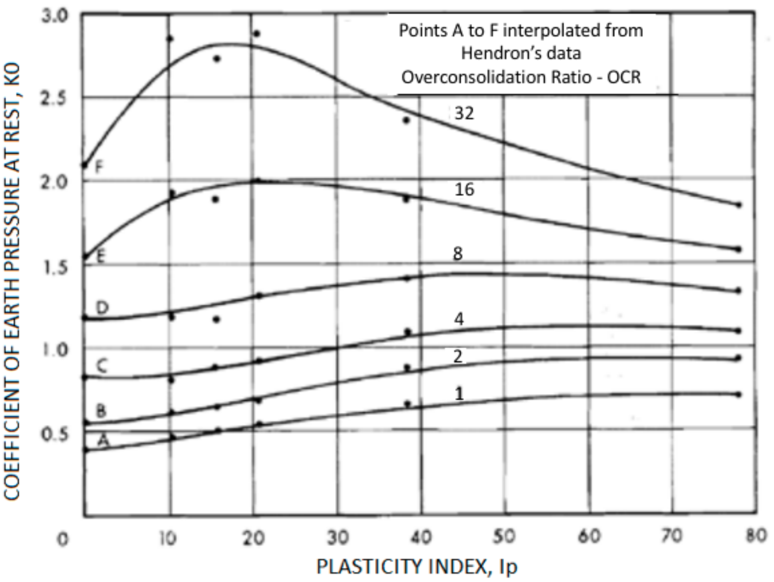

Figure 5.15: Relationship between K_0, I_P and OCR (modified from L'Heurex et al. (2017) as collected from Brooker and Ireland (2017))

low OCRs. By the use of experimental data and the regression analyses, L'Heurex et al. (2017) came up with expression 5.27, which fits well with Norwegian clays. As seen, this expression is not dependent on the plasticity, which makes sense as Norwegian clays tend to have low plasticities.

$$K_0 = 0.53 \cdot OCR^{0.47} \tag{5.27}$$

Note that the correlation between K_0 and I_P seen in figures 5.14 and 5.15 may still be valid, although as discussed in this section, not for Norwegian clays. This fact proves an important point in regards to correlations between basic parameters of soil and its mechanical properties; many of these correlations tend to be valid only for the circumstances for which it was developed, and should be treated with care when applied to different circumstances.

Chapter 6

Experimental Relationships Derived from GEODIP SP8 Database

In this chapter, correlations for Norwegian soils will be explored. In several cases, the correlations found will be compared to relationships which have been discussed in the previous chapters. The data which has been used to find these correlations has been collected from GEODIP's high quality database for clay materials (SP8). Access to this database was granted by the Norwegian Geotechnical Institute. The purpose of the analyzes in this chapter is to see how well properties of natural Norwegian clays compare to theoretical relationships. Mostly, the data will only be presented in plots. In cases where it is relevant, further data will be presented in tables.

It should be noted that any errors in the results or assumptions that have been made is entirely the responsibility of the candidate, and should not reflect badly on NGI.

6.1 Background on GEODIP's SP8

The data which has been used to find correlations in this chapter has been collected from GEODIP's SP8 (Soil Parameters in Geotechnical Design). The database has been compiled by NGI, and includes data from high quality block samples on clay. The database includes already existing data as well as supplementary data from research and development assignments. All data has been collected during the time period 1982-2010 (Paniagua et al., 2017).

For this thesis, the database was available as an Excel-file. In the database, data from CPTU-tests, high quality index tests, and results from oedometer tests, undrained triaxial tests and direct shear tests were available. In the analyzes performed in this chapter, data from oedometer and triaxial (CAUC) tests have been used. For the most part, Norwegian onshore clays have been used in the analyzes, and in several cases, data for quick clays have been removed.

Note that all the data in GEODIP's SP8 are categorized as being of high quality in accordance with the classification of soil samples included in the Norwegian Geotchnical Society NGF (2013). This quality criteria is based on the initial void ratio and the axial strain at the in-situ stress, and may be seen in table A.1. All of the data compiled in GEODIP's database is classified as being of quality class 1 or 2 (Paniagua et al., 2017).

Some definitions which will be used in this chapter is illustrated in figure A.1, which is a modified version of a figure collected from the database.

6.1.1 Testing Sites

The database contains results from both Norwegian and international sites. Both onshore and offshore soils have been tested. For the purpose of this thesis, Norwegian onshore clays have been the focus, although in some cases soils of other origins have been included.

Table A.2 includes a summary of all the sites which have been included in this thesis, along with the soil type and the sampling method used. Note that the database includes additional sites which has not been included in table A.2. In the figures illustrating correlations, the testing site which has been included has been stated.

6.1.2 Sampling Methods

The quality of a soil sample greatly affects the test results of the sample, as well as the validity of the results. Sample quality depends on a number of factors. A main factor in sample quality is the sampling method which has been used. Some methods may lead to disturbances in the structure of the soil sample or volumetric strains.

The results in this chapter is presented with regard to sampling size, meaning that soil samples of similar sampling methods have been compared. In cases such as activity (see sectiom 6.2.1), data from varyious sampling methods have been compared. This is because such correlations compare properties which have the unit of percentage, and thus the sample size should not matter to the same degree as for other properties.

Most of the data which will be examined in this chapter is collected from samples taken by a Sherbrooke block sampler(denoted "block" in table A.2), in which the sample size is 250 mm (Emdal et al., 2016). The Sherbrooke block sampler uses three circumferentially placed cutters, which is combined with water pressure to core out an annulus around the soil block which is sampled. Tests on such samples tend to be of high quality. The structure of the clay will keep it confined, which means that it stands by itself without the need of a testing tube or other confining materials. For samples containing silt or materials with coarser grains, this may cause some problems as it does not possess the same ability to stand on its own as clay (Emdal et al., 2016). Sample methods which provide 54 mm and 72 mm samples have also been included.

6.2 Correlations Between Index Parameters

6.2.1 Activity

Figure 6.1 shows the activity of Norwegian clays. Note that in this plot, varying sample sizes have been plotted together. The activities have been plotted along with typical values of activity for various minerals (see table 4.3). Quick clays have been marked by an “x”. From the figure, it is apparent that all the clays plotted have low activities. The clay sampled from Johan Castberg is the one with the highest activity, and this is also the only offshore-clay which has been plotted. Thus, it may possess different qualities than the remaining soils.

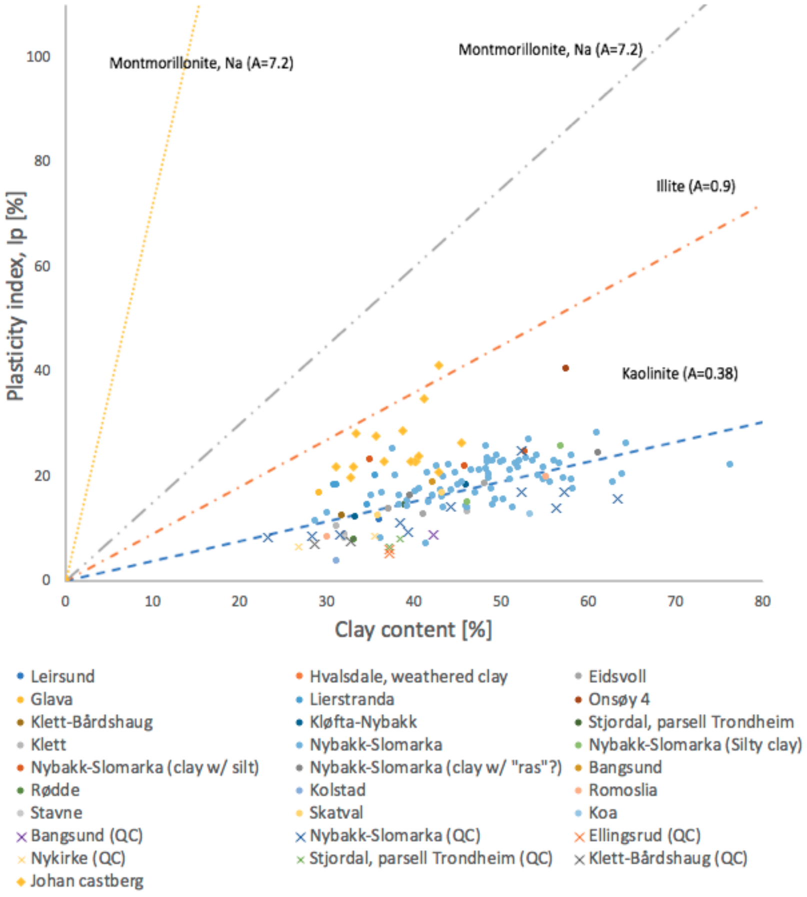

Figure 6.1: Activity of clays compared to the activity of known minerals

The same clays seen in figure 6.1 has been plotted in figure 6.2. Here, the activities have been plotted on a template of figure 4.4, which illustrates how soils may be defined in accordance with their activities. In this plot, an offshore-clay from Ghana has also been included, which makes for an interesting comparison. As seen in the plot, the clay from Ghana is the only one which is classified as being active. These figures confirms the already established fact that Norwegian clays are generally of low activity, which indicates a low plasticity of the clay phase.

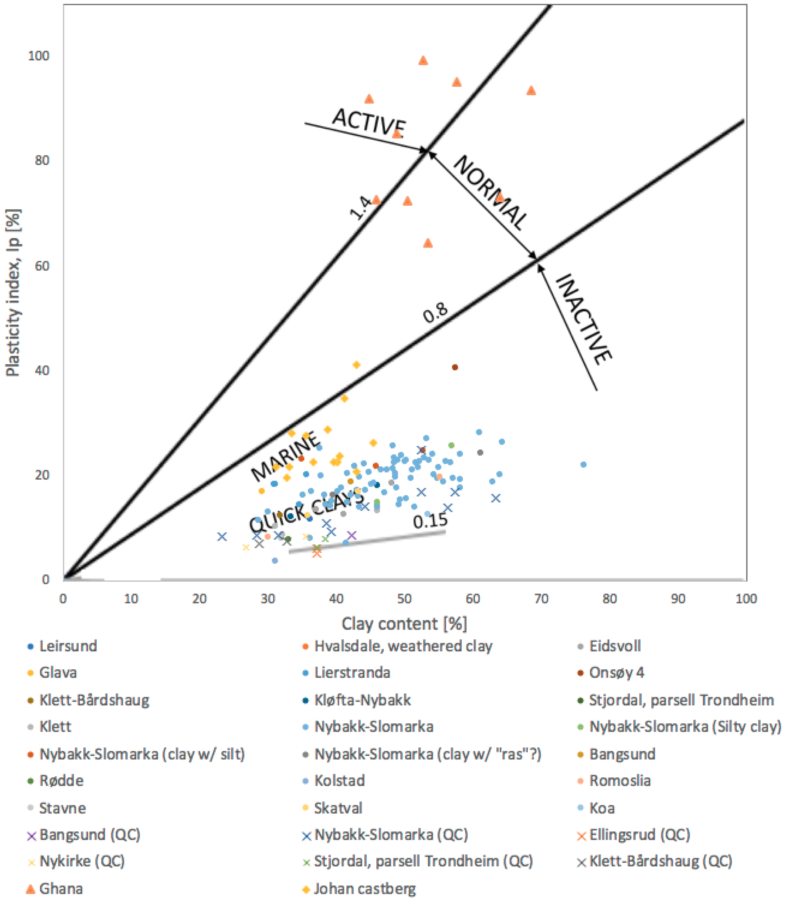

Figure 6.2: Activity of clays in relation to classification of activity, chart template redrawn from Janbu (1989)

6.2.2 Sensitivity

As established in section 4.4, a relationship exist between the liquidity index and the sensitivity of a clay. Such a relationship has been plotted in figure 6.3, with a line indicating the relationship. The relationship seen is on the form of expression 6.1, which is the same expression seen plotted in figure 4.8.

Note that a crucial limitation in this plot is that there is a limited amount of results plotted. This is due to limited data on S_t and I_L in the database. Only from Sherbrooke block samples have been analyzed. The plotted data does however fit very well with the relationship described by expression 4.7 (with k = 2.65), with the exception of the results from Kløfta-Nybakk.

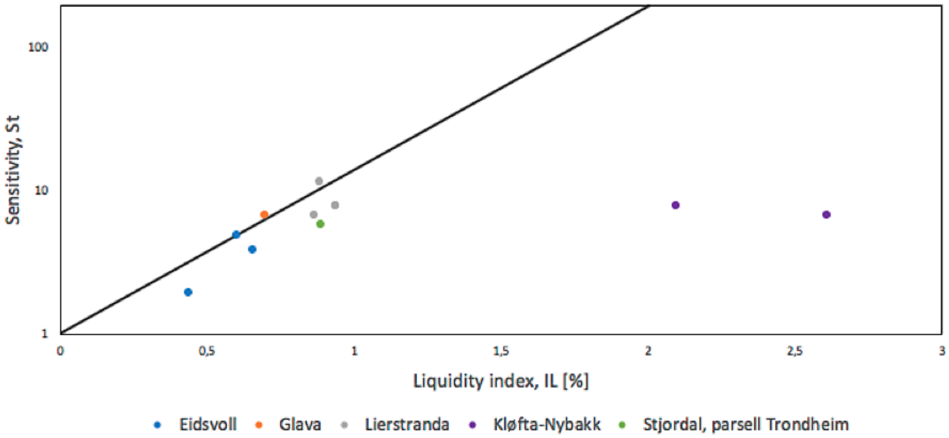

Figure 6.3: Relationship between sensitivity (S_t) and liquidity index (I_L) for clays, with a relationship drawn up, following expression 4.7

$$S_t = exp(2.65 \cdot I_L) \tag{6.1}$$

It is also interesting to explore whether there is a relationship between the sensitivity and the plasticity of a soil. This has been plotted in figure 6.4 a). There does not seem to be any correlation worth mentioning. The same may be said for sensitivity and clay content of a soil (figure 6.4 b), although the tendency of a correlating relationship is present to a larger extent than what is seen in figure 6.4 a). A clearer correlation may be found if more data was analyzed.

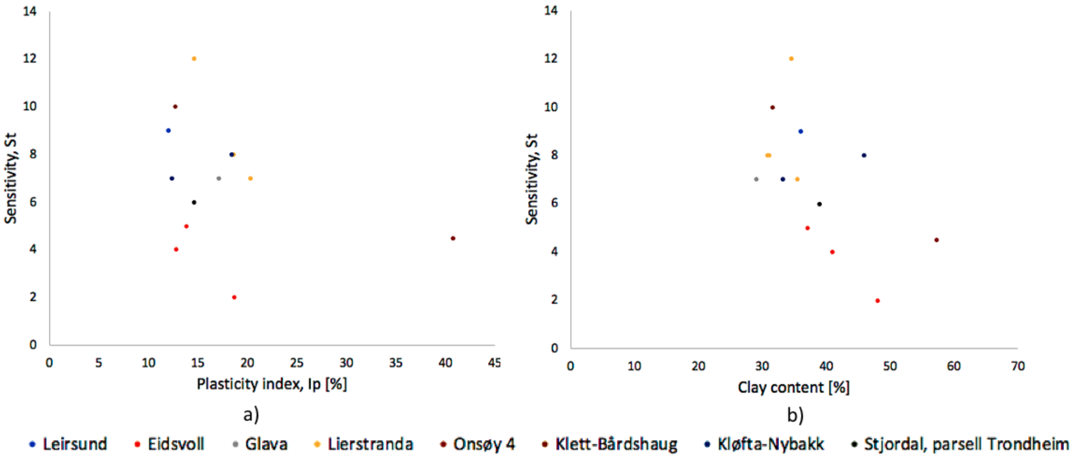

Figure 6.4: a) sensitivity plotted against plasticity index for Norwegian soils b) sensitivity plotted against clay content for Norwegian soils

6.2.3 Water Content

As discussed in section 3.7.1, the water content of a soil is thought to be associated solely with the clay-fraction of the soil. As such, it is interesting to see how the water content of a soil relates to the clay content. This relationship has been plotted in figure 6.5. The results suggests a clear correlation, which has been marked by dotted lines, within which typical values for Norwegian soils seem to plot (note that the amount of data plotted is limited, and the typical values may vary from what is illustrated in the figure). As seen in the figure, there is no clear distinction between quick and non-quick clays in terms of water content. The dotted lines have been found through trial and error, and the area may be expressed by 6.2 for the upper limit and 6.3 for the lower limit.

$$w = 22 + 0.5 \cdot clay - content[\%] \tag{6.2}$$

$$w = 8 + 0.5 \cdot clay - content[\%] \tag{6.3}$$

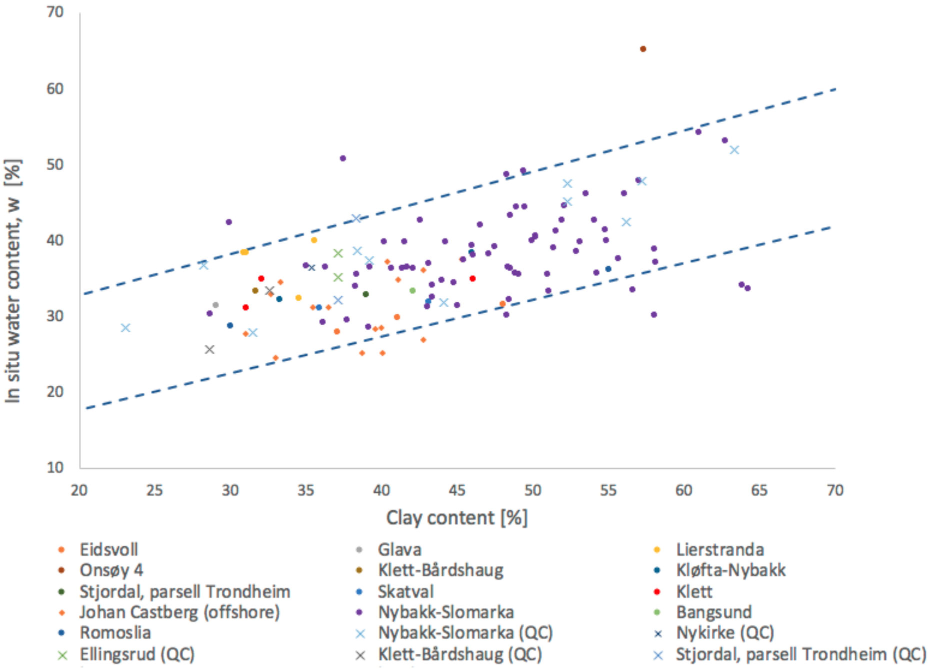

Figure 6.5: Relationship between clay content and natural water content

Since a correlation between the clay content of a soil and its water content is evident, it is also of interest to investigate whether a relationship exists between the liquidity index and the clay content. As previously discussed, the liquidity index may be viewed as the water content of a soil relative to its plasticity, and as such, it may be of interest to compare the relationship between I_L and the clay content to the relationship between the water content and the clay content. In figure 6.6, I_L seems to be scattered randomly. However, for the non-quick clays, there seem to be a correlation, as indicated by the dotted lines. The I_L-values of the quick clays (marked by an “x”) are significantly higher than for the non-quick clays. This makes sense, as quick clays are known for having a water content which is disproportionately high. Note that the dotted lines in figures 6.5 and 6.6 have been found by trial and error to make the best fit for these specific results, such as for figure 6.5. The upper and lower limit for these results may be expressed by 6.4 and 6.5, respectively. As mentioned several times, these relationships are specific for the data of the plotted soils and does not include quick clays. It does however suggest a linear relationship between both w and clay content, and I$_L$ and clay content.

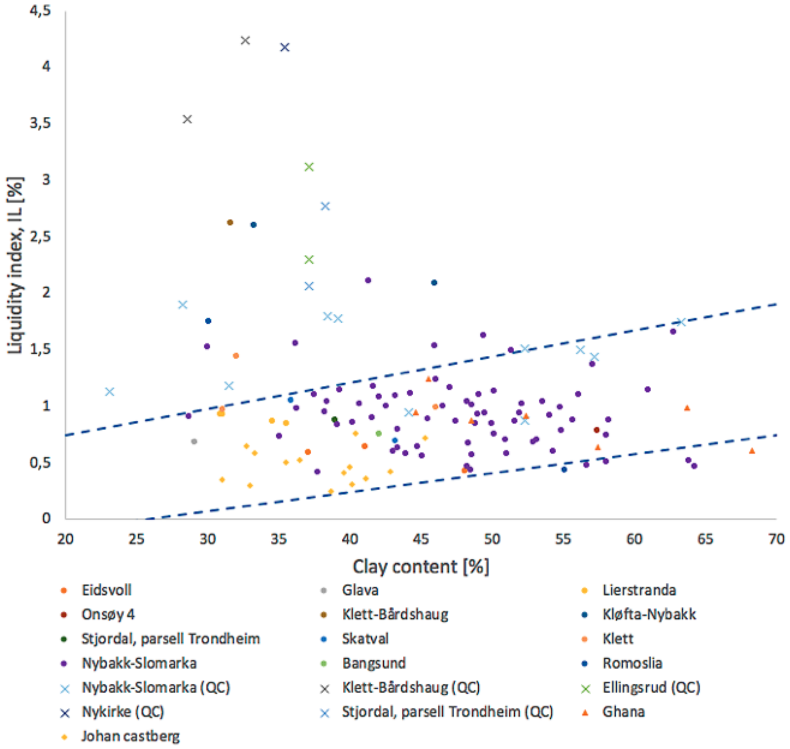

Figure 6.6: Relationship between clay content and liquidity index

$$I_L = 0.02 \cdot clay - content[\%] + 0.29 \tag{6.4}$$

$$I_L = 0.02 \cdot clay - content[\%] - 0.44 \tag{6.5}$$

6.3 Stiffness

6.3.1 Modulus Number and the Importance of its Definition

In section 5.1.2, the relationship between the stiffness of a soil and its water content was discussed. In this section, the importance of the definition of the modulus number will be discussed. Because the stress-stiffness curve varies in accordance with stress, one needs to be clear about which part of the curve is used to define m. Most commonly, the modulus number is defined as the slope of the linear curve in the normally consolidated area of the soil, and intersecting at some reference pressure point, σ'_r. The value of σ'_r may vary in accordance with the definition which is used. Sometimes $\sigma'_r = 0$ is used (denoted m_0), while in other situations, a pressure value ($\sigma'_r \neq 0$) is chosen. The difference in how the modulus number may be defined is illustrated in figure A.1. The main point is to find a modulus number that fits best with the curve. The stiffness which is described is the same, but the value of the modulus number may drastically vary, making it important to separate the two.

As will be seen in the following, the relationship between the stiffness and the water content of a soil may vary in accordance with the modulus number. Figure 6.7 illustrates the relationship between the water content and the modulus number m_0, while figure 6.8 illustrates the same relationship, with m intersecting through σ'_r. Both relationships have been plotted on a template of figure 5.1 (Janbu, 1989). Note that the same soils have been used, and thus, they have the same stiffness. The difference between them in relation to water content indicates a large difference between their stiffness, but this is merely due to difference in definition.

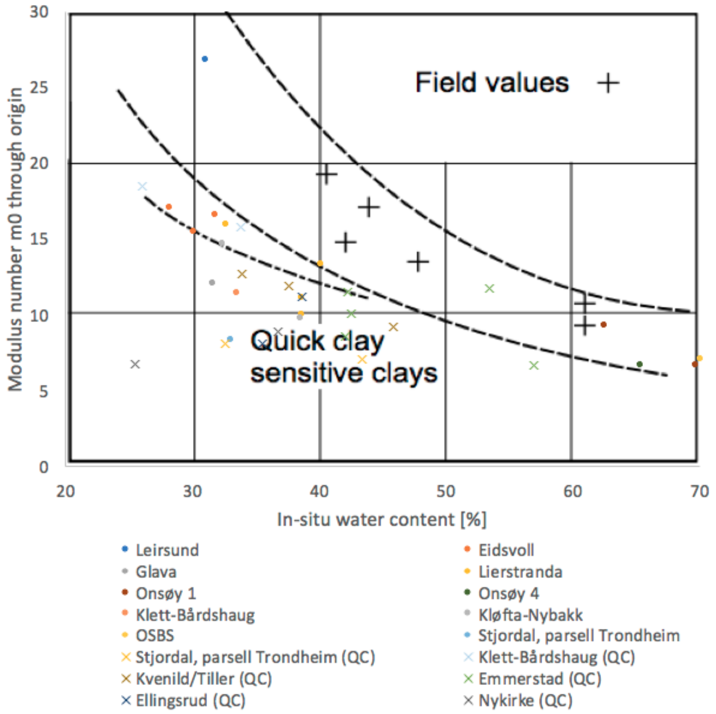

Figure 6.7: Relationship between modulus number through origin (m_0) and natural water content, template from Janbu (1989)

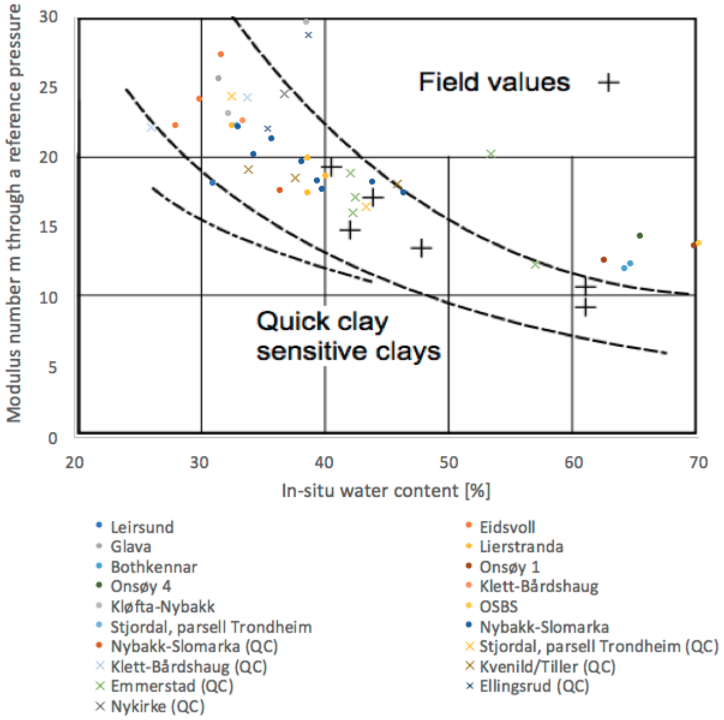

Figure 6.8: Relationship between modulus number through reference pressure σ'_r (m)

As illustrated, both modulus numbers seem to differ a bit from figure 5.1. While m_0 tend to plot on the sensitive side for all the clays, m tends to plot in the normal area for both quick and non-quick clays. Ideally, one may expect the quick clays (marked by an "x") to plot on the lower side while the non-quick (marked by "•") soils should plot in the marked area.

In figure 6.9, both modulus numbers are plotted in the same figure. Again, it is obvious that m plots higher than m_0. This emphasizes the previously mentioned importance of clarity in the definition of the modulus number.

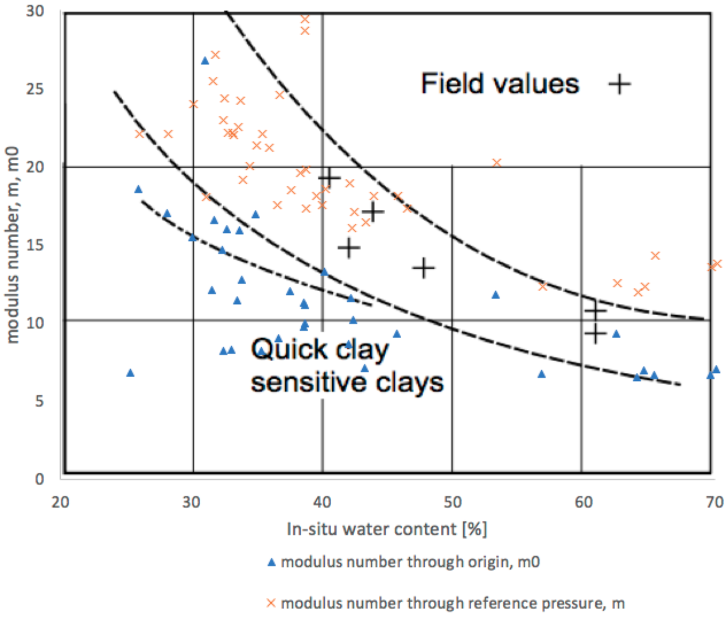

Figure 6.9: Comparison between using m and m_0 in relation to water content, template from Janbu (1989)

6.3.2 NC- and OC-Stiffness in Relation to Water Content

Figure 5.2 illustrated how typical normally consolidated clays tend to vary with water content. Empirical results for Norwegian soils are plotted in figure 6.10, as NC-stiffness against water content and void ratio. The NC-stiffness is found as "Mmin" in GEODIP SP8 (see figure A.1), and the void ratio has been found as a function of water content(expression 2.10), with an assumed value of $G_s = 2.7$ (see table 2.2). The plotted data proves that the relationship described in figure 5.2 is quite accurate for Norwegian soils. The values differ a bit from E_{oed}^{ref}, but tend to plot around the area marked for NC-clays, with some deviation. However, the deviation is small, and with a limited amount of data, it is not fair to call the deviation the norm. Note that all data is taken from Sherbrooke block samples.

A correlation between OC-clays and water content and void ratio may also be found(OC-stiffness has been found as Mmax in GEODIP SP8, see figure A.1). Figure 6.11 illustrates this relationship, and it is clear from the figure that the relationship resembles the one seen for NC-stiffness in figure 6.10. A similar correlation for the OC-stiffness found through trial-and-error, has been drawn up, as seen by the dotted lines. The lines represents a typical area for the plotted soils, and indicates a correlation.

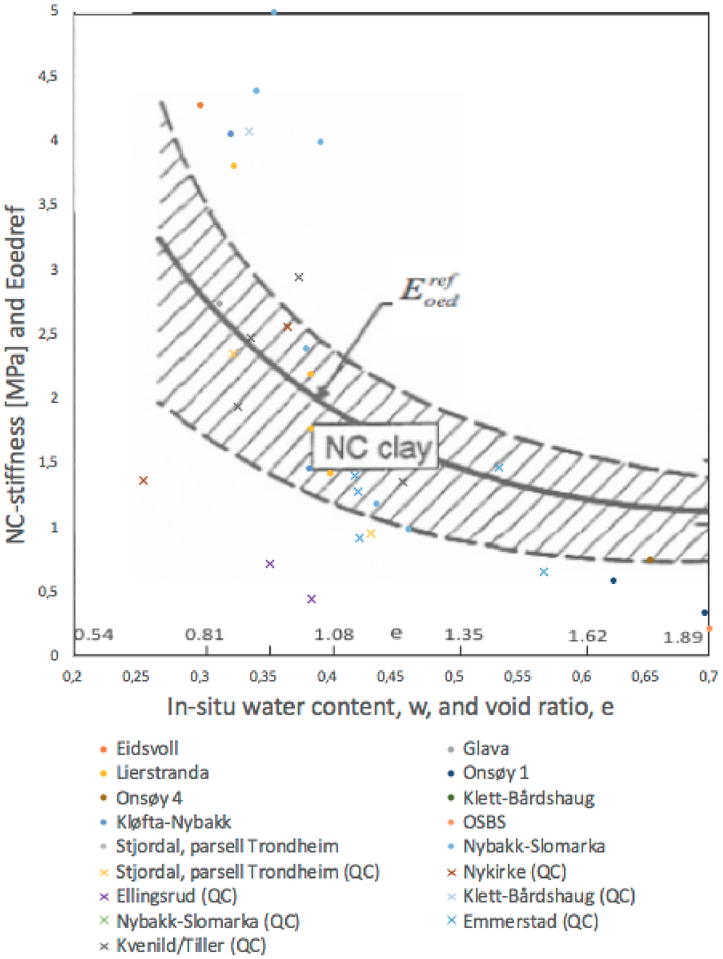

Figure 6.10: Relationship between NC-stiffness(and E_{oed}^{ref}) and water content(and void ratio), template redrawn from Janbu (1989)

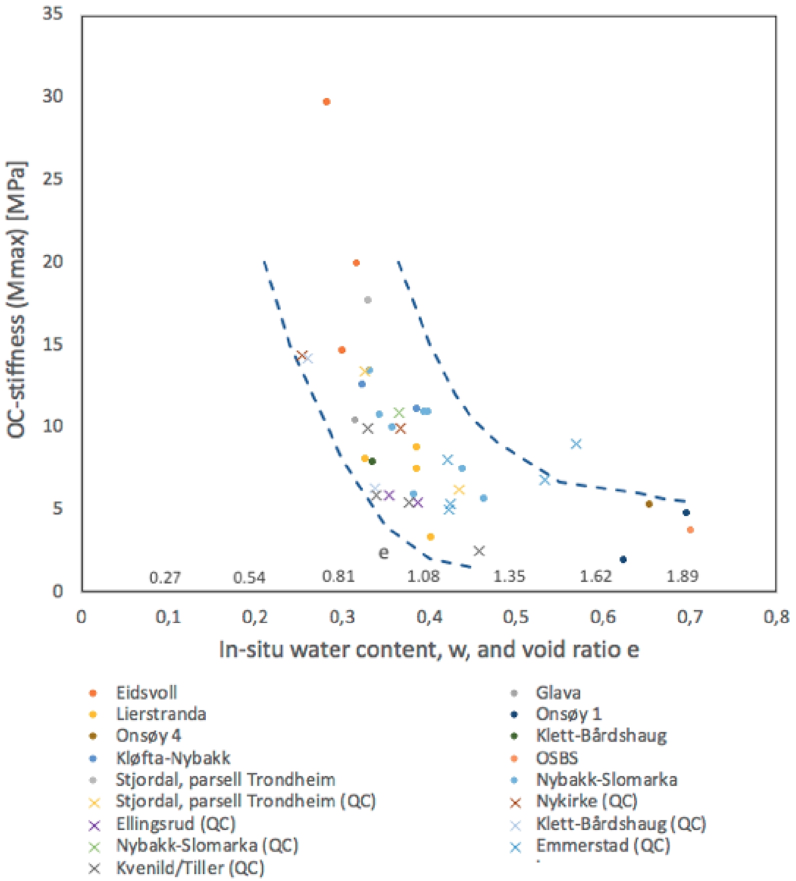

Figure 6.11: Relationship between OC-stiffness and water content (and void ratio)

It was mentioned in section 5.1.1 that the rartio between OC- and NC-stiffness tends to be in the range of 5:1. By plotting the available data of NC- stiffness and OC-stiffness vs. water content in the same plot, it is possible to draw out a trendline for each data series. This has been done in figure 6.12, with the trendline for NC-stiffness marked in green, and the OC-trendline marked in pink. Choosing the water content for which the density of the data is the highest (around w = 0.38), a red line is drawn through both trendlines. The relationships between ΔOC and ΔNC should theoretically be around 5:1. However, as seen in figure 6.12, the relationship seems to be closer to 4:1 (ΔNC is close to 2, while ΔOC is approximately 7.5-8). The reason for this deviation may come from how the stiffness is defined (see figure A.1), or from limited amounts of data, or even by how the manner of which the trendlines were drawn. Another theory is that the deviation from the expected relationship is a result of the long history of consolidation.

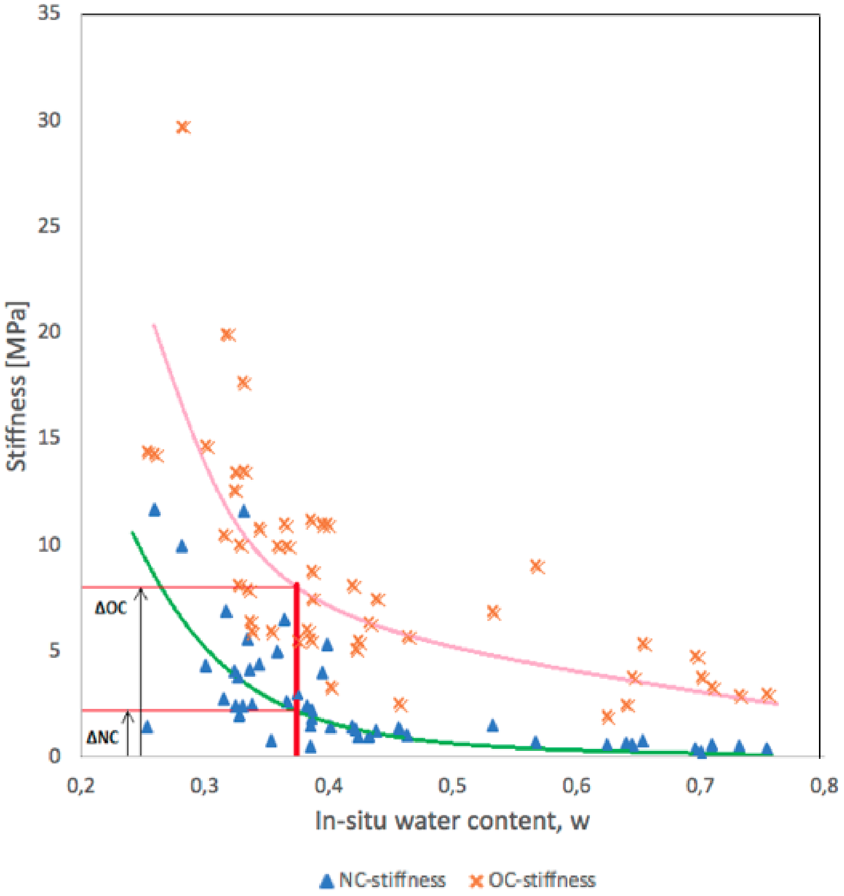

Figure 6.12: Comparison between NC- and OC-stiffness in relation to water content

6.3.3 Clay Content and Stiffness

Due to the fact that stiffness is so clearly dependent on water content, a correlation may exist between the stiffness of a soil and its clay content. This has been plotted for OC-stiffness in figure 6.13 a), and for NC-stiffness in figure 6.13 b). No apparent correlation may be made from the figures. The results seems to be randomly scattered. It is therefore concluded that for Norwegian soils, the amount of clay does not impact the stiffness in any considerable manner. It should be mentioned that the clays all have similar ranges of activities (see figured 6.1 and 6.2), which suggests soils of similar composition. Thus, the stiffness of the soils may be affected by the clay content for soils of higher activities. Based on this, it is hard to make a conclusion for soils in general, although the soils examined does not show signs of correlation.

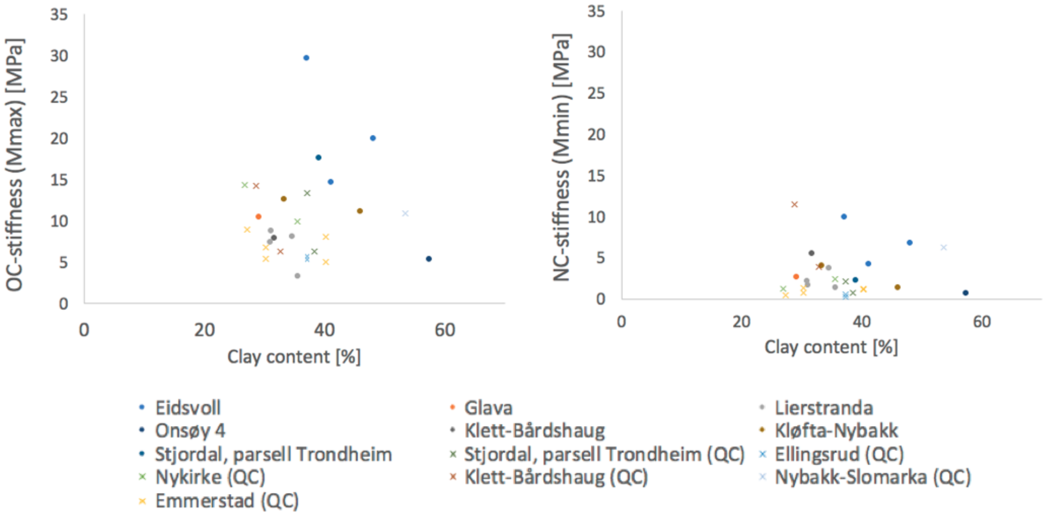

Figure 6.13: a) relationship between OC-stiffness and clay content b) relationship between NC-stiffness and clay content

6.3.4 Stiffness and Plasticity

As discussed in section 5.1.3, a correlation between stiffness and plasticity is well-established. One of the relationships which were discussed was the relationship between the normalized stiffness in accordance to shear strength, OCR and plasticity. Using figure 5.3 from Duncan and Buchignani (1976) as a template, results from CAUC triaxial tests were plotted. The results found with the basis of 50% mobilized shear strength may be seen in figure 6.14. In this figure, most of the data plotted in the area for highly plastic soils. However, most of the clays plotted have low plasticities (see table 6.1), and should ideally plot higher in the chart.

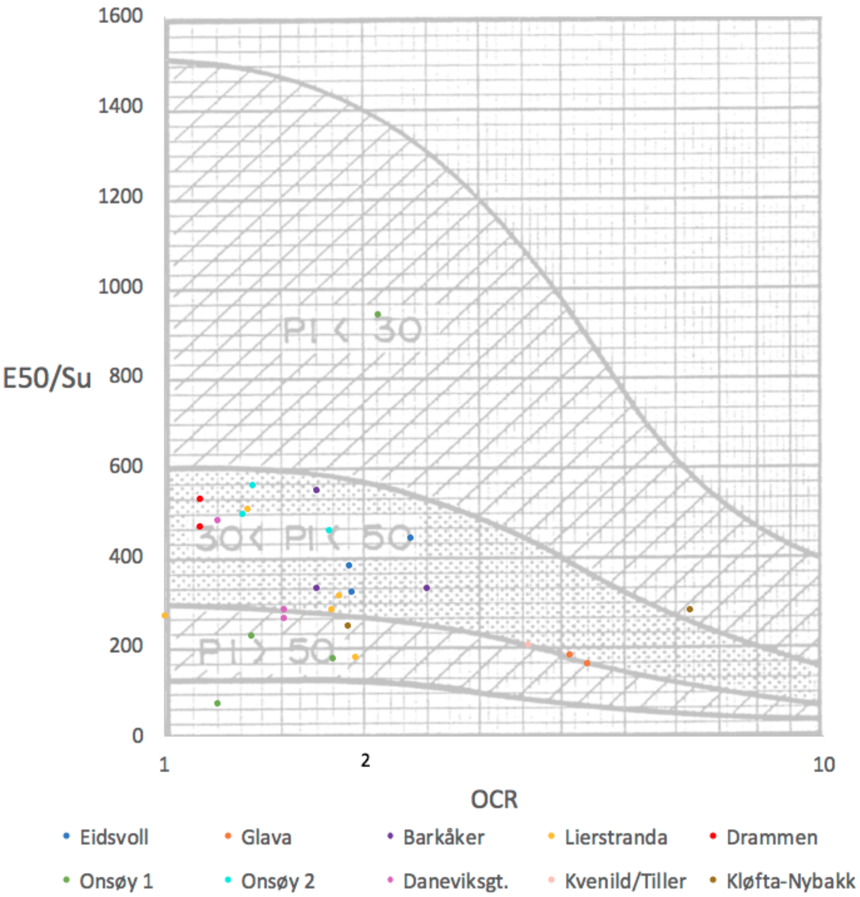

Figure 6.14: Relationship between stiffness E_{50} at 50% mobilized shear strength normalized to Su and OCR, template from Duncan and Buchignani (1976)

Plotting the same values while using the stiffness at only 10% mobilized shear strength(see figure 6.15) provide results which fit better with the chart. This stiffness is of course higher, which leads to the data plotting higher in the chart.

The results are likely a result of the fact that Norwegian clays generally have lower plasticities than clays from other places, which leads to the requirement of a higher normalized stiffness for Norwegian clays in order to fit with the relationship in figure 5.3. A comparison of the stiffnesses has been plotted in figure 6.16. Here, the stiffness at 10% of mobilized shear strength is marked by "x", and the stiffness at 50% of mobilized shear strength is marked by "△".

As illustrated in both figure 6.15 and 6.16, the values for the stiffness at 10% of mobilized shear strength correlates better with the relationship seen in figure 5.3.

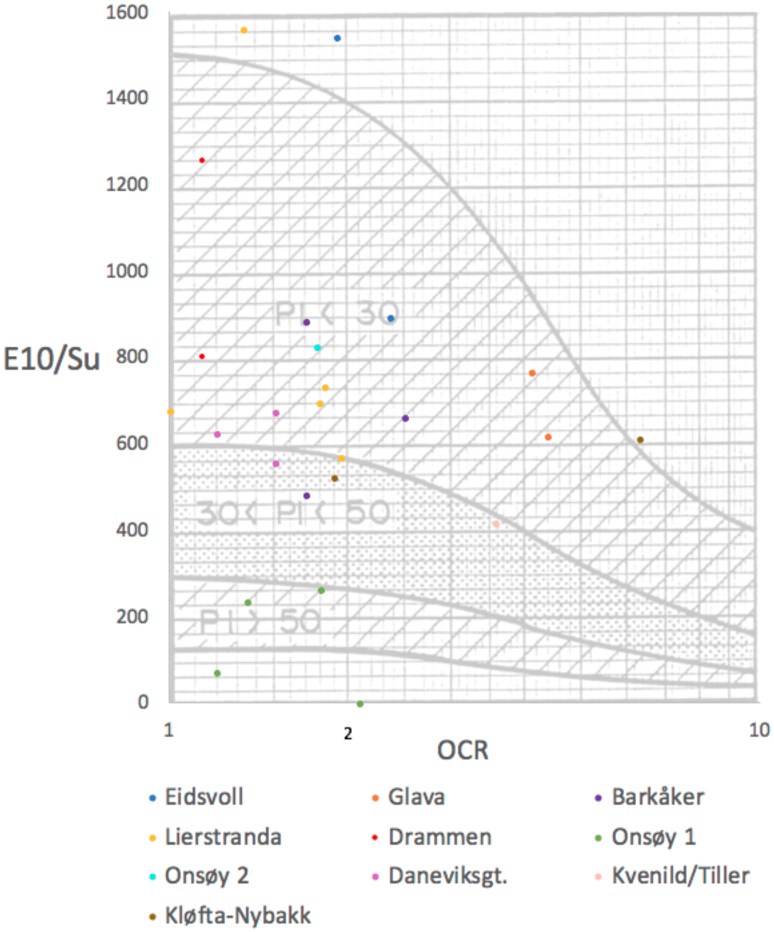

Figure 6.15: Relationship between stiffness E_{10} at 10% mobilized shear strength normalized to Su and OCR, template from Duncan and Buchignani (1976)

Table 6.1: Data for soils plotted in figures 6.14, 6.15, 6.16 and 6.17, from GEODIP SP8

Site	$\frac{E_u^{10}}{s_u}$	$\frac{E_u^{50}}{s_u}$	I_p [%]	OCR
Eidsvoll	892	443	12.8	2.36
	1514	321	18.7	1.91
	1624	379	13.8	1.90
Glava	618	162.5	17.1	4.4
	767	182.5	18.2	4.1
Baråker	660	330	11.5	2.5
	483	331	10.7	1.7
	883	546	10.7	1.7
Lierstranda	567	175	20.3	1.94
	733	314	18.6	1.83
	694	283	18.6	1.79
	1561	506	14.6	1.3
	676	269	14	1
Drammen	803	528	15.5	1.13
	1259	467	14.9	1.13
Onsøy 1	-	938	32	2.1
	263	172	34	1.8
	234	224	28	1.35
	71	74	38	1.2
Onsøy 2	824	457	35.9	1.77
	-	495	41.5	1.31
	-	559	40.7	1.36
Daneviksgt.	557	262	29.27	1.51
	675	283	29.3	1.51
	624	480	20.1	1.2
	2506	1928	17.95	1.2
Kvenhild/Tiller	416	13	13.57	3.56
Kløfta-Nybakk	612	18.4	18.4	6.25
	523	12.4	12.4	1.89

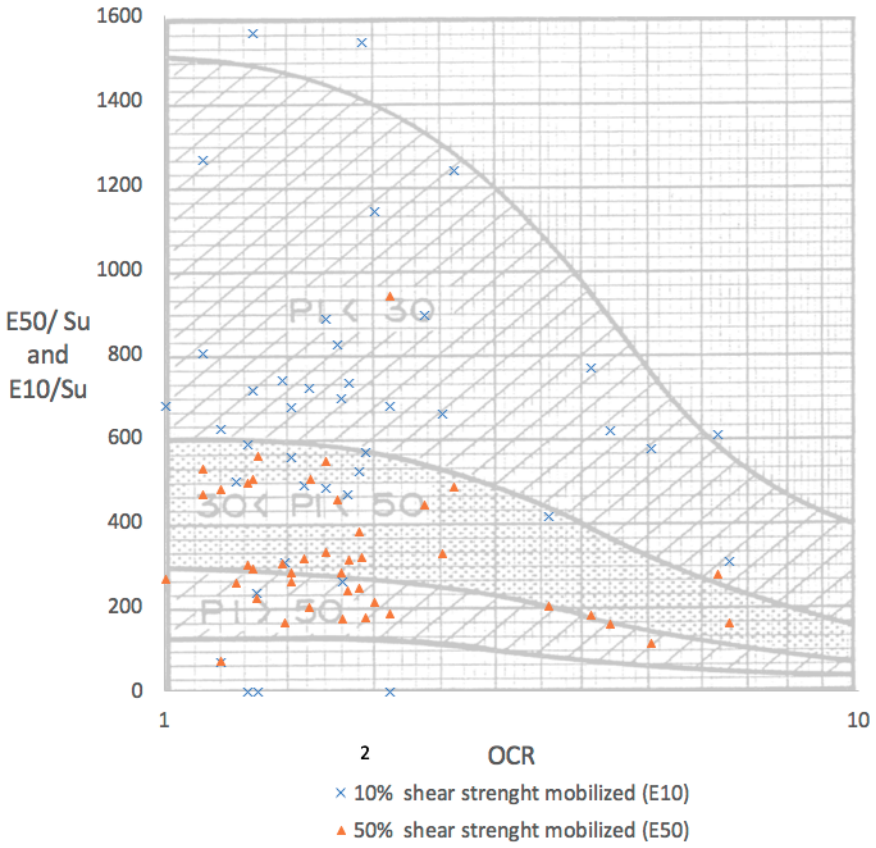

Figure 6.16: Comparison of results using stiffness at 10% mobilized shear strength (E_{10}) and at 50% mobilized shear strenght (E_{50})

By the definition of NC-clays which claims that soils are normally consolidated if OCR < 2 (Janbu, 1989), most of the soils analyzed are normally consolidated (see table 6.1). Thus, expression 5.5 is valid. Expression 5.5 has been plotted alongside the soils from table 6.1 in figure 6.17. In the figure, it is evident that the relationship is fairly valid, although the Norwegian soils tend to plot lower than the line, suggesting the multiplying factor should be lower. A line fitted to the results for the Norwegian soils have been found, in which the expression providing the best result may be seen in eq. 6.6. Note that this result has some limitation due to the low number of soils plotted. The results suggest that the stiffness of Norwegian soil is less dependent on the plasticity than indicated by expression 5.5.

$$E_u^{50} = \frac{600 \cdot s_u}{I_p} \tag{6.6}$$

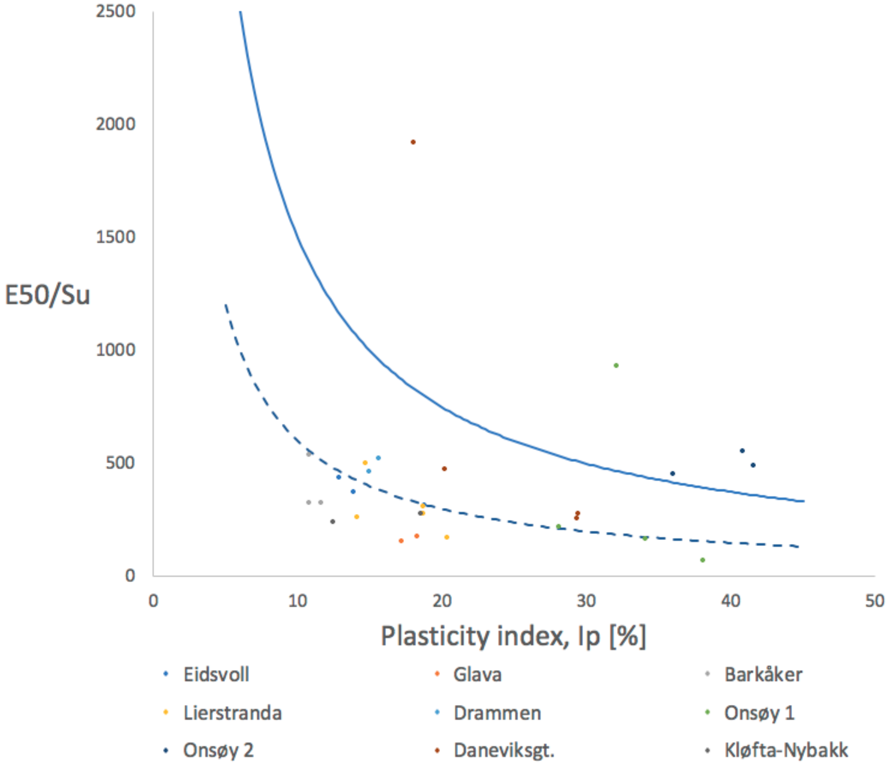

Figure 6.17: Correlation between stiffness and plasticity plotted alongside expression 5.5 and a fitted line expressed by eq. 6.6

6.3.5 Compressibility

The compressibility of soil, sometimes referred to as the inverse of the stiffness, was seen plotted in figure 5.5. It is desirable to see whether experimental data fits with the relationship seen in the figure. The correlation illustrated in fig 5.5 may be described in terms of C_c by expression 5.13. For this purpose, the compressibility C_c has been found by equation 5.16, with the assumption of soft clay (e=1), and λ^* found by equation 5.14, where $\lambda = \frac{1}{m_0}$ is assumed to be true.

The experimental data has been plotted in figure 6.18. The line described by expression 5.13 appear to be a bit low compared to the data.As seen in section 6.3.4, the stiffness was lower than suggested by expression 5.5. This indicates that the compressibility should be higher than suggested, since it is the inverse of stiffness. A line which fits better to the results have been plotted as a dotted line in figure 6.18. The line is expressed by 6.7.

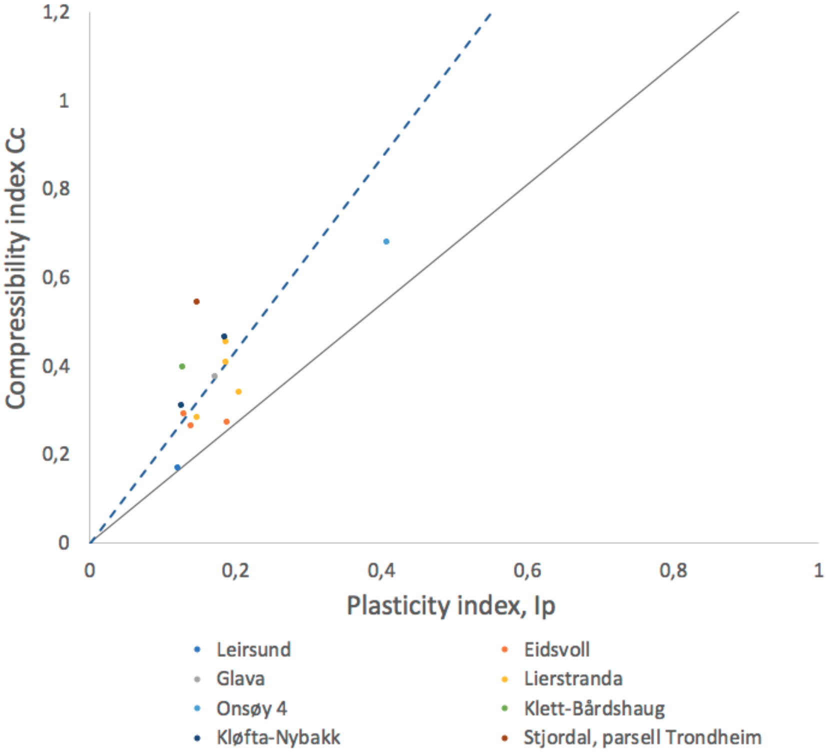

Figure 6.18: Relationship between compressibility index (C_c) and plasticity index (I_P), plotted alongside expression 5.13 and a fitted line expressed by eq. 6.7

$$Cc = 2.18 \cdot I_P \tag{6.7}$$

Expression 6.7 has also been plotted alongside expression 5.13 in a plot of experimental data for a Norwegian soil compared to a soil from Ghana. The soil from Ghana is an offshore clay with an average plasticity index of 83.8%, while the soil from Nybakk-Slomarka has an average plasticity index of only 19.6% (found from GEODIP SP8). It is evident from the figure that the Norwegian soil has a compressibility which falls between expressions 5.13 and 6.7, while the Ghanaian clay plots below expression 5.13. This indicates a strong correlation between a soils plasticity and its compressibility, with a low dependency on I_p for Norwegian soils of low plasticity.

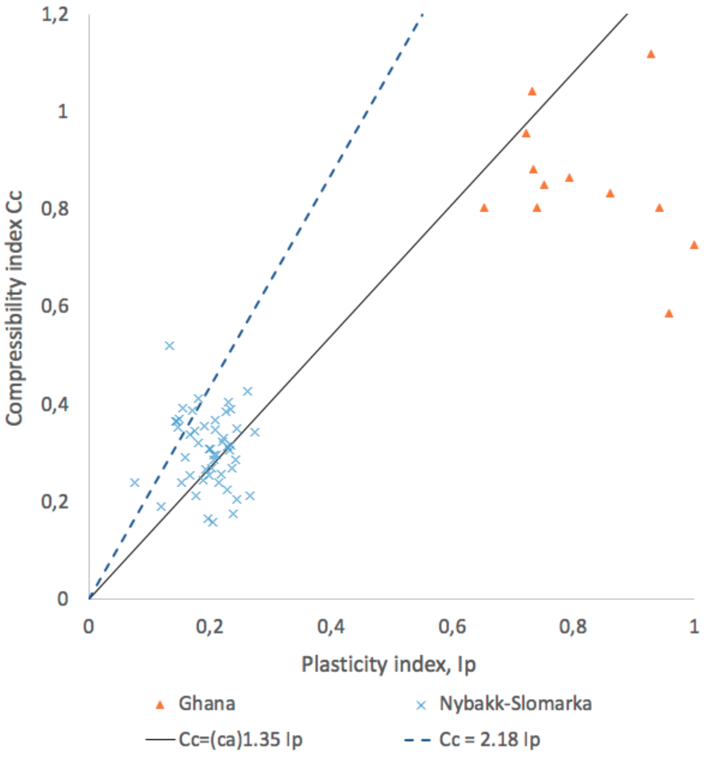

Figure 6.19: Comparison between a Norwegian and a Ghanesian soils relationship between C_c and I_P, plotted alongside expressions 5.13 and 6.7

6.4 Shear Strength

The shear strength of soil was discussed in section 5.2, and found to be a function of the water content and the liquidity index of the soil. These relationships have been plotted for Norwegian soils in accordance with the discussed correlations. Figures 5.7 and 5.9 have been used as templates for undrained and remolded shear strength, respectively. Note that data series marked by an “x” indicates that the sample size of the data is unknown, and thus one must be cautious in its interpretation. The inclusion of this data is merely based on the fact that there were limited amounts of relevant results available.

6.4.1 Undrained Shear Strength

In figure 6.20, results of the undrained shear strength and liquidity index has been plotted. From the results, the correlation does not seem to be as strong as indicated in section 5.2.1. However, the data plots close to the suggested relationship, and since the amount of data plotted is limited, a conclusion can not be made upon the validity of the suggested correlation.

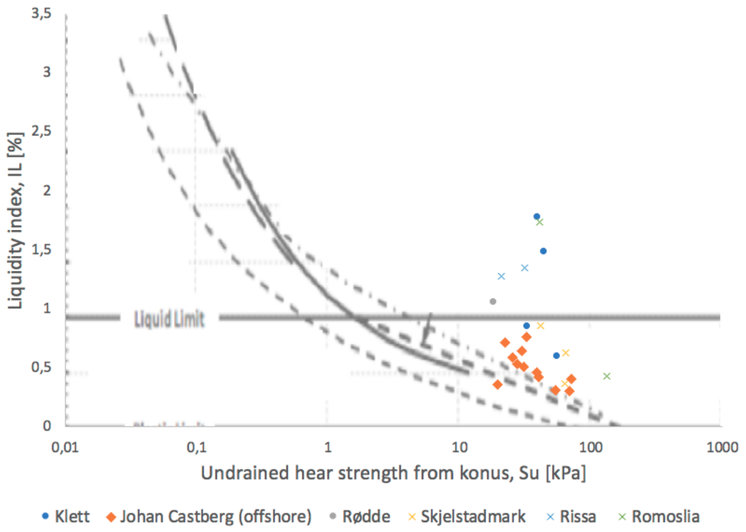

Figure 6.20: Relationship between liquidity index and undrained shear strength, template modified from Vardanega and Haigh (2014)

In section 5.2.1, a relationship between the undrained shear strength and the natural water content was discussed. A relationship on the form of expression 5.19 has been fitted to experimental data of Norwegian clay in figure 6.21, expressed by 6.8. The material constants a and b are found empirically for several data series as seen in the figure. The correlation is not a perfect match, but the median of all the data. A correlation on the suggested form is evident.

$$w = 290 \cdot s_u^{-0.6} \tag{6.8}$$

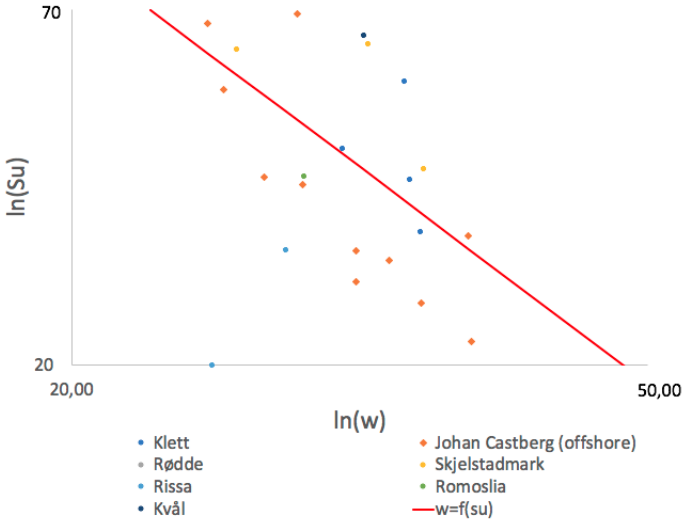

Figure 6.21: Relationship between the natural water content and undrained shear strength of Norwegian soils

6.4.2 Remolded Shear Strength

From data plotted in figure 6.22, it is clear that the relationship between the shear strength and the liquidity index discussed in section 5.2.2 is valid for remolded soil.

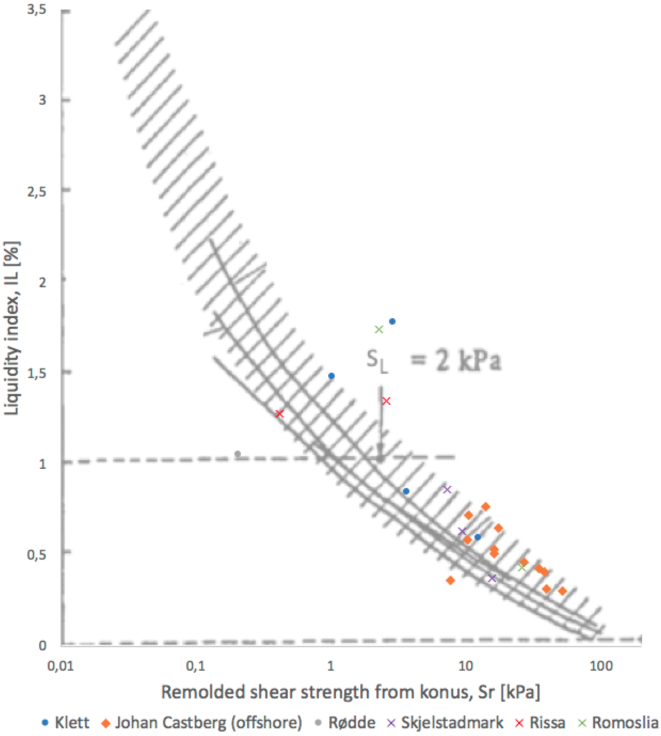

Figure 6.22: Relationship between liquidity index and remolded shear strength, template modified from Wood (1990)

Expression 5.20, relating the undrained shear strength and the liquidity index, has been plotted along with the remolded shear strength and liquidity index of Norwegian soils in figure 6.23. The expression is valid for the soils within the plastic area, and has thus only been plotted for this area (figures 6.22 and 6.23 illustrate the same relationship).

Comparing the results seen in figure 6.23 to figure 5.11, the consolidation state of the soil may be indicated, as discussed in section 5.2.2. The offshore soil from Johan Castberg appears to fall into category B (*overconsolidated soils*). However, Johan Castberg consists of mostly normally consolidated clays. The results from Skjelstadmark falls into category A (*normally consolidated insensitive soils*), B, and C (*naturally sensitive soils*). The soil from Skjelstadmark all have OCR less than 2, and has not been described in GEODIP SP8 as being sensitive. The result from Romolslia which is included in figure 6.23 also plots as an overconsolidated soil, which is accurate as the OCR for the soil exceeds 8. The samples from Klett plots around A and B. The soil samples plotted are not classified as sensitive, but both are slightly overconsolidated (OCR = 2.11 and 3.31). The results of the Norwegian soils seems to correlate with the consolidation history seen in figure 5.11 quite well, although not perfectly.

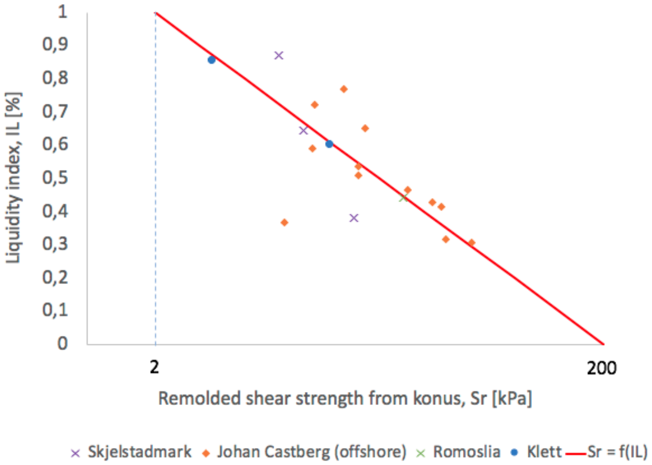

Figure 6.23: Relationship between liquidity index and undrained shear strength, template modified from Vardanega and Haigh (2014)

6.4.3 Comparison of Undrained and Remolded Shear Strength

In figure 6.24 a), the undrained and remolded shear strengths have been plotted against the liquidity index, and in figure 6.24 b) the same properties have been plotted against the natural water content of the soils. As seen in the figures, the water content of the undrained soils is higher than the remolded, which emphasizes the importance of soil structure in relation to the water content of the soil.

Figure 6.24 a) illustrates that the difference between the remolded and natural soil when compared to the liquidity index is larger than when compared to the natural water content. It is thus clear that it is the relative content of water rather than the water content in natural state which has the strongest correlation to the shear strength. Remolded soils are soils which have lost its original structure, and comparing figure 6.24 to values of liquidity limit for different clay minerals (see table 4.1) clearly illustrates that clay minerals with a higher degree of structure (such as montmorillonite) has a higher liquid limit. Thus, as the undrained shear strength describes the shear strength of soils with a more intact structure than the remolded, it makes sense for the liquidity of such soils to be higher than that of remolded soil. This is clear in figure 6.24.

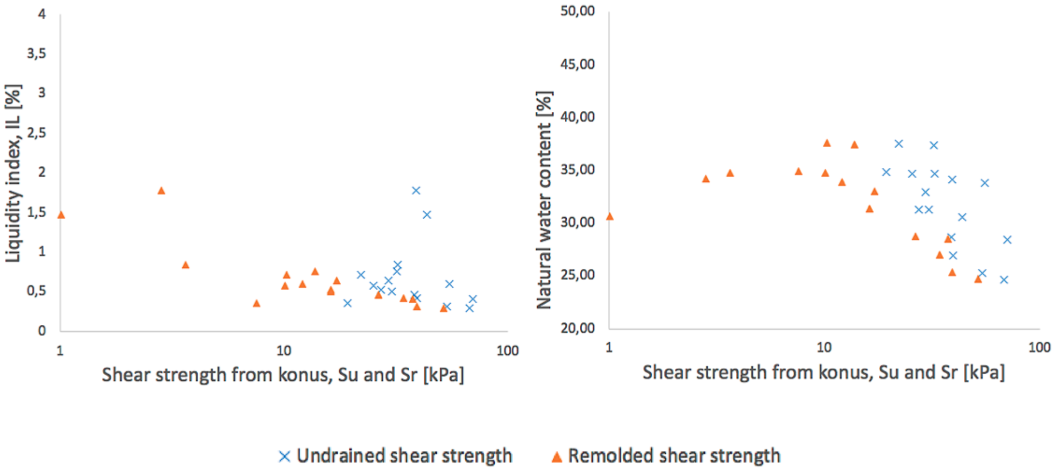

Figure 6.24: a) Comparison between s_u and s_r, and I_L b) Comparison between s_u and s_r, and w

6.5 Impact of Plasticity on Friction angle

In figure 6.25, the critical state slope (M, found in accordance with equation 5.22) of soils has been plotted against the soils plasticity index. The results have been plotted on a template of a redrawn version of figure 5.13 from Wood (1990). As discussed in section 5.3, such a plot may be a useful indicator of the mineral content of the soil. From figure 6.25, it is apparent that all the Norwegian soils plot close to kaolinite. However, as previously mentioned, it is necessary to act with caution when determining the mineral content of soils.

Although the figure gives an idea of which minerals may be present, no conclusion can be made in this regard without actually checking the soil content. It is also an important point that the soil is not fully a clay, and a large part of the soil is likely consisting of other minerals and maybe even organic contents. The fact that the data plots so close to kaolinite is likely a result mainly of the soil having a generally low plasticity. It does not however mean that the soil can not consist of kaolinite-clays, it merely states the importance of caution when interpreting the results. Hence, the results plotted in figure 6.25 would be more informative if detailed data of the mineralogy of the plotted soils were available.

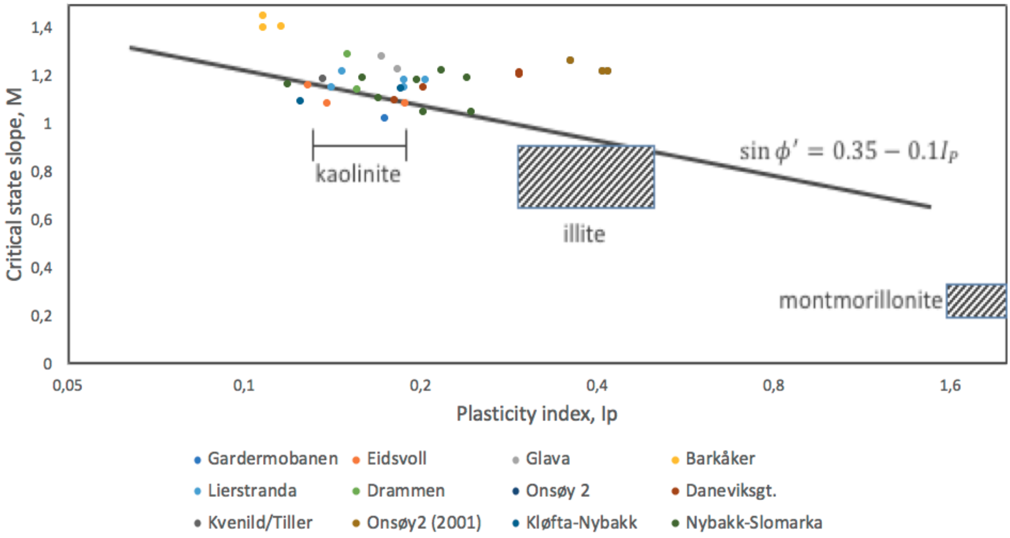

Figure 6.25: Relationship between critical state slope M and plasticity index I_P, template redrawn from Wood (1990)

Chapter 7

Discussion and Conclusion

This aim of this thesis was to find correlations between properties in geotechnical engineering. Several relationships for basic strength and stiffness parameters have been explored, based on literature and experimental data. The results indicate a strong dependence on the water content. Properties such as natural water content, plasticity and water content relative to the plasticity index (I_L) have been proved to be unquestionably defining of the mechanical properties of a soil. The correlations between properties were mainly discussed in chapter 5 and 6.

7.1 Discussion

Something which is seen repeatedly for results of Norwegian soils is that the soils generally have low plasticities. Section 6.2.1 illustrated that the activity of the Norwegian soil was low, and the effect of this on other parameters was seen in the correlations that followed. In several cases it was proved that the behavior of the Norwegian soil was less dependent on the plasticity than the empirical results indicated. This was apparent for both stiffness (section 6.3.4) and compressibility (section 6.3.5). The expressions seen in chapter 5 that are used to define these parameters were found to be overestimating the impact of the plasticity, leading to revised expressions for the data plotted in chapter 6.

In some cases, such as for the at rest earth pressure, which was discussed in section 5.4, the impact of the plasticity can be neglected. The effect of the plasticity was seen as so insignificant that it is ineffective in predicting the behavior of typical Norwegian soil. This relationship was not explored further for the soils in SP8, but indicated the importance of plasticity with respect to soil behavior.

With respect to mineralogy, the soils that have been tested indicated clay minerals of low plasticity, with activities that plots around the activity of kaolinite (see figure 6.1). This indicates that large parts of the clay minerals present may consist of kaolinite or similar minerals. Note that the soil is most likely composed of several minerals, both clay and coarser materials (many minerals that are typically found in soil has not been discussed in this thesis). Hence, no conclusion can be made on the mineral content of the Norwegian soils based solely on the results in this thesis, although the results seen for the activity may serve as an indicator.

A theory regarding the low plasticity is that it is a result of the effect of previous ice ages on the soil. Plasticity is a direct result of the crystalline structure of the soil. Most of the soil in Scandinavia has been subjected to large glacial loads over a long period of time, and although these loads have been long removed, the soil structure has been affected by this. Such loads have likely affected the original crystallinity that the soil had, and thus lead to a lower plasticity. This suggests that the plasticity of soil is a result of the consolidation history, as well as the mineralogy.

It is plausible to assume that the crystallinity of a soil will also affect its shear strength. Intuitively, it would make sense for highly structured soils with strong bonds between the particles to require more force in order to break apart. As the volume gets larger with no additional clay particles, the void ratio increases and so does the distance between the particles. However, considering the theory of glacial loads affecting the structure of Norwegian soils, the strength may not be a function merely of crystallinity. Norwegian soil has been subjected to compaction, which is also something that has affected the strength. Due to this fact, it makes sense for the strength of a soil to have a stronger correlation with the relative water content than the natural water content, since this insinuates that the low plasticity has been taken into consideration (see figure 6.24). As seen in sections 5.2 and 6.4, the liquid limit is strongly correlated to the shear strength. Since the liquid limit is a relative value, it is easier to compare its relationship to the strength of Norwegian soils to the general relationship which was discussed in section 5.2. It is apparent that the correlation to the liquidity index is strongest for the remolded shear strength, while the undrained shear strength seems to be less dependent on I_L. Of course, the results are based on a limited amount of data which may affected its validity. This is true for several of the results which has been found.

The most important consequence of all the correlations that have been found in the thesis is the large degree to which the behavior of a soil is dependent on its location. All of the factors that affect the soil behavior, including its mineralogy and composition, stress history, water content, plasticity and more, depend on factors that are definite results of the location. As such, it is crucial to be aware of the differences in soil in accordance with location, as the expected outcome of a soil will vary majorly as one moves from one location to another.

7.2 Conclusion

The purpose of this thesis was to find correlations between soil parameters, with a special focus on Norwegian soil. Soil behavior was discussed and linked up to basic properties of soil, as well as the mineralogy of clay minerals. Several relationships between basic index properties and mechanical parameters have been discussed. As this is a topic which can possibly be very large, the mechanical properties were limited to basic properties of strength, stiffness and compressibility.

In chapter 6, the correlations discussed in the previous chapters were compared to results for Norwegian soils. The results showed a generally low activity and plasticity of the soil, and the impact it had on the mechanical properties of the soil. The correlations that were found for Norwegian soils proved to be less dependent on the plasticity than what was indicated in literature. This was particularly true for values of stiffness and compressibility, and expressions that fit better with the experimental data were suggested (note that the suggested expressions were based on a limited amount of results, which in turn limited the validity of the expressions).

Shear strength was found to be correlated to the liquidity index of the soil, and the results for the Norwegian soils in chapter 6 fit quite well with the theoretical correlations discussed in chapter 5. Since the liquidity index describes the water content in relation to the plasticity index, the fact that Norwegian soils are generally of low plasticity is already accounted for in the case of shear strength, indicating that it is not dependent on the crystallinity of the soil to the same degree as what was seen for the stiffness.

The impact of the soil content with respect to mineralogy was also discussed. It was debated whether it was the mineral content of the soil or the consolidation history that has the biggest influence on the plasticity of Norwegian soil. As the composition of the soils investigated in this thesis was unavailable, it is difficult to make a conclusion about this manner, although the results suggest that both matters have an impact on the plasticity.

The dependency on water content and plasticity is evident from the correlations that have been discussed in this thesis. Another important aspect of this thesis is the dependency on location seen for the correlations. As discussed in chapter 3, soils are transported and weathered by on-going processes. This means that the minerals present soil is highly dependent on the processes that have occurred to it throughout time and the environment of its deposition. Other aspects which may affect the behavior of the soil, such as its stress history, is also a result of the location of the soil. This indicates the importance of site-specific data when using soil as a medium. The correlations that have been discussed for Norwegian soils are valid for the environment in which it exists.

Appendix A

Supplementary Information for GEODIP SP8

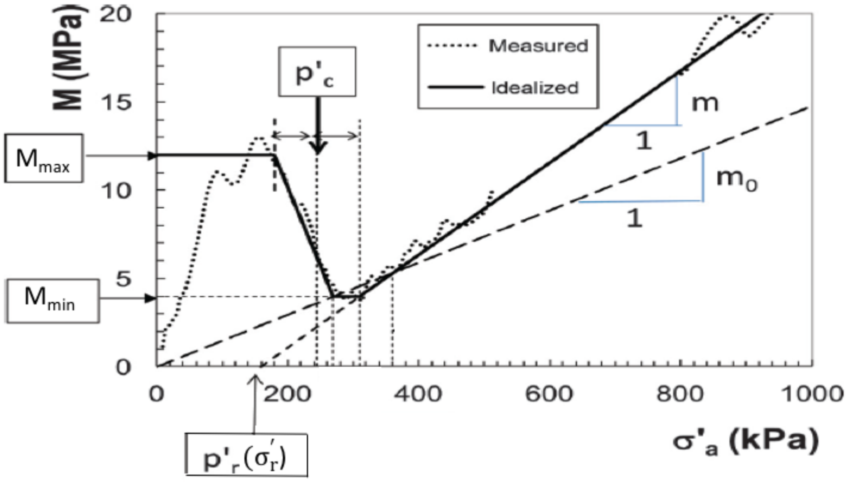

Figure A.1: Definitions of parameters from oedometer results, modified from GEODIP's SP8

Table A.1: Evaluation of sample quality (NGF, 2013)

OCR	$\Delta e/e_0$			
1 to 2	<0.04	0.04 to 0.070	0.070 to 0.14	>0.14
2 to 4	<0.03	0.03 to 0.050	0.050 to 0.10	>0.10
4 to 6	<0.02	0.02 to 0.035	0.035 to 0.07	>0.70
Quality	1: very good to excellent	2: good to fair	3: poor	4:very poor

Table A.2: Information about testing sites from GEODIP's SP8 (Paniagua et al., 2017)

Site name	**Location**	**Soil type**	**Sampling method**
Eidsvoll	Akershus	Firm to stiff clay (silty)	Block
Emmerstad	Akershus	Quick clay	Block
Gardermobanen	Akershus	Clay / Quick clay	Block
Hvalsdalen	Akershus	Firm to stiff clay	Block
Kløfta-Nybakk	Akershus	Clay - Quick clay	Block
Leirsund	Akershus	Clay	Block
Nybakk-Slomarka	Akershus	Silty clay, clay and quick clay	72 mm Block
Drammen	Buskerud	Soft clay with thin silt/sand layers	Block
Lierstranda	Buskerud	Soft clay	Block
Daneviksgate	Buskerud	Soft clay	Block
Koa	Nord-Trøndelag	Quick clay	72 mm Block
Bangsund	Nord-Trøndelag	Clay & quick clay	54 mm
Glava	Nord-Trøndelag	Medium stiff to stiff clay	Block
Skjelstadmark	Nord-Trøndelag	Clay	54 mm
Ellingsrud	Oslo	Quick clay, silty	Block
Rødde	Sør-Trøndelag	Quick clay	72 mm
Rissa	Sør-Trøndelag	Soft & quick clay	72 mm
Klett	Sør-Trøndelag	Soft silty quick clay and clay	72 mm & miniblock
Kolstad	Sør-Trøndelag	Quick clay	75 mm
Kvenhild-Tiller	Sør-Trøndelag	Soft to medium quick clay	Block
Romoslia	Sør-Trøndelag	Clay	72 mm
Stavne	Sør-Trøndelag	Clay & quick clay	72 mm
Stjørdal, parsell Trondheim	Sør-Trøndelag	Silty clay - clay & quick clay	Block
Klett-Bårdshaug	Sør-Trøndelag	Quick clay	Block
Nykirke	Vestfold	Quick clay	54 mm
Barkåker	Vestfold	Clay	Block
Onsøy/OSBS	Østfold	Soft to medium clay	Block
Ghana, Gulf of Guinea	Offshore	Soft and very plastic clay	72 mm
Johan Castberg, Norway	Offshore	Clay	72 mm
Bothkennar	Scotland	Soft clay/silt	Block
Skatval	Nord-Trøndelag	Quick clay	72 mm Block

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