

Influence of Physical Properties of Marine Clays on Electric Resistivity and Basic Geotechnical Parameters

Alberto Montafia

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Norwegian University of Science and Technology Department of Civil and Transport Engineering



Norwegian University of Science and Technology NTNU

Department of Civil and Transport Engineering Geoechnical Engineering Research Group

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Name:				
Alberto Montafia				
Professor in charge/supervisor:				
Arnfinn Emdal				
Other external professional contacts/supervisors:				
Rolf Sandven (Multiconsult AS)				

Adding resistivity measurements to classical cone penetration tests (CPTU) provides further information useful for stratigraphy interpretation. Resistivity CPTUs (R-CPTU) have already been used for quick clay mapping, but there are still uncertainties related to the interval of resistivity values corresponding to quick clays and to whether resistivity is able to give information on geotechnical parameters that can then be utilized in engineering design. The results of four R-CPTU soundings, carried out in sites characterized by leached clays with different properties in eastern and central Norway, were complemented with their corresponding laboratory data in order to get an improved definition of the range of values associated to each soil type. Chemical analyses of the pore water and salinity measurements were also undertaken as to improve the understanding of the physical phenomena that regulate and determine soil's bulk resistivity. It was observed that the role of salinity becomes less important in this process as salt content itself reaches very low values, and below a certain threshold concentration it appears as if the contribution of salinity is almost negligible. As long as the feedback that resistivity gives in distinguishing sensitive clay from quick clay is cencerned, it appeared as if the differences in mechanical properties of the two soil types were not evident enough to reflect into different R-CPTU measurements. More successful results were achieved when soil types with more dissimilar characteristics were considered. The diffusion of R-CPTU in geotechnical investigation practice in Norway is still limited, but it is gaining in popularity due to the very little additional effort required to acquire this information. The potentiality of R-CPTU will be better exploited once that more data from sites with leached, unleached and eventually also non-marine clays will be collected.

Keywords:

- 1. Resistivity
- 2. R-CPTU
- 3. Quick clay
- 4. Geotechnical investigations



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Spring 2013 for

Alberto Montafia

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Introduction

The Norwegian water and energy authority NVE, the Railroad department Jernbaneverket and the Road department Statens Vegvesen SVV have started a collaboration within the NIFS project. A part of this project concentrates on quick clay, a very relevant topic in central and eastern Norway. The Norwegian Geotechnical Institute NGI, SINTEF and Multiconsult AS are also taking part in this research program. A major effort is put into trying to identify quick clay formations in a faster and more reliable way. The goal of this work is to achieve a better understanding of the relation between traditional CPTU parameters and soil resistivity measured with R-CPTU, studying the mechanisms controlling soil resistivity and investigating whether it is possible to deduce geotechnical parameters from resistivity. A better definition of the characteristic resistivity ranges associated to different soil types is also sought after.

Content

The report shall give comprehensive information on the topics involved in the study:

- Soil formation processes, soil physical properties and their influence on soil electrical properties
- Pore water chemistry and its influence on soil electrical and geotechnical properties
- Electric resistivity theory and its applications in soil science and geotechnics

Information on the above mentioned points should be the result of a research in available literature. An experimental part shall also be included, consisting of both laboratory and field investigations. Laboratory testing will mainly involve index testing, measurement of undisturbed and remolded shear strength, assessment of grain size distribution and measurement of pore water salininty. When available, other geotechnical data of interest can be included. The goal of the field work will primarily be to expand the database containing electrical resistivity measurements and gain familiarity with the investigation method. Achievements and shortcomings of the results shall be commented upon. Indications and suggestions on how to proceed in this research are appreciated.

Delivery

The report shall be delivered in the form of a descriptive technical report. Delivery on June the 10th, 2013.

NTNU – June 2013

Arnfinn Emdal

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Abstract

Adding resistivity measurements to classical cone penetration tests (CPTU) provides further information useful for stratigraphy interpretation. Resistivity CPTUs (R-CPTU) have already been used for quick clay mapping, but there are still uncertainties related to the interval of resistivity values corresponding to quick clays and to whether resistivity is able to give information on geotechnical parameters that can then be utilized in engineering design. The results of four R-CPTU soundings, carried out in sites characterized by leached clays with different properties in eastern and central Norway, were complemented with their corresponding laboratory data in order to get an improved definition of the range of values associated to each soil type. Chemical analyses of the pore water and salinity measurements were also undertaken as to improve the understanding of the physical phenomena that regulate and determine soil's bulk resistivity. It was observed that the role of salinity becomes less important in this process as salt content itself reaches very low values, and below a certain threshold concentration it appears as if the contribution of salinity is almost negligible. As long as the feedback that resistivity gives in distinguishing sensitive clay from quick clay is cencerned, it appeared as if the differences in mechanical properties of the two soil types were not evident enough to reflect into different R-CPTU measurements. More successful results were achieved when soil types with more dissimilar characteristics were considered. The diffusion of R-CPTU in geotechnical investigation practice in Norway is still limited, but it is gaining in popularity due to the very little additional effort required to acquire this information. The potentiality of R-CPTU will be better exploited once that more data from sites with leached, unleached and eventually also non-marine clays will be collected.

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1. Introduction

1.1. Background and scope

Part 6 of the NIFS project, coordinated by NVE, Jernbaneverket and SVV has its main focus on quick clay. NGI, SINTEF and Multiconsult AS are also collaborating in the NIFS project, and a major effort is put into trying to identify quick clay in faster and more reliable way. The use of geoelectrical investigation methods such as electrical resistivity tomography (ERT) for quick clay mapping in Norway and Sweden has proven to be a useful tool for this purpose. In order to improve the reliability of this method, cone penetration tests with electrical resistivity measurements (R-CPTU) were also carried out. The measuring device in this case is in direct contact with the surrounding soil, while in the former case the soil's resistivity is inferred by surface measurements. Several authors have put their efforts into defining the range of resistivity values that characterize the different soil types, especially for leached marine clay. Unfortunately there are still uncertainties concerning the boundary values for potential quick clay and the relation between soil's electrical resistivity and its physical and geotechnical properties.

The fall semester project "Assessment of R-CPTU results in Marine Clays" investigated a possible correlation between resistivity and the dimensionless CPTU parameters B_q and R_f , respectively called pore pressure ratio and normalized side friction. The results thereby obtained were not clear enough to identify the sought after correlations, since there was the need of a larger amount of data and of information on the physical and geotechnical properties of the investigated soils. The present work intends to study the physical and geotechnical properties of soils and relate them to their electrical features. The influence of the soil's liquid phase properties, such as the amount of dissolved electrolytes, will be taken into consideration, as well as the characteristics of the solid fraction. Data coming from the new testing sites will contribute to clarify the eventual correlation between the normalized CPTU parameters already considered and others such as the normalized cone resistance Q.

1.2. Structure

In order to understand the electrical characteristics of clay, it is first necessary to explain how clay minerals are formed, define their properties and describe how their interaction with the depositional environment affects several aspects of the soil deposit. An account of the characteristics of the soil's liquid phase is also provided as well as one about the changes that pore water undergoes as a consequence of the physical, chemical and geological processes it is subjected to. In the following chapters the theoretical aspects of electrical resistivity are introduced, and an overview is given on how these adapt to soils and particularly clays. The test sites are then presented, followed by an explanation of the investigation methods and a description of the equipment. All results obtained from field and laboratory investigations are commented, and the performance of the equipment is assessed. Field and laboratory results are integrated in order to research possible underlying correlations. Finally, summary of the results obtained in this work and suggestions on how to carry on this research topic will be provided in the closing sections.

2. Soil: formation and transformation

In order to understand how phenomena such as conduction of electric current take place inside soil masses, it is necessary to be acquainted with the processes by which soil is formed and how its characteristics change in time. This initial chapter introduces these topics, so as to become more familiar with the terms often used to describe a soil's structure, texture and fabric. Soil is a combination of solid, liquid and gaseous substances, where the solid fraction forms a skeleton with voids filled by liquids or gases, or both together. Soil characteristics depend on the mutual interaction between these three phases, and they can therefore be very different both in terms of physical and mechanical properties. The size of the particles included in the solid phase can span from several centimeters to fractions of a millimeter. Their shape can be close to spherical, needle-like or similar to a thin, flat plate. Organic matter can also be found in soils. Size, shape, and properties of soil particles determine the possible ranges of physical and chemical properties of a soil. All these factors are then mainly a direct consequence of soil mineralogy (Lancellotta, 2004).

2.1. Clay

The fraction of solid particles whose size is smaller than 2 μ m is referred to as clay, and according to Norwegian practice, when the fraction of clay particles in a soil is greater than 30% of the total weight, then the soil is classified as clay. Clay is actually a term that indicates both a size of soil particles and a category of minerals, even if not all clay minerals are smaller than 2 μ m and not all particles below this size are clay minerals. Commonly clay constitutes the smaller fraction of solid particles of a soil, but its presence, also in relatively small amounts, significantly influences the soil's behavior. (Lancellotta, 2004)

One of the most prominent distinctions between clay minerals and non-clay minerals is that the former are generally platy, or in few cases needle-shaped, whereas the latter are usually bulky. Hence the surface area per unit weight of clay minerals is some orders of magnitude higher than the one of non-clay minerals. In addition, clay minerals have a negative net electrical charge, interact with water when mixed to it and have a high weathering resistance. The most common clay minerals are kaolinite, illite, smectite and chlorite. The different rock types they originate from eventually influence pore water pH, concentration and type of electrolytes dissolved in the soil's pore water. Drainage and weather conditions (temperature and precipitations) also affect the formation process. Alteration of some clay minerals can result in other species of clay minerals when there are electrolytes available for chemical reactions (Mitchell and Soga, 2005).

2.1.1. Clay formation

Clay minerals are so-called secondary minerals as they originate from the weathering of silicates. According to Eberl, Farmer and Barrer (1984) clay minerals can form by precipitation from a solution or by reaction between amorphous constituents. Once formed, they can be stable enough to persist in their current environment or they can undergo chemical reactions which affect the chemistry but leave the structure relatively unaltered. In any of these cases, the surrounding environment plays a major role in determining the outcome of the transformation process. With the exception of residual soils, soil seldom deposits where it is formed and it will thus be subjected to conditions different from the ones where it originated.

Soil composition, history, present state and changes in the surrounding environment are all reflected into its structure. A soil's structure is defined as the combination of its fabric and its inter-particle force system. Most fine grained soils are characterized by fabrics composed of particle sizes ranging from 10^{-6} to 10^{-3} m. Voids not occupied by solid particles are also considered to be part of the soil's fabric. Bennett and Hulbert (1986) have highlighted the critical importance of the chemistry of the depositional environment in determining the characteristics of the fabric in fine grained soils. This principle, known as the *principle of chemical irreversibility of clay fabric*, applies to the early stages of fabric formation, when the particles deposit and can flocculate. In its later stages, as the influence of gravity increases, mechanical forces become more important than the chemical ones in determining the characteristics of the soil mass.

2.1.2. Electrical properties of clay minerals

Clay particles are characterized by a net negative electrical charge, caused by being combinations of tetrahedral and octahedral sheet silicates where certain cation substitutions can occur within the sheet structure. In this process, known as *isomorphous substitution*, the original cations in the silica sheets (represented by black spheres in Figure 2-1) are substituted by other cations with smaller valence, resulting in a final negative net charge (Bennett, Bryant & Hulbert, 1991). Because of their platy shape and their very small size, the ratio between the surface area of clay minerals and their mass can be very high. Therefore, properties and behavior of clays are to a great extent controlled by surface forces. The charge unbalance can be compensated by internal adjustments of the solid lattice, by cohesion with the surface of another element of the same substance or by attraction and adsorption of molecules from the adjacent phase (Mitchell and Soga, 2005). The latter solution is common, and cations are attracted and retained on the surface of the particles. Since these cations can be substituted anytime by other cations, also of other types, they are called exchangeable cations. Løken (1968) asserts that monovalent cations such as sodium or potassium are more likely to be replaced by cations of higher valence such as calcium or magnesium, but these bivalent cations are less apt to force into solution trivalent ions, like trivalent iron or aluminum, and take their place as adsorbed cations.



Figure 2-1: Octahedral (left) and tetrahedral (right) silica sheets (from http://claymin.geoscienceworld.org)

2.2. Pore water

The liquid contained in most soil systems generally consists of water and a variety of types of dissolved electrolytes in different proportions. Organic compounds instead are abundant in soils contaminated by spills or leachate. Type and amount of ions that can be found in determinate pore waters are a direct consequence of the original depositional environment and the geological processes the soil deposits have undergone. Water forms a polar molecule with uneven charge distribution, which is therefore attracted to the ions dissolved in solution. Ions are attracted to the side of the water molecule with opposite electric charge and will eventually hydrate.

A list of the most abundant ions dissolved in seawater, which is the initial environment where marine soils are formed, can be seen in Figure 3-5. The mutual proportions between the ionic species typically found in Norwegian clays is somewhat different, but still the most common cation species in marine soils are sodium, potassium, calcium and magnesium. Sulfate, chlorine, phosphate and nitrate are common anions, but a significant amount of carbonates and bicarbonates can be found as well. In residual and non-marine soils instead, sodium is less common that calcium and magnesium respectively, but more frequent than potassium. According to Rosenqvist (1954) sodium, magnesium, chlorine and sulfates are still traces of the original sea water composition, while calcium, potassium, carbonates and bicarbonates result from weathering reactions.

2.2.1. Changes in pore water chemistry

The original chemical composition of the pore water can change as a consequence of several geological (physical) and chemical processes. Leaching for instance can remove electrolytes from a given site and eventually transport them to another one. In the new environment, chemical weathering reactions with clay particles can take place and cations can be exchanged with the silica sheets. Some of these chemical reactions do not affect deeply the structure of the clay particles involved, but they still result in changes of the physical properties of the soil (Eberl et al., 1984). The process known as isomorphous substitution is the most frequent cause for cation exchange between clay particles and adjacent phase. The ease which cations in the mineral lattice are replaced with depends on their valence, relative abundance and size. Furthermore, environmental conditions like temperature and the clay mineral species itself play a major role in this process. The two general principles that regulate cations replace the larger ones and higher valence cations are replaced by ones with lower valence. Changes in the relative amounts of different ion types usually have a greater effect on the remolded shear strength than on the undisturbed strength as they would mainly interfere with the tendency of the suspension to re-flocculate.

2.3. Interactions in the soil-water-electrolytes system

The concepts introduced in the present section will help clarifying the statements of Paragraph 2.2.1. Clay particles balance their negative surface net charge by adsorbing cations from the adjacent phase. The adsorbed cation species change as the chemistry of the pore water is altered. Excess cations can be found as constituents of salts, eventually dissolved in pore water when present. Interactions in the soil-water-electrolyte system are hence controlled by factors such as electrolyte concentration and physical environment, and take place continuously, starting from the very first instants of soil formation. The characteristics of the diffuse double layer hereby presented affect the flocculation process during clay deposition, which in turn will determine how the soil will weather.

2.3.1. Diffuse double layer

Since the surface of clay particles is characterized by a negative charge, the concentration of cations in its proximity is high compared to the cation concentration at a certain distance from particle surface because of electrostatic interaction forces. The tendency of the two concentrations to even out is limited by the constrictions imposed by the electric field originating from the clay particle surface and its effects on the single cation species. The distribution of monovalent ions in the close surroundings of a clay particle's surface is therefore usually represented by two curves, representing cation and anion concentrations, which converge to the same asymptotical value. The term diffuse double layer then usually indicates the system composed of the charged clay particle surface and the distribution of adsorbed charges in its adjacent phase.



Figure 2-2: Schematization of the diffuse double layer (from appliedgeophysics.lbl.gov)

The most common double layer theory was developed by Derjaguin & Landau in 1941 and further extended by Verwey & Overbeek in 1948, and is referred to as the DLVO theory. Its ability to give a quantitative description of phenomena occurring in real soils is fairly limited (Bostrom, Williams & Ninham, 2001), but an understanding of the elements involved in the theory can be useful since the properties diffuse double layer actively affects the fabric of clayey soils during their deposition and formation. It is especially the thickness of the diffuse double layer that determines the fabric of a fine grained soil. As a result of a mathematical analysis of the phenomenon, double layer thickness can be calculated as:

$$t = \sqrt{\frac{\varepsilon_0 DkT}{2n_0 e^2 v^2}} \qquad \qquad Equation \ 2-1$$

The terms that appear in this expression are:

- Permittivity of vacuum ε₀ (constant)
- Dielectric constant D, defined as the ratio between the permittivity of the medium ϵ and the permittivity of vacuum ϵ_0
- Boltzmann constant k (constant)
- Temperature T
- Concentration of ions n₀
- Electronic charge e (constant)
- Ionic valence v

Hence, assuming all the other factors are kept constant, the thickness of the diffuse double layer is inversely proportional to the square root of the ion concentration, and again inversely proportional to the ionic valence of the species involved. The actual effect of a variation of any of the terms that appear in Equation 2-1 is somewhat different than the one that can be calculated: increases in electrolyte concentration have proven to reduce the thickness of the double layer more than what the theory states, and the presence (also in small amounts) of multivalent cations has deep effects on mutual interaction between different diffuse double layers (Mitchell and Soga, 2005).

2.3.2. During deposition: flocculation

Since most of the soils are usually transported away from the place they originate from, they can eventually deposit in water. The way clay particles arrange when they sediment from suspensions is usually more complex than the way coarse grained materials do. Van Olphen (1977) defined and described the modes of particle association in clay suspensions using the concepts of aggregation (face to face contact) and flocculation (edge to edge or edge to face contact). Basically, particles can be found either flocculated or deflocculated, in an aggregated or dispersed state: the factor that determines how "open" the soil structure will be is the thickness of the diffuse double layer.



Figure 2-3: SEM micrographs from kaolinite suspensions in the absence (a and b) and presence (c and d) of a flocculant agent (from Zbik et al., 2008)

Particle association during deposition is the starting point in the determination of soil fabric and its structure. How the particles will associate depends on the chemical properties of the depositional environment as stated in the principle of chemical irreversibility. Recalling the concepts presented in paragraph 2.3.1, the thicker the diffuse double layer, the smaller the tendency for particles in suspension to flocculate (Mitchell and Soga, 2005). Thus, clay particles in water rich in electrolytes are more likely to flocculate giving rise to a porous structure with open voids. The high availability of dissolved ions significantly reduces the thickness of the diffuse double layer and the intensity of repulsive electrostatic forces. In fresh water instead, clay particles tend to align to each other face to face, generating an aggregated structure that does not leave much space for wide voids. It is not uncommon though to find aggregated clusters that have flocculated (Lancellotta, 2004).

2.3.3. After deposition: weathering

Chemical and biological weathering processes can potentially completely change the physical and chemical properties of a soil mass. During these processes some materials are broken down and some new ones are formed (as what happens with clay itself). Since water is required in order for most of the chemical weathering processes to take place, it directly affects the pore water chemistry by changing types and concentrations of ions in solution. As a consequence, the flocculation process after soil is remolded can be altered. This however does not necessarily lead to lower remolded strength. The most common chemical reactions that weather down geological materials are hydrolysis, chelation, cation exchange, oxidation and reduction and carbonation. Hydrolysis dissociates water molecules yielding H⁺ ions capable of replacing existing cations in the mineral lattice. Basically, in acid environments with high availability of H⁺, such substitutions can be abundant. By chelation, complex minerals are broken down and their metal ions are removed from solution because of further bonding with other chemicals. Oxidation and reduction change the valence of cations and make new reactions possible. Finally, with carbonation it is possible to bind carbonate or bicarbonate to other chemical compounds.

2.4. Quick clay

All the concepts illustrated in the paragraphs above contribute to understanding how quick clay are usually formed and why they exhibit such extreme characteristics. Quick clays are most commonly clays consisting of non-swelling clay minerals that have deposited in marine environments and have been leached by fresh water as a result of geological processes such as land heave. Some non-marine clays though display typical quick clay behavior when organic compounds are present in their pore water, with similar effects (Lundström, Larsson & Dahlin, 2009). The cations that could be found in the original pore water significantly decrease in concentration. Low salt content, lower than 2 g/l according to Torrance (1974) is a necessary condition for marine clay to become quick, but it is not sufficient: leached clays that have undergone deep weathering do not exhibit the typical quick clay behavior. Nonetheless, quick clays with salt content as high as 5,6 g/l have been reported in Sweden by Andersson-Sköld et al. (2005).

After leaching, the soil skeleton maintains its aspect but the electrical forces that hold the clay particles together become increasingly repulsive, since the diffuse double layer at this stage, according to Equation 2-1, has a much greater thickness than when the particles flocculated during deposition. What is left then is a soil with a brittle solid structure and large voids filled with fluid. When the soil skeleton is destroyed, it collapses onto its own pore water and its consistency consequently turns into something very similar to a viscous fluid (Lancellotta, 2004). The scarcity of dissolved cations prevents a re-flocculation of the suspension, and given the high water content the remolded shear strength is consequently very low. Quick clays typically have water content higher than liquid limit, hence liquidity index greater than 100%. The relatively high water content is the result of flocculation during the deposition process, but the decrease in liquid and plastic limits that cause an increase in liquidity index is caused by leaching, ion exchange or the action of dispersing substances (Rankka, Andersson-Sköld, Hulten, Larsson, Leroux & Dahlin, 2004).

Only laboratory testing is able to prove the quick behavior of a given clay. According to Norwegian standards, a clay is quick when its remolded shear strength is lower than 0,5 kPa and its sensitivity (ratio between undisturbed shear strength s_u and remolded shear strength s_r) is higher than 30 (NGF Melding nr. 2). In Sweden for instance the definition of quick clay is slightly different since its remolded shear strength must be lower than 0,4 kPa and its sensitivity higher than 50 (Karlsson and Hansbo, 1989). In Canada sensitive clays are those with remolded shear strength lower than 1kPa and liquidity index higher than 120%.

3. Resistivity

3.1. Theory

When electric current is streaming inside a material, it meets a certain resistance to its flow. As a result, the potential V drops if measured in two points along the direction of the flow. The resistance R is inversely proportional to the cross sectional area A and directly proportional to the length L of the object current is streaming through. These two concepts are formalized as:

$$R = \frac{\Delta V}{I}$$

$$R = \rho \frac{L}{A}$$
Equation 3-1
Equation 3-2

The proportionality constant ρ is called electrical resistivity and in an electrical circuit it can be calculated as:

$$\rho = \frac{\Delta V L}{I A}$$
 Equation 3-3

and is expressed in Ohm-meters (Ω m). In electrically homogeneous materials the real resistivity is measured straight away, whereas in inhomogeneous materials the measured resistivity is a weighted average of the featured real resistivity values and it is called apparent resistivity. Ohm's law (Equation 3-1) can also be written in vector form:

$$\rho = \frac{E}{J}$$
 Equation 3-4

where \mathbf{E} is the electric field and \mathbf{J} is the current density. If current is put in the ground by means of a single point-like electrode (a source), it will start flowing in all directions inside the semi-space defined by the ground itself. If the ground is electrically homogeneous, the voltage drops will define hemispherical equipotential surfaces. Current density then decreases as the surface of the hemispheres gets larger and larger, since the same current intensity must cross increasingly broader surfaces. The electric field is also equal to the negative gradient of potential.

$$J = \frac{1}{2\pi r^2}$$
 Equation 3-5
$$E = -\frac{dV}{dr}$$
 Equation 3-6

$$\rho = -\frac{dV \, 2\pi r^2}{dr \, I} \qquad \qquad Equation 3-7$$

$$dV = -\rho \frac{l}{2\pi r^2} dr \qquad Equation 3-8$$

$$V = \int dV = -\int \rho \frac{I}{2\pi r^2} dr = \rho \frac{I}{2\pi r}$$
 Equation 3-9



Figure 3-1: Current lines and equipotential surfaces generated by a current well and sink (from www.ngi.no)

If a current sink is added at a certain distance from the source, then the potential distribution in the ground will be different, as shown in Figure 3-1. In the sink B (refer to Figure 3-2) current will flow with the same intensity but with opposite sign with respect to the source A. Still, according to the principle of superposition, the potential at any point P in the ground is equal to the sum of the voltages from the two electrodes. So if the potential is measured in any two points M and N it will be equal to:

$$V_{M} = \rho \frac{I}{2\pi} \left[\frac{1}{AM} - \frac{1}{MB} \right]$$
Equation 3-10
$$V_{N} = \rho \frac{I}{2\pi} \left[\frac{1}{AN} - \frac{1}{NB} \right]$$
Equation 3-11

The potential drop between point M and point N can be written as:

$$\Delta V = V_M - V_N = \rho \frac{I}{2\pi} \left\{ \left[\frac{1}{AM} - \frac{1}{MB} \right] - \left[\frac{1}{AN} - \frac{1}{NB} \right] \right\}$$
 Equation 3-12

giving the following expression for resistivity:

$$\rho = \frac{2\pi\Delta V}{I} \left\{ \left[\frac{1}{AM} - \frac{1}{MB} \right] - \left[\frac{1}{AN} - \frac{1}{NB} \right] \right\}^{-1} = RK \qquad Equation 3-13$$

K is known as the *geometrical factor* and R is the measured resistance. The expression given above means that ground resistivity can be measured using two pairs of electrodes, one sending in and current, the other one measuring the voltage drop. The geometrical factor is a function of the spacing between electrodes as stated in Equation 3-13.



Figure 3-2: Generalization of an electrode array (from Reynolds, 2011)

3.2. Resistivity in soils

Excluding soils containing highly conductive minerals, where electricity flows because of the movement of electrons in a lattice, electricity is generally conducted by ions. Ions are several orders of magnitude larger in size than electrons and are furthermore found in hydrated form, surrounded by water molecules. In some cases hydrated ions and pores in the soil have comparable size and their flow is therefore hindered. Besides this consideration, resistivity in a soil is mainly determined by the electrical conductivity of its pore water and by its fabric, especially grain size distribution and texture. Temperature, saturation and mineralogy also have an impact on the measured bulk resistivity. While the mechanisms that control bulk resistivity in sands and other geological materials like rocks are fairly well understood, the number of parameters actually influencing resistivity in natural clays is large, and to what extent each of these affect the conductive properties of the soil still remains unclear.

3.2.1. Measuring soil resistivity

For geotechnical purposes, electrical resistivity can be measured both in situ and on samples retrieved for laboratory testing. Field measurements are commonly carried out by performing an Electrical Resistivity Tomography (ERT) or R-CPTU soundings. Kalscheuer et al. (2013) however have also applied different electromagnetic geophysical methods such as radiomagnetotellurics and controlled source magnetotellurics with success at Smørgrav, a research site of NGI featured in this study.

ERT's are capable of giving a 2D image of the subsurface along a chosen profile, which can also be hundreds of meters long. Electrode arrays are placed along the direction of the planned section with an initial spacing, and then the whole array is shifted along the profiling line. Once the line is scanned with the first electrode spacing, the spacing is increased and the lined is scanned again. The depth that electrodes are able to pick up signals from is proportional to the spacing between the current electrodes. This procedure is repeated until the desired investigation depth is reached. By performing measurements on several parallel and perpendicular sections it is possible to extrapolate a 3D image of resistivity variations in the ground. Raw data measured in the field gives the apparent resistivity of the ground. The data is then inverted in order to get a geological model of the subsurface. If the inversion is correct then the true resistivity from the different parts of the model will be very similar to the actual resistivity of the corresponding part in the ground

In order to achieve a significantly higher accuracy, it is necessary to perform the measurements directly in the soil mass. With R-CPTU soundings it is possible to obtain a detailed one-dimensional resistivity profile along the length of a borehole. The measured resistivity represents a weighted average of the values found in a small volume of soil around the conductivity probe, and can therefore be considered as the true resistivity the soil penetrated by the piezocone.

It is also possible to measure electrical resistivity on clay samples in laboratory conditions. A simple way of performing such measurements is placing two metal plates at the two opposite sides of a sample and reading the resistance the sample yields. A similar procedure was used by Ottesen (2009), but issues concerning repeatability of the measurements and choice of the material the

plates were made of emerged from that experience. More sophisticated custom built cells that make use of electromagnetic radiation, where slurries can also be placed overcoming the problem of measuring with the previous method remolded samples, are presented in Cerato and Lin (2012).

Measuring resistivity in soils using direct current can induce undesired polarization effects that are often irreversible. For this reason it is common practice to use alternating current, which implies deciding at what frequency, or in what frequency range, the measurements should be carried out. Conductive properties of clays are frequency dependent and can be studied either by direct measurement of the impedance (equivalent to resistance in direct current circuits) or by measuring the dielectric permittivity of the medium. The frequency dependence of the dielectric permittivity is usually called dielectric dispersion or relaxation. Both impedance and permittivity are complex quantities and can be divided into a real and an imaginary component. The real part of dielectric permittivity is univocally related to the soil's electrical conductivity, and this characteristic is used in several remote sensing geophysical methods as well (Reynolds, 2011). Furthermore, an analysis of the dielectric relaxation is able to give information on the soil's geochemistry, which includes mineralogy and pore water chemistry (Cerato and Lin, 2012)

3.2.2. Characteristic values

In geotechnical engineering electrical resistivity measurements are believed to have a great potential in order to locate and map quick clay formations in a faster and more effective way. Different soil types have different characteristic resistivity values which can be used to identify them. Unfortunately these values are often comprised in overlapping ranges, thus giving rise to interpretation problems. Resistivity measurements alone cannot be used for geotechnical engineering purposes, but must be paired with other common geotechnical investigations.

Specifically in leached marine clay, which can potentially be quick, there are different indications on where the upper and lower bound of the characteristic values should be placed. Solberg et al. (2008) proposed the range 10 Ω m to 80 Ω m based on a survey in Buvika, but suggested to extending the upper limit to 100 Ω m according to data collected in Rødde (Solberg et al., 2012). Both sites are located in Norway in the Sør-Trøndelag region. Lundström (2009) then gives indications that clay with resistivity as low as 5 Ω m can be quick. However the most commonly accepted resistivity interval for possible quick clay is 10-100 Ω m, which is a wide range considering that there is a factor of ten between the upper and the lower bound. The table below gives an overview of the resistivity ranges considered to be characteristic of different soil types by Berger (1980).

Soil material	Resistivity range
Unleached marine clay	1-20 Ωm
Leached marine clay	20-90 Ωm
Clay, dry crust	70-300 Ωm
Silt, saturated	50-200 Ωm
Sand, saturated	200-1000 Ωm

Table 3-1: Resistivity intervals corresponding to different soil types (after Berger, 1980)

3.2.3. Resistivity and geotechnical parameters

Despite ongoing research, there is still no complete understanding on which soil properties control the measured resistivity values. The amount of salt dissolved in pore fluid is probably the most relevant factor that controls resistivity in marine clays. Long et al. (2012) have gathered data from sites in southern and central Norway, finding a very strong correlation between salt content and resistivity (Figure 3-3). What can actually be seen is that at high salt contents, more than 8-10 g/l, resistivity tends to constant values around 5 Ω m. As the salt content decreases reaching 5 g/l, resistivity rapidly increases, approaching 100 Ω m at salt content levels lower than 2 g/l. Salt content dissolved in pore fluid lower than 2 g/l though, as proposed by Torrance (1974), is not a sufficient condition for quick clay. Clays deposited in non-marine environments may also have very low salt content. For a more detailed analysis then, the influence of the type of salt and the valence of the dissolved ions should also be taken into consideration.



Figure 3-3: Soil resistivity as a function of salt content as found in five different Norwegian sites (from Long et al., 2012)

Long (2012) also investigated the relationship between resistivity and clay content and between resistivity and plasticity index. Clay content is expected to be inversely proportional to measured resistivity since the ions on the clay particles' surface facilitate the flow of electric current. Deposits in sites with lower clay content naturally tend to show higher resistivity values. This dependency on clay content is also highlighted in Simoni and Vannucchi (2006), but in a completely different context. In their work, they measure conductivity using a custom built R-CPTU probe on artificially prepared samples consisting of sand-clay mixtures with clay percentages ranging from 1% to 10%. Two sodium chloride pore water concentrations are compared, 0 g/l and 100 g/l. While there is no substantial variation in conductivity at extremely high salt content, the increment in conductivity in absence of NaCl is by about 25% at the two limits of the clay content.

As long as plasticity is concerned, in Long (2012) high resistivity values occurred with low plasticity indices, but the scatter in resistivity values in medium plastic clays (IP between 10% and 20%) is significant. Since remolded shear strength is directly related to the salt content, it is also possible to see a sharp drop in resistivity as remolded shear strength increases. Despite this strong dependence, clays with remolded shear strength higher than 0,5 kPa may show resistivity values between 10 Ω m and 100 Ω m, and silty clays with quick behavior might have resistivity exceeding 100 Ω m.

3.2.4. Pore water conductivity

Seawater is the environment where most quick clays have deposited during the last glaciation, therefore an overview of it electrical properties is hereby presented. Seawater represents in many cases the original conditions from which clay deposits have evolved and turned into at present date. Park and Burt (1965) quantify the contribution to the total conductivity of the different salts and electrolytes dissolved in seawater at 23°C. A whole 88% of the total conductivity is due to the presence of only two salts: 73% is due to sodium chloride NaCl and another 15% can be imputed to the dissolution of magnesium chloride MgCl₂. When looking at electrolytes instead, 93% of the total conductivity of seawater can be ascribed to the presence of chlorine Cl⁻ (64%) and sodium Na⁺ (29%). These relative contributions hold when the relative abundances of the involved chemicals are those reported in Figure 3-4 and Figure 3-5.

Electrolyte	Equivalent/ liter*	Weight (%)	Conductivity (%)
NaCl	0.4192	68.08	73
$MgCl_2$	0.1092	14.45	15
Na_2SO_4	0.0576	11.36	5.8
$CaCl_2$	0.0207	3.20	3.1
KCl	0.0093	1.93	2.1
$NaHCO_3$	0.0024	0.557	0.21
KBr	0.00084	0.278	0.19
H_3BO_3	0.00044**	0.075	
$SrCl_2$	0.00032	0.070	0.05
NaF	0.00007	0.009	

Figure 3-4: Percentage contribution of various electrolytes in sea water to its overall electrical conductance at 23°C (from Park and Burt, 1965)

Ion	Equivalent/liter*	Weight (%)	Conductance (%)
Na ⁺	0. 483	30.7	29
Mg^{+2}	0.109	3.7	2.7
Ca+2	0.021	1.2	0.77
K^+	0.010	1.1	1.1
Sr^{+2}	0.0001	0.0	0.004
Cl-	0.558	55.2	64
SO_4^{-2}	0.057	7.7	2.3
HCO3-	0.002	0.1	0.06
Br ⁻	0.001	0.2	0, 12

Figure 3-5: Percentage contribution of major ions in sea water to its overall electrical conductance at 35‰ and 23°C (from Park and Burt, 1965)

If conditions for chemical weathering are unfavorable and the pore water composition is not affected by severe leaching or other geological processes, it is reasonable to expect that its properties are still similar to the ones illustrated above. In the previous chapter though, much has been said concerning the chemical processes taking place in the pore water that can potentially lead to a complete alteration of its original characteristics. Hence, it often happens that the electrolytes found in pore water in leached clays are different from those reported by Park and Burt (1965) and occur most certainly in different relative amounts. McCleskey (2010) performed a vast number of measurements on many different salt species in order to determine the specific conductivity of every electrolyte involved in his study. The final goal of that work is providing a tool that can successfully calculate electrical conductivity in natural waters once their chemical composition and their temperature are known.

3.3. Models

Since describing soils in terms of the factors constituting their fabric is a complex task, theoretical equations capable of calculating a soil's bulk resistivity have yet to be developed. Attempts to describe the behavior of different soil types by using simplified empirical models, however, have been more successful. Such models take into consideration some of the physical properties that are easiest to measure, as for instance pore water conductivity or soil's dielectric properties (Persson, 2002).

3.3.1. Granular soils

The models proposed for granular soils are based on the assumption that the flow of electricity in the soil mass happens only through the pore water, hence the solid particles are not conductive.

Formation Factor: The concept of Formation Factor was introduced by Archie in 1942. It simply states that in clean saturated sands and sandstones there is a direct proportionality between the bulk resistivity ρ_t and the pore water resistivity ρ_w . The proportionality factor is the Formation Factor F:

$$F = \frac{\rho_t}{\rho_w} \qquad \qquad Equation 3-14$$

An empirical correlation expresses F by means of the soil's porosity n:

$$F = n^{-m}$$
 Equation 3-15

The value of the empirical exponential factor m ranges from 1.3 for loose sands to 2 for highly cemented sandstones.

Other models: other resistivity models find more complex correlations between the Formation Factor and soil properties that are introduced in their basic assumptions. The Capillary Model for instance postulates that electricity flows through a number of imaginary tubes formed by the interconnection between the pores. In this case F is correlated to the soil sample's porosity and the ratio between the length of these tubes and the actual length of the sample, called tortuosity. If the

sample's porosity is known, tortuosity can then be used to calculate the soil's hydraulic conductivity. A much more complicated expression appears in the Cluster Model where the soil is structured as clusters and electricity is allowed to flow through the inter-cluster voids, through the intra-cluster voids and through a combination of the two. This model appears to be well-suited for highly conductive pore water systems (Mitchell and Soga, 2005).

3.3.2. Clays

The models developed to describe fine grained soils also consider the ability of the ions concentrated on the surface of the negatively charged particles to conduct electricity. For this purpose, the resistivity of the solid phase ρ_s is introduced as a parameter.

Two-Parallel-Resistors Model: In this model the soil's resistivity is imagined to be equivalent to the one of a system composed by two parallel resistors, one representing the solid phase and one representing the liquid phase (Waxman and Smits 1968). It is more convenient to express the relation between the parameters in terms of electrical conductivity:

$$\sigma_t = X(\sigma_w + \sigma_s) \qquad Equation 3-16$$

The proportionality constant X is an equivalent of the inverse of the formation factor F. The twoparallel-resistors model is most successful when describing soils with highly conductive pore water. The shortcomings of this simple model, which nevertheless yields good fits of ρ_t versus ρ_w in diverse geological materials such as granite (Matsui et al., 2000), are mostly related to the uncertainties concerning ρ_s . The first issue is determining a sufficiently accurate value of ρ_s . Assuming ρ_s to be constant for instance does not take into account its dependency on the electrolyte concentration in the pore water, just as the same problem would occur if the conductivity of the dry sample were to be measured.



Figure 3-6: Idealization of the Two-Parallel-Resistors Model

Three-Element Network Model: A third resistor, actually proportional to the soil resistor and the water resistor put in series, is added as a possible path for the flow of electricity. Empirical constants then multiply each element of the system in order to account for their relative influence on the final result, thus expressing bulk conductivity as follows:

$$\sigma_t = \frac{a\sigma_w\sigma_s}{(1-e)\sigma_w + e\sigma_s} + b\sigma_s + c\sigma_w$$
 Equation 3-17

Since e is the soil's void ratio, the meaning of the constants a, b and c and the equivalent resistor model would then be:



Figure 3-7: Idealization of the Three Element Network Model

Such a model allows for a better fit with the data also for lower values of pore water conductivity. The empirical constants a, b, and c would then be obtained by statistical regression of the data. Nevertheless, the issues related to the conductivity of the solid particles are the same as those presented for the previous model.

4. Background of the sites

4.1. Esp in Byneset

On January the 1st, 2012 a quick clay slide took place in Esp in Byneset just outside Trondheim, Sør-Trøndelag, Norway. The slide scar is about 150 m wide and 450 m long and the material flowed about 870 m away from its original site.

In connection with this event, Trondheim municipality, NGI and NGU have carried out investigations in the area that all indicate the presence of quick clay. More investigations with special focus on sample collection for laboratory testing have been completed in the context of the NIFS project (NIFS Data Report N.34, 2012). In addition to these investigations, the Geotechnical Division of NTNU carried out more measurements and collected more samples from the site.

Norway's Geophysical Survey NGU has also produced subsurface 2D electrical resistivity profiles, showing that not far from the studied borehole (H1101), resistivity ranges from approximately 80 Ω m to around 20 Ω m. Although the values do not match perfectly, its trend with depth agrees fairly well with the one measured with R-CPTU (Solberg, Dalsegg, L'Heuereux & Rønning, 2012).



Figure 4-1: Overview of ERT profiles and boreholes at Esp (from NGU)

4.2. Leira

Field investigations at Leira have been carried out by Multiconsult AS as part of a project for quick clay mapping commissioned by NVE. The goal of this campaign is to update the locations where quick clay can be found and their extension, and to assess the risk connected to quick clay occurrence. The site has a quite irregular topography, with ravines and fairly steep slopes, but nonetheless it is densely built. The borehole included in this study is surrounded by a small parking lot, a house built on two levels and a road.



Figure 4-2: Map over quick clay slide danger in the Leira-Fossegrenda area (from www.skrednett.no)

4.3. Dragvoll

The area surrounding the NTNU campus at Dragvoll is currently used mostly for farming purposes. The test site is located in a field which is only very slightly sloping towards northwest. The ground is surrounded by two creeks, a smaller one on the southwestern end and a larger one on the northwestern boundary. A paved road and a rock outcrop covered in high tree vegetation surround the area respectively on its northeastern and its southeastern sides. The area is also used for research purposes within salt diffusion in clay, and the soundings carried out in relation with this work are located around 15 meters southwest of the salt wells placed there.



Figure 4-3: Map of the Dragvoll site showing the position of the salt wells, of ERT profile and of boreholes D1, D3 and D4

Dragvoll is known to have very soft marine clay sediments, found in fairly homogeneous deposits. Data from seismic reflection investigations show that bedrock is approximately 40 m below the surface, and highlight the presence of a thin reflector around 10 m depth in the area where the R-CPTUs and the salt wells are located. 2D resistivity profiles of the site show that the soil's resistivity is quite homogeneous and has typical values around 40-50 Ω m (G. Sauvin, personal communication, 2013).

4.4. Smørgrav

Smørgrav is one of NGI's quick clay research sites, located at Vestfossen in the Øvre Eiker municipality in Buskerud, southwest of Oslo. An extensive field and laboratory investigation campaign that combined a variety of investigation methods was undertaken in 2009. Rotary pressure soundings, CPTUs with and without resistivity measurements were all carried out in order to verify the consistency of the results. Undisturbed samples were also taken with 54mm and 72mm pistons to perform a number of laboratory resistivity measurements and geotechnical analyses. Laboratory analyses also include pore water chemistry and mineralogy analyses. The data featured in the present work comes from borehole 505, which was chosen as a reference borehole in NGI's report (NGI Internal Report SIP12 – Correlation between horizontal and vertical resistivity measurements, 2009).

More recent work by Kalscheuer et al. (2013) provided 2D electrical resistivity profiles in the same area, and the correspondence between the values given in the two works is very good. A peculiar feature of this site is the very low resistivity values corresponding to quick clay layers.



Figure 4-4: Subsurface interpretation of Smørgravbased on data obtained by different geophysical investigations and comparison with R-CPTU results (vertical rectanglesseen at y=30m and y=120m)(from Kalscheuer et al., 2013)

5. Field and laboratory work

5.1. Previous field investigations

Data from the R-CPTU soundings performed by NGI using NTNU's conductivity module in the Snåsa municipality are also included in this context. These R-CPTUs were already used in the Fall semester project, but since no soil samples were collected from these boreholes it is only possible to utilize the resistivity and CPTU measurements. For this reason, data from Snåsa will appear only in Paragraph 7.4, nevertheless giving an important contribution to drawing the conclusions of this work. Of the four boreholes that come from the site, boreholes 20, 21 and 22 are actually close to each other located in an area called Jørstad, whereas borehole 35 is located almost one kilometer northeast of the others, in an area named Våg.

5.2. Present field investigations

In connection with this study, R-CPTU soundings were carried out in three different locations in the surroundings of Trondheim. The Geotechnical division of NTNU used its own equipment to perform the soundings at Esp, Dargvoll and Leira, respectively in October 2012, March 2013 and May 2013. The original data from Leira was provided by Multiconsult AS, whose drilling team in November 2012 used a R-CPTU probe produced by Geotech similar to the one owned by NTNU (see Paragraph 0). In May 2013 NTNU went to the Leira site to perform a R-CPTU in the same location of borehole L17, where Multiconsult had run their sounding. In this way it was possible to have a direct comparison between the performances of the two appliances. Measurements at Smørgrav instead were performed by NGI in 2009 using a piezocone produced by ENVI, which can also be fitted with a conductivity module.

NTNU retrieved samples with the 54 diameter steel piston sampler from Byneset, Dragvoll and Leira. At Byneset the samples were taken continuously between 3 m depth to 10,8 m depth. Similarly at Dragvoll, where the shallowest sample though is from 2 m depth, but no material was retrieved between 7 m and 7,8 m depth. In May an additional sample was also collected from Leira between 11 m and 11,8 m depth, since Multiconsult had previously already retrieved several 72 mm samples as deep as 35 m. According to NGI's report on the Smørgrav test site, 72 mm samples were taken from 1 m to 9 m depth while 54 mm cylinders were used for deeper samples.

5.2.1. Equipment description

R-CPTUs generally consist of conventional piezocones, adapted in such a way that a conductivity module can be fitted at a certain distance behind the cone, between the unit containing the cone penetrometer and the battery pack. This means that resistivity is actually measured at a certain distance behind the cone. There are usually four electrodes on the conductivity adaptor, placed with equal spacing. This corresponds to a classical Wenner- α configuration, but other commercialized modules may actually have a different electrode configuration. Current is sent in from the two outer electrodes while the two inner electrodes measure the difference in potential.



Figure 5-1: NOVA piezocone assembled with its conductivity module (from www.geotech.se)

Resistivity probes owned by NTNU and Multiconsult are both produced by the Swedish company Geotech, and their 44 mm diameter is slightly larger than that of the cone penetrometer. This could result in disturbance of the soil in the close surroundings of the probe, but resistivity measurements on intact clay and on remolded clay have proven to be substantially equal (Löfroth, Suer, Dahlin, Leroux and Schälin, 2011). The cone penetrometer itself in both cases belongs to the NOVA series, which allows for wireless data transmission. The conductivity adaptor measures a voltage that is the converted to electrical conductivity (in mS/m) by means of two calibration factors. The middle point of the electrode array, whose length is 15 cm, is about 55 cm above the cone.

The Envi equipment used by NGI has slightly different characteristics: conductivity is measured about one meter behind the penetrometer, its diameter is 36 mm just like the drilling rods, and the electrodes are spaced with a slightly greater distance with respect to the Geotech module, since the distance between the outer pair is 20 cm. As a consequence this equipment samples resistivity from a slightly larger volume of soil compared to the one owned by NTNU, resulting in a lower sensitivity to small features (NGI Internal Report SIP12, 2009). Theoretically, these differences however should not produce significant deviations in the values measured by the two devices if the soil layers encompass the whole probe.

5.3. Principles of CPTU

In a cone penetration test (CPTU) a cone is pushed down in the ground with a constant penetration rate of 20 +/- 5 mm/s. The cone penetrometer is able to measure the cone resistance q_c , the side friction f_s and the pore pressure behind the cone u_2 . The inclination of the piezocone with respect to the vertical axis is also measured to correct the depth for deviations of the system. Measurements are performed with a frequency that ensures detailed information on ground conditions, that is every one or two centimeters of advancement. Combining the data measured versus depth it is possible to assess quite reliably the stratigraphy of the sub-surface and estimate geotechnical parameters directly applicable in geotechnical design.



Figure 5-2: schematization of a CPTU piezocone

The cone resistance q_c though is corrected for the effect of pore pressure, and it is especially important in soft clays where relatively high pore pressure values and relatively low cone resistance values are measured. If the ratio between the cross section of the stem inside the cone penetrometer and the nominal cross section of the cone is referred to as a, then the corrected tip resistance q_t is calculated as:

$$q_t = q_c + (1 - a) * u_2$$
 Equation 5-1

The net tip resistance q_n is defined as:

$$q_n = q_t - \sigma_{v0} \qquad Equation 5-2$$

where $\sigma_{\nu 0}$ is the total in situ vertical stress. It is furthermore possible to obtain dimensionless parameters useful for soil classification combining the ones already available. Q is referred to as the normalized tip resistance and is equal to:

$$Q = \frac{q_n}{\sigma'_{\nu 0}} \qquad Equation 5-3$$

 $\sigma'_{\nu 0}$ is the in situ vertical effective strength. When q_n is normalized by $(\sigma'_{\nu 0} + a)$, where a is the soil's attraction, the deriving parameter is called N_m or cone resistance number. The net tip resistance might as well be normalized by the preconsolidation effective stress σ'_c , obtaining an analogous dimensionless parameter which would account for the effect of overconsolidation. Dividing the sleeve friction by the net tip resistance yields a dimensionless parameter called normalized friction ratio R_f :

$$R_f = \frac{f_s}{q_n} \qquad \qquad Equation \ 5-4$$

The pore pressure ratio B_q can be calculated once the in situ pore pressure u_0 is known:

$$B_q = \frac{u_2 - u_0}{q_n} \qquad \qquad Equation 5-5$$

Robertson (1990) proposed a soil classification method based on these normalized parameters. What is emphasized in this classification method is actually the soil's behavior. The area of the graphs in

Figure 5-3 where data from quick or sensitive clay is meant to be is designated with number 1. There are a number of similar charts proposed by other authors in the past years, some of which use different parameters to classify the soil's behavior.



(*) HEAVILY OVERCONSOLIDATED OR CEMENTED

Figure 5-3: Robertson's soil classification charts from 1990

There are some shortcomings in this interpretation procedure though. Due to the normalization of the measured parameters, intended to counterbalance depth effects, fine-grained soils penetrated at shallow depth where the overburden is small will usually appear as coarser materials. Normalizing then with respect to overburden can be problematic in layered soils with different specific weight, so can it be with respect to in situ pore pressure distribution since the usual assumption of hydrostatic distribution is rarely encountered (Fellenius and Eslami, 2000). Nonetheless Robertson's charts from 1986, which use the cone resistance and not the normalized cone resistance, can still be used.

The dimensionless parameters used by Robertson are not the only ones that can be used for the purpose of soil classification. Fellenius and Eslami (2000) for instance propose other sorts of normalized parameters: an "effective" pore pressure ratio is introduced along with an "effective" cone resistance. These numbers are defined as:

$$B_E = \frac{u_2 - u_0}{u_0}$$

$$q_E = q_t - u_2$$
Equation 5-7

The effective cone resistance is used in the classification method proposed by Fellenius and Eslami themselves in 1997, shown in Figure 5-4, together with the measured sleeve friction. This classification method is going to be used in addition to the one proposed by Robertson, too see whether it is of interest when dealing with sensitive clays.



Figure 5-4: The Eslami-Fellenius profiling chart (1997)

Other very important features of CPTU testing are the possibility of obtaining undrained shear strength profiles and overconsolidation pressure in the penetrated cohesive soils.
5.4. Laboratory testing

Index testing, Atterberg's limits and grain size distribution were carried out in NTNU's geotechnical laboratory. The samples from Byneset were all analyzed by Jeremy R. King between November 2012 and Febraury 2013, and several oedometer and triaxial tests were also performed on that material. The samples from Dragvoll between 2 m and 6,8 m were tested by Karl Fredrik Moe in the 2012 fall semester as a part of his semester project, while analyses on the samples between 8 m and 10,8 m depth were carried out specifically for the present study. Material retrieved from Leira was tested both in NTNU's laboratory and in Multiconsults's one. Results from both sources are hereby mentioned. Pore water of all the samples was also analyzed. Its chemical composition was determined for all the samples from Dragvoll and for some of the samples from Byneset, as part of the doctorate research undertaken by Tonje Heide Helle on salt diffusion in clays. These analyses were carried out by two different laboratories: the Department of Geosciences of the University of Oslo tested the samples from Byneset and the ones below 8 m depth from Dragvoll, while the shallower ones from Dragvoll were sent to the Chemical department of NTNU. The pore water's total salt content was measured in the geotechnical laboratory only on the samples from Leira and on some samples from Dragvoll, because data from Byneset was already available. These latter measurements were performed using the conductivity meter produced by Radiometer Copenhagen. All the tests listed above had also been conducted on the samples recovered from a borehole in proximity of the R-CPTU carried out at Smørgrav, including those concerning pore water chemistry. Moreover, soil mineralogy was also analyzed on those samples.

6. Results

In this chapter the results of the field and laboratory investigations are combined, summarized and interpreted. A discussion on the value, consistency and reliability of the soundings' output follows the description of the results from the single sites. Possible sources of error are also presented for the laboratory results. The detailed account of the Smørgrav site including mineralogy and pore water chemistry can be found in NGI's report and only its main features and characteristics are hereby described.

6.1. Byneset

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6.1.1. R-CPTU
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Figure 6-1 shows the results of the CPTU sounding performed at Esp in Byneset, together with the resistivity profile along the length of the borehole. Pore pressure response is good, and it is always significantly higher than the hydrostatic pore pressure distribution. Only from 5,5 m to 6,5 m depth u_2 decreases noticeably, and it is possible to associate a probable layer of silty material to this response since also tip resistance and side friction exhibit a sharp increase. At depths between 10 m and 20 m q_t , u_2 and f_s increase quite evenly, except for small increments in tip resistance at 12,5 m and 17,5 m depth where very small drops in pore pressure can also be seen.



Figure 6-1: Tip resistance, pore pressure, side friction and resistivity, borehole 1101 Byneset

Because of predrilling, resistivity values can be taken into consideration from 2,5 m depth. Between 2,5 m and 18 m depth resistivity never exceeds 65-70 Ω m: the highest resistivity is reached at around 6,5 m depth, and then it steadily decreases with depth until it touches values around 18 Ω m at 18 m depth. Based on these results, it seems reasonable to conjecture that the thickness of the coarse grained material at 6,5 m depth is not large enough to appear distinctively on the resistivity profile.

Dimensionless CPTU parameters shown in Figure A-2 in Appendix A - Field Investigations, suggest that highly sensitive clay can be found at depths greater than 10 m. From that depth down the normalized tip resistance Q does not show significant deviations from values around 1,75 and the pore pressure ratio B_q exceeds 1. Decrements in B_q can be noticed at 12,5 m and 17,5 m depth, where some stiffer layers were assumed to be. In the same depth interval the normalized side friction R_f increases from 2% to 3%, since the measured side friction does not drop to very low values.

6.1.2. Laboratory

Samples for laboratory testing were retrieved every meter between 3 m and 10,8 m depth. Results of index testing and Atterberg indexes are given in Figure B-1 in the Appendix B - Laboratory testing. Although there are no samples from further than 11 m depth, there is proof of quick clay from fall cone test at 10 m. Water content tends to diminish from around 45% to 30% as depth increases, but it is also possible to notice how the natural water content becomes significantly higher than the liquid limit below 7 m. Clay content also decreases gradually from 39% to 26% just below 10 m, and then it increases again to 33%-34%. Whether this trend continues at greater depth, it is not possible to know.

Salt content, measured in the geotechnical laboratory by means of the conductivity meter, is very low: only 0,5-0,6 g/l below 5,6 m depth. Around 4 m depth salt content is relatively higher, about 2,2 g/l, but this value is still quite low on an absolute scale. Results from borehole 11 in the NIFS report number 34 (2012), which is around 30 m south of the borehole where the samples hereby tested come from, show that salt content just below 4 m depth is reportedly 0,67 g/l while just below 5 m it is 0,74 g/l. A comparison between the different measured salt contents is given in the table below:

Byneset									
Depth (m)	3,75	4,60	5,65	6,70	7,70	8,55		9,65	10,55
Salt (mg/l)	2200	1000	900	500	600	600		500	600
Source*	Geo	Geo	Geo	Geo	Geo	Geo		Geo	Geo
Depth (m)					7,20	8,60	8,75	9,70	
Salt (mg/l)					838	958	981	1867	
Source*					UiO	UiO	UiO	UiO	

Table 6-1: Total salt dissolved in pore water at Esp, from laboratory and chemical analyses.

* Geo=NTNU Geotech. lab; UiO=OsloUniversity Dpt. of Geosciences; NTNU=NTNU Dpt. of Chemistry

6.2. Dragvoll

6.2.1. R-CPTU

Due to uncertainties concerning the equipment when the soundings were carried out at Dragvoll, measurements were repeated several times on two different days. All the boreholes are located only few meters away from each other. On the first day, only the first sounding (denoted as D1) yielded satisfactory results regarding tip resistance and dynamic pore pressure, while all the following were affected by problems with the equipment. Before the second day of testing, the performance of the piezocone was verified in a load cell and the issued that emerged from that assessment were eventually sorted out.

R-CPTUs performed in boreholes D1, D3 and D4 are shown collected together in Figure 6-2. It is possible to recognize a top layer extending to about 3 m depth consisting of farming soil and clay. The top of the sensitive clay layer can be located at 4 m depth, where q_t values are very low and show very little increase with depth. As long as side friction is concerned, the three profiles show the same trend until 8 m depth: stable, almost constant values of 3 kPa (D1 and D4) and 1,5 kPa (D3). After 8 m, side friction recorded in D1 keeps on climbing up to almost 9 kPa at 17,5 m while the other two plots persist in their original trend. At 10,2 m all three soundings indicate the presence of a sand layer, while shallower sand layers do not seem to appear in D1.



Figure 6-2: Tip resistance, pore pressure, side friction and resistivity, Dragvoll

Given how low the resistivity values are and how little variation there is, there are very good reasons to question their correctness. This issue is going to be discussed in detail in Paragraph 6.6.

 B_q , R_f and Q give approximately the same indications in all three boreholes. In all three cases Q behaves exactly as expected when penetrating a layer of quick clay. In boreholes D3 and D4 normalized pore pressure at 4 m depth is already equal to 0,84 and it becomes greater than 1 in both cases before 6 m. Between 7 m and 14 m, where the soundings were ended, B_q is stable around 1,25 and 1,35 respectively. In D1 instead, B_q constantly exceeds 1,6 below 11 m depth. Normalized side friction resembles the trends seen in f_s plots; the lowest values are registered by D3 and steady around 1% throughout the extension of the sensitive clay layer, whereas those registered by D4 are at most 1% larger.

6.2.2. Laboratory

Laboratory testing confirmed the quick nature of the clay, placing its upper limit around 4,5 m depth. Below 5 m depth, remolded shear strength was constantly equal to or less than 0,1 kPa, and very little effort was needed in order to completely remold the clay. Water content has a slightly decreasing trend with depth going from 40% at 2 m depth to 30-31% just below 10 m depth. Anyway, the ratio between natural water content and liquid limit is larger than 1 at every depth, but it becomes greater than 1,6 below 5 m depth. The clay layer can be divided into three sections based on clay content: above 8 m depth particles smaller than 2 μ m account for 33% +/- 3% of the weight of the soil, while this fraction increases up to 44% with a peak of 49% between 8 m and 10 m. Below 10 m clay content is again approximately 30%.

Low electrolyte concentrations were measured in the pore water of this clay. According to the chemical analyses done at the University of Oslo there are as little as 350 mg of dissolved solids per liter of pore water in the sample retrieved from 6,6 m depth. Salt content was measured also in the lab on samples between 8,5 m and 10,7 m, for a direct comparison between the values measured with the conductivity meter: although the match is not perfect, according to both data sets the salt content is lower than 1 g/l.

Dragvoll										
Depth (m)	2,45	3,45	4,45	5,45	6,60	8,35		9,6	10,05	
Salt (mg/l)	729	649	587	500	352	912		838	866	
Source*	NTNU	NTNU	NTNU	NTNU	NTNU	UiO		UiO	UiO	
Depth (m)						8,47	9,17	9,5	10,15	10,7
Salt (mg/l)						750	880	880	750	880
Source*						Geo	Geo	Geo	Geo	Geo

Table 6-2: Total salt dissolved in pore water at Dragvoll, from laboratory and chemical analyses

* Geo=NTNU Geotech. lab; UiO=OsloUniversity Dpt. of Geosciences; NTNU=NTNU Dpt. of Chemistry

6.3. Leira

6.3.1. R-CPTU

Cone penetration testing carried out at Leira outlined an almost continuous presence of clay between 10 m to approximately 33 m depth. Figure 6-3, which features a comparison between the R-CPTUs carried out by Multiconsult and NTNU at only few meters distance, shows that this formation is not uniform. Between 10 m and 15 m tip resistance and side friction are higher than what is recorded at greater depths. This is more visible in the Multiconsult plot than in the NTNU plot, where this difference is smaller. The two plots have an almost perfect match as long as pore pressure is concerned, but there are considerable differences in tip resistance and sleeve friction reading that affect the dimensionless parameters. The circumstances that have lead to such different measurements are not clear. u_2 builds up regularly down to 32 m depth, where at first it decreases by a couple of hundreds of kPa, and then plunges close to zero at 33,5 m. The first decrease is visible in both soundings, while the second one is featured only around 37 m depth, where the measured values exceed 2000 kPa. There is a good match with q_t and f_s , which do seem to indicate the presence of a stiff, coarse grained material at 35 m depth.



Figure 6-3: Tip resistance, pore pressure, side friction and resistivity, comparison between measurements by Multiconsult (blue) and NTNU (red).

Although it has not been verified whether the resistivity values measured by Multconsult are actually correct, they look much more plausible than those picked up by NTNU, hence only the former ones will be hereby discussed. Resistivity measured by NTNU seems to suffer from the same problem that appeared at Dragvoll and will therefore be dealt with in Paragraph 6.6. Between 10 m and 14 m resistivity is stable at values around 80 Ω m, followed by a sort of "transition zone" where values quickly decrease down to about 55 Ω m. Down to 32 m it is possible to notice a steady decrease in resistivity even though the graph is not a smooth line. Finally, resistivity jumps back up to high values up to 100 Ω m where the deep layer of coarse grained material is thought to be.

Q values are similar in the two data sets, and are calculated to be over 10 are calculated for the stiffer clay layer, where B_q is around 0,5 and normalized side friction between 1% and 2%. The two R_f plots are very similar to each other, and although R_f in this depth interval is not very high in absolute terms, it is still significantly higher than the average 0,4% that characterizes the following 16 m. Pore pressure ratio in the sensitive clay layer is significantly larger in NTNU's CPTU, (1 versus 0,8) and is closer to would be expected by a quick or highly sensitive clay.

6.3.2. Laboratory

Laboratory testing was carried out on small 72 mm diameter samples, about 10-12 cm long taken between 15 m and 33 m depth and on one complete 54 mm cylinder from 11-11,8 m. Falling cone test reveals the presence of quick clay between 17 m and 29 m depth. As expected the natural water content in this depth interval is significantly greater than the liquid limit, but due to how the samples were stored it was not possible to measure the natural water content in the two deepest samples at 31 m and 33 m. Index testing was conducted on samples from the same borehole also in Multiconsult's laboratory, and according to the results of both analyses the clay layer between 10 m and 15 m is not sensitive, with undisturbed shear strength reaching peak values of 130 kPa and remolded shear strength around 25 kPa. The oedometer test carried out on a sample from 11,30 m depth shows that the soil is heavily overconsolidated (OCR around 4,6) and the water content is also lower than in the lower layers. Extremely low water contents instead were measured below 33 m depth where visual inspection of the samples highlighted the abundant presence of sand and gravel. There seems to be no clear trend in the clay content at Leira. The measured values range from 29% to 40%, and most likely this is due to the presence of numerous thin layers of coarse grained material. In the layer of stiff clay above the sensitive clay, the fraction of solid particles with size smaller than 2 μ m is 38%, slightly higher than in the deeper layers.

Salt content was measured on every available sample. The results are very similar to those obtained from Byneset, as in the sensitive clay there is as little as 0,72 g of electrolytes dissolved per liter of pore water, while the highest electrolyte concentration is 1,1 g/l. Also in the stiff clay layer the salt content is very low, only 0,54 g/l which is actually lower than in the quick clay.

6.4. Smørgrav

6.4.1. R-CPTU

Figure 6-4 shows the results of R-CPTU soundings as presented in the paper presented by Rømoen et al. (2010). The red markers represent the values used to calculate B_q , R_f and Q, which were then compared to soil properties found from laboratory testing. Very high tip resistance values associated to the upper dry crust are quickly followed by a steadily increasing trend that takes q_t from almost 500 kPa to almost 1000 kPa in the range from 3 m to 20 m depth. Around 19 m depth q_t remains stable under 1000 kPa. Side friction exhibits a similar behavior, increasing until 18 m depth and then decreasing down to zero at 23 m depth. Pore pressure builds up steadily and evenly throughout the whole length of the sounding.



Figure 6-4: Tip resistance, pore pressure, side friction and resistivity, Smørgrav (modified from NGI)

Resistivity decreases from values around 50 Ω m at 2,5 m to 10 Ω m around 9 m depth, reaching a minimum of 3 Ω m below 15 m. There is no significant change in resistivity recordings that corresponds to the decrement in side friction and the stabilization of tip resistance. According to these values, the most likely location of a layer of quick or sensitive leached marine clay is at shallow levels. Unleached clay with lower sensitivity is possibly expected below 8-9 m depth.

Dimensionless parameters portray a slightly contrasting picture. The typical vertical or slightly negative trend of Q is evident below 9 m, though the difference between the calculated value of 14 at 2,5 m and 5 at 9 m is actually not very large. Pore pressure ratio is highest below 20 m where it is very close to 1, but it is stable around values of 0,8-0,85 in the overlying 9 meters. From 4 m to 10 m B_q goes from 0,6 to 0,8 as depth increases. According to the normalized side friction plot, the most sensitive layer is located somewhere between 5 m and 20 m depth since it is in that range that R_f reaches its minimum values. The drop from 2,5% to 1,5% seen at 17,5 m depth is probably due to the fact that side friction f_s was sampled at depth where it peaked, nonetheless there actually is a slight fall in R_f at those depths.

6.4.2. Laboratory

Laboratory testing confirms that the top couple of meters consist of dry crust. Right below the dry crust the natural water content is measured to be close to the liquid limit, but still slightly lower, whereas at larger depths the ratio between water content and liquid limit is consistently greater than 1. It is apparently below 15 m that the two water contents are again equal. The variations in water content reflect to a great extent the variations in remolded shear stress, which indicate the presence of quick clay between 5 m and 12,5-13 m depth. Below 15 m the remolded shear strength is stable around 5 kPa. Clay content in this deposit is not uniform. Above 5 m it is just above 40%, but at 4 m it jumps up to 56%. In the quick clay layer and down to 15 m it ranges from 36% to 44%. Finally, clay content is once again higher (between 55% and 61%) in the deepest meters of the borehole.

The salt content measured in this clay's pore water is the highest among those hereby reported, since it ranges from 1,2 g/l to 4,1 g/l where the clay is known to be quick. There is a constant increase in salt content with depth starting at 10 m below surface, where it is equal to 2 g/l, and at 20 m depth the concentration is as high as 10 g/l.



Figure 6-5: Variation in salt content with depth at Smørgrav (modified from NGI)

6.5. Comments

In this paragraph the contribution of resistivity readings and dimensionless parameters to interpret the subsurface is evaluated, and their ability to give consistent, matching indications is assessed. The features of both field and laboratory investigations that appear very unusual or do not seem to be correct are also pointed out, and a discussion on the reliability of the analyses and the possible sources of error is presented.

6.5.1. Byneset

Indications on the depth of the quick clay layer at Esp are slightly contradictory if the interpretation is based only on the dimensionless parameters which the Robertson charts make use of (see Figure A-3 in Appendix A - Field Investigations). While Q and B_q assume the typical trends and values that characterize sensitive clay, R_f is slightly higher than expected in this kind of soil and it is actually lower where it is known that the clay is not quick. It is still important to recall, though, that the presence of quick clay below 10 m is only conjectured since there is no proof from laboratory data. Resistivity below 5 m ranges from 60 Ω m to 18 Ω m, both values are included in what is generally recognized to be the interval corresponding to leached marine clay. An explanation for this decreasing trend can be found in the NIFS data report n. 34 (2012), which actually indicates that salt content increases up to almost 9 g/l in the deeper layers. This though is only a hypothesis based on data obtained from other boreholes around the slide scar.

6.5.2. Dragvoll

At this site the repeatability of CPTU is satisfactory when considering tip resistance and pore pressure measurements, but there are some discrepancies when sleeve friction is taken into account. Given the characteristics of the clay tested in the laboratory and the ease with which it is remolded, the most likely values of f_s are those recorded during D3. Since the plots of boreholes D3 and D4 are basically parallel and react to the same features in the ground in a very similar way, there is a doubt that something might have affected the zero value readings. Side friction recorded in borehole D1 is not consistent with the behavior of the soil observed in the lab. These soundings and the ERT profiles of the area have given proof that the ground conditions are homogeneous, enough to relate the data from samples retrieved in borehole D1 to the R-CPTU measured in boreholes D3 and D4.

6.5.3. Leira

At Leira the resistivity profile measured by Multiconsult shows features that are consistent with the other parameters measured in the CPTU test. Water content in this layer is some percentage points lower than in the deeper layer and there are no significant differences in bulk density. Pore pressure response u_2 indicates clearly that the clay is not rich in silt, otherwise it would have most likely shown a much more uneven plot, and in fact its clay fraction is slightly larger than in the sensitive layer. It is very unlikely that this layer is not saturated; hence phenomena like those occurring in the dry crust tend to be excluded. Only in his site resistivity shows a change in values that corresponds to a change in soil behavior.

6.5.4. Smørgrav

Data from Smørgrav can give rise to different interpretations depending on what plots are used: there is an apparent conflict between the indications given by the normalized parameters and the resistivity plot. B_q for instance peaks at about 20 m depth, but resistivity there is so low that most of the interpretations would lead to exclude the presence of unleached clay. Laboratory tests in this case confirm the interpretation based on resistivity. R_f on the other hand gives more accurate information on the depth of the quick clay layer between 5 m and 12,5 m. The interpretation based on resistivity in this case could be misleading since between 9 m and 12,5 m all the values are lower than the widely accepted lower bound of 10 Ω m. Therefore, extreme caution should be used before excluding sensitive or quick clay when these small values are recorded. At the same time, it appears that soil resistivity at this site is very low compared to measured salt contents. This could be either due to some fault in the resistivity probe itself or to some other soil characteristics, which might have appeared from laboratory testing. Finally, another curious feature of this clay is that there is barely any improvement in remolded shear stress as the salt content increases below the quick clay.

6.5.5. Reliability, uncertainties and sources of error

Field results

Some issues related to reliability, sources of error and uncertainties must be mentioned. The first potential major source of error is that the four data sets were measured by three different devices, and only for the R-CPTU at Leira there is a direct comparison between the performances of two different probes. Furthermore it is not known if any of the probes are properly calibrated, or how accurate the measurements are. The values measured by NGI's probe though proved to be quite similar to those measured on samples in laboratory conditions and to those reported by Kalscheuer et al (2013), but such a good agreement was not obtained in 2009 with NTNU's probe and samples retrieved by Ottesen (2009).

The issue of calibration was already highlighted by Aasland (2010) when the conductivity of a NaCl solution in water at different concentrations was measured with NTNU's equipment, and then compared to literature values. In that occasion a factor of 2,28 was found between the measured values and the correct ones. Since the conductivity module has to be calibrated with its paired piezocone (R. Sandven, personal communication, 2013), that adjustment could not be applied to the present soundings: the older cone was still produced by Geotech, but it was a Classic and not a NOVA (see Paragraph 5.2.1). A direct comparison between resistivity measured by NTNU's R-CPTU probe and the one owned by NGI is also featured in Aasland (2010), and in this case there a factor of about 1,38 between resistivity measured by the Envi probe and the one recorded by Geotech. In order to achieve this result the correction to the conductivity values mentioned above was also applied.

Laboratory results

The greatest uncertainties and possible sources of error concerning laboratory data are mostly related to the measurement of the salt content. The charts associated to the conductivity meter of the geotechnical lab are not able to accurately convert the readings into salt content when the latter is lower than 1 g/l. The procedure to convert very low readings to total dissolved salts consisted in the following steps:

- The conductance of a NaCl solution with concentration ranging from 0 to 1 g/l was measured with the conductivity meter and a conversion chart from conductance to NaCl was put up. It was found that the relation between salt content and conductance at such low ion concentrations was almost linear. Note that conductance and conductivity are two different entities, since the former is dependent on the measured volume of water (in mS) while the latter is an intrinsic property of the liquid (in mS/m).
- Once the equivalent NaCl content was known, the conductivity of the solution (in mS/m) was calculated dividing the NaCl concentration (in mg/l) by 4,9.
- Finally, the equivalent TDS was found by multiplying the calculated conductivity by 6,8, which is a typical proportionality factor for natural waters. All the proportionality factors were taken from the website of Eutech Instruments (http://www.eutechinst.com /techtips/tech-tips40.htm)

Some inconsistencies were also found in the results of the chemical analyses performed in the NTNU chemical department, since the carbonate analysis was left out. The amount of carbonate ions was then calculated by balancing the electrical charges of cations and anions, assuming that the electrical balance (EB) was exactly 0%. Chemical analyses are usually repeated several times to check that EB is smaller than 5%, but since it was difficult to extract enough pore water from the samples such verification was not possible. The total electrolyte concentration calculated in the manner hereby explained is not exact, but it is still a satisfactory estimate. A calculation of the electrical balance performed with the program PHREEQC would have included all the ionic species and would have therefore given accurate results.

6.6. Issues concerning NTNU's resistivity module

The R-CPTUs at Dragvoll and Leira have proven that the conductivity module owned by NTNU does not measure the correct values. There are several factors that can cause such errors, but most likely they are determined by problems either with the calibration coefficients or with the electric current input. Recalling what was stated in Paragraph 3.1, the equation below allows transforming differences in potential between two electrodes into resistivity when using a Wenner- α array:

$$\rho = \frac{2\pi a\Delta V}{I} = KR \qquad Equation \ 6-1$$

The parameter a is the mutual distance between the electrodes. Since resistivity is a property of the soil, the difference in potential ΔV depends on the current intensity I. If the actual current input is different from the one that is meant to be, which is the current intensity used to calibrate the module, this deviation will be reflected into ΔV .

The calibration coefficients determined by the producer have a role similar to the one of the geometric factor K, but they are meant to calculate conductivity σ and not resistivity:

$$\sigma = A * C^B \qquad Equation 6-2$$

A and B are the coefficients and C is the digital unit recorded by the module. Although it cannot be completely excluded that these coefficients in the NTNU module are not correct, it is anyway extremely unlikely since they are similar to those for the one owned by Multiconsult (see Table 6-3). Figure 6-6 shows a comparison between the digital unit C measured by the two devices in the same borehole at Leira. C has been back calculated from the conductivity values reported in the log files using Equation 6-2. The two plots are supposed to be slightly different from each other because the different probes have different calibration coefficients, but in this case it is evident that the dissimilarity between the measured values is much larger than what it should be.



Figure 6-6: Digital unit C as measured by the two Geotech modules at Leira

It is possible to see that the response of the NTNU probe appears to be somehow dampened, but still able to react to some changes in soil properties. An attempt to find new A and B coefficients was tried in order to make the two conductivity plots match. A summary of the original and modified coefficients can be seen in Table 6-3. The values measured by Multiconsult are assumed to be correct, and are hence used as reference.

Table 6-3: Calibration coefficients	as found by	Geotech (original)	and modified coefficients.
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Figure 6-7: Effect of the modified parameters on the conductivity values measured with NTNU's module.

The two curves turn out to be very similar with the new parameters. Finding these new coefficients was not only important in order to correct the readings at Leira, but for Dragvoll as well. Even though there are no previous R-CPTU data from Dragvoll, there are values from several ERT profiles that can be used for a comparison (G. Sauvin, personal communication, 2013). The 2D profiles show that soil conditions, as long as resistivity is concerned, are very homogeneous and there are no significant deviations from values of 40-45 Ω m. This is exemplified in Figure 6-8, which corresponds to ERT profile 7 (see map of site, Figure 4-3).



Figure 6-8: Dragvoll, ERT Profile 7 (courtesy of G. Sauvin)



Figure 6-9: Dragvoll, conductivity plot before and after correction, and comparison with average depth values calculated from ERT (courtesy of G. Sauvin)

Figure 6-9 shows the effect of the transformation on the resistivity values measured in boreholes D1, D3 and D4, compared with the values obtained by averaging out resistivity from ERT at every depth. Although the plot in the middle is quite "fuzzy" and irregular, which is probably a consequence of the amplification caused by the modified coefficients, the values are compatible with those seen in the 2D profile. This result validates to a certain extent the trustworthiness of the corrections, and data measured by the NTNU conductivity module can still be used if it is inverted and the new coefficients are applied.

7. Correlations

The experimental part of this Master Project is intended as a deeper study of the results obtained in the fall 2012 semester project "Assessment of R-CPTU results in sensitive marine clays". In that occasion, only R-CPTU soundings were available and the main focus was on investigating a possible correlation between the traditional CPTU dimensionless parameters and resistivity values measured with R-CPTU probes. Unfortunately it was not possible to retrieve samples for laboratory testing from the locations involved in that study, and the considerations thereby conjectured could not be verified on the same soils. Correlations similar to the ones described above, as well as other ones, were put up in occasion of the present work using the data obtained from the new test sites, given the availability of samples suited for laboratory testing.

7.1. Summary of previous results

The dimensionless CPTU parameters considered in the semester project were the normalized friction ration R_f and the pore pressure ratio B_q . A direct correlation between these two parameters and the soil's resistivity could not be established, although some kind of mutual dependency did seem to appear. The results concerning B_q were somewhat contradictory and difficult to interpret and explain, whereas those concerning R_f seemed to be easier to understand. Both B_q and R_f were regarded as possible indicators of clay's sensitivity. Marine clays show a sharp increase in sensitivity as the salt content becomes lower than 5 g/l (Rankka et al., 2004), hence an inverse relation between B_q and salt content seemed reasonable. R_f instead was thought to be directly proportional to the salt content. At the same time, salt content is considered to be the main parameter controlling electric resistivity in marine clays.



Figure 7-1: Correlation between sensitivity and salt content (from Long, 2012)

A hypothetical relation between the dimensionless CPTU parameters and resistivity could be supposed: in marine clays B_q is inversely proportional to resistivity while R_f is directly proportional to it.

The results obtained were quite different than how they were expected to be. B_q actually decreased as the resistivity increased, but on the other hand the correlation with R_f was closer to the predicted one. It seemed that the relation between the two quantities was not unique and it depended on an unknown parameter, which was thought to be a physical property of the soil. Robertson (1990) however warns that sleeve friction measurements are less reliable than tip resistance or pore pressure measurements, and it is not excluded that some of the offset between those that appear as different trends, is due to data inaccuracy. The influence of grain size distribution on resistivity was believed to be discriminating factor between the parallel trends, but it was speculated that other factors that could influence both B_q and R_f , such as overconsolidation ratio, could determine which of the parallel trends was the one to follow.

7.2. Correlation between resistivity and physical properties

It seems reasonable to assume that the two main contributions to the final bulk resistivity value of a soil come from the pore water and solid skeleton. Pore water resistivity is fairly easy to measure in the lab, while measuring the conductivity of solid fraction of a soil can prove to be more difficult. When bulk resistivity close to the higher bound of the interval are generally those whose salt content is extremely low. Nonetheless, as explained in Paragraph 3.2, there are a number of factors besides salt content that determine the bulk resistivity of a marine clay. Furthermore, if these factors are pinpointed, the real challenge is quantifying their actual influence on the final resistivity value.

7.2.1. Pore water resistivity

Some empirical models describing the relation between bulk electrical resistivity and the one of its pore water were introduced in Pragraph 3.3. They were separated in two groups, one suited for soils with non-conductive solid particles and the other one for soils with conductive solid skeleton. The models developed for the latter soils have the inconvenience of taking into account the resistivity of the solid particles, which is not always possible to measure. The simplest of the models developed for clean sands normalizes the bulk resistivity with the pore water resistivity, yielding the so-called formation factor F. In clean sands this ratio constant if pore water resistivity is only changing parameter. The concept of normalizing bulk resistivity with pore water resistivity was adopted also in this instance as a starting point to understand how fluctuating F could be in soft clays.

Byneset					Dragvoll				
Depth (m)	TDS (mg/l)	EC (mS/m)	EC/TDS	Depth (m)	TDS (mg/l)	EC (mS/m)	EC/TDS		
7,2	838	105,18	7,97	2,45	729,75	91,80	7,95		
8,6	958	119,28	8,03	3,45	649,74	78,42	8,29		
8,65	981	121,69	8,06	4,45	587,50	70,60	8,32		
9,7	1867	242,21	7,71	5,45	500,44	59,98	8,34		
				6,6	352,65	42,44	8,31		
				8,35	912,00	109,57	8,32		
				9,6	837,92	100,74	8,32		
				10,05	866,35	104,36	8,30		

Table 7-1: TDS, conductivity and proportionality factor from chemical analyses.

The conductivity of the pore water samples sent to chemical laboratories, measured in mS/m, was determined by multiplying the number of dissolved cations (in meq/l) by a factor of 10 as suggested in Appelo & Postma (2005). Such a factor is corroborated also by other sources, as Talling (2009). The table above gives an overview of the conductivity values calculated with this procedure, as well as the ratio between TDS and conductivity.

The proportionality factors given in the table above are somewhat higher than those used to convert the readings of the conductivity meter into salinity as explained in Paragraph 6.5.5, but it must be kept in mind that those were suited for natural freshwaters. The factors hereby obtained were used to calculate the electrical conductivity of the Byneset samples which were not sent for chemical analysis and the conductivity at Smørgrav. Total dissolved salts at Leira were also recalculated using these factors, so as to compare the difference with the previous ones and to determine conductivity consistently. A table reporting salinity and conductivity of all the samples is can be found in Appendix D.

In order to simulate the in situ conditions, water resistivity was adjusted for temperature, measured by the CPTU probe, using the formula given in Equation 7-1. Because no such data was available for Smørgrav, it was assumed that the average temperature in the soil volume was 7,5°C.

$$\sigma(T) = \sigma(25) * [1 + a(T - 25)]$$
 Equation 7-1

The terms that appear in the equation above are:

- $\sigma(T)$, conductivity at temperature T (°C)
- $\sigma(25)$, conductivity at 25°C
- a, empirical coefficient (°C⁻¹)
- *T*, temperature at which conductivity is desired

Hayashi (2003) calculates the empirical coefficient α for a variety of waters with different electrolyte concentrations, and based on the results of his work it was considered reasonable to use in this circumstance the constant value a=0,019 °C⁻¹.



Figure 7-2: Soil resistivity plotted versus pore water resistivity, all sites

Figure 7-2 seems to give two indications on how soil and pore water resistivity relate to each other. Excluding two points from Byneset, one of which represents the sample from 9,7 m depth where the discrepancy between the salt content measured in the lab and the one determined by chemical analysis is very large, it appears that pore water conductivity is the most important factor controlling soil resistivity, but that is true only until ρ_s reaches the threshold value of approximately 11 Ω m. Unfortunately there is only the data from Smørgrav that are included in that range, and this conjecture cannot be confirmed until more data is available. Beyond this limit the two entities seem to be almost independent from each other: soil resistivity at Dragvoll for instance is barely affected by the sharp increase in pore water resistivity, and at Leira there is the variation in bulk resistivity is large when compared to the small change in fluid resistivity. The point representing the stiff clay layer at Leira is the one with highest bulk resistivity. Hence, the chart suggests that the resistivity of the pore water, which basically determined its salinity, stops being the most influential factor controlling bulk resistivity above a certain limit. Furthermore, it must be pointed out that temperature plays a significant role in the relation between water salinity and resistivity: it is therefore simpler to compare the salinity of different samples, but that would not reflect part of the in situ conditions.



Formation Factor F

◆ Byneset (NTNU)
 ◆ Leira (Multiconsult)
 ◆ Smørgrav (NGI)
 ◆ Dragvoll (NTNU)

Figure 7-3: Dependency of the Formation factor F on the soil's resistivity, all sites

With reference to Figure 7-3, the first impression of very low bulk resistivity values measured at Smørgrav is confirmed by the low F characterizing that site. Low F means that bulk resistivity is low compared to water resistivity, and the high F has opposite meaning. It is remarkable how the sample with highest bulk resistivity from Smørgrav, which was retrieved from 2,5 m depth and that is probably still part of the dry crust, has such a low bulk resistivity especially when compared to other samples with similar bulk resistivity. Some points from Dragvoll as well exhibit low F, but they occur at high ρ_w values, where it was suggested that water resistivity lost its main role in determining ρ . On the other hand there is fairly good agreement between the samples with water resistivity close to the threshold value, which are characterized by F between 3 and 4,5 except for a couple of samples from Leira. In this case its bulk resistivity is quite high compared to its pore water resistivity. The amount of available data is not sufficient to determine whether there is a mutual dependency between F and bulk resistivity, whereas the hyperbolic trend in the plot versus water resistivity is only due to the fact that F is plotted against its inverse. In this chart though points seem to align along different hyperbolas, which could be the consequence of another physical property of the soils, possibly density or water content. Points aligned on the inner hyperbolas in fact are those with higher water content.

7.2.2. Pore water salinity

It is common practice to correlate bulk resistivity to the concentration of electrolytes dissolved in the soil's pore water, and several authors have tried to correlate directly the two quantities. Electrolytes though are dissolved in the liquid phase, which is only a certain percentage of the whole system. Hence, correlating bulk resistivity to the salt concentration per unit volume of soil might yield a better correspondence than comparing it to a concentration per unit volume of pore water. The initial assumption needed to calculate this total salt concentration is to consider the density of water constant and equal to 1 kg/l, which is a fairly accurate approximation since deviations from this value in the considered interval of temperature and salinity are very small.

$$S = \frac{M_E}{V_W} \approx \frac{M_E}{M_W}$$
Equation 7-2
$$w = \frac{M_W}{M_S + M_E}$$
Equation 7-3

The terms that appear in the above equations are:

- *S*, electrolyte concentration in g/l or mg/l of pore water
- M_E , mass of the total dissolved salts
- V_W , volume occupied by the liquid phase of the soil
- M_W , mass of the water in a given volume of soil
- *W*, natural water content
- *M_s*, mass of the soil particles

Given the way w is usually calculated (Stanens Vegvesen, 2007), the sum at the denominator represents the mass of the sample after being dried in the oven. The amount of salt per unit weight of the soil is then calculated as:

$$S' = \frac{M_E}{M_S + M_E + M_W} \qquad Equation 7-4$$

Inserting Equation 7-2 and Equation 7-3 in Equation 7-4, the following expression for S' will be obtained:

$$S' = S * \frac{W}{1+W} \qquad Equation 7-5$$

S' as presented in the formulation above represents the amount of salt per unit *mass* of soil since it was assumed that 1 l of water weighed exactly 1 kg. The effect of this correction is visible at low salt contents, where the scatter is somehow reduced, as shown in Figure 7-4.



Salt content

Byneset (NTNU)
 Leira (Multiconsult)
 Smørgrav (NGI)
 Dragvoll (NTNU)

Figure 7-4: Dependency of soil resistivity on total dissolved salt content measured as mg/l of pore water (left) and as mg/kg of soil (right)

What is shown in the figure above basically confirms the conjectures that followed from Figure 7-2: below salt concentrations of 1 g/l of pore water, or equivalently 300 mg/kg of soil, there are factors that become more important than salinity in controlling the soil's resistivity. At such low concentrations, it might also be crucial what electrolyte species are found in the pore water as well as their relative abundance.

7.2.3. Water content and density

Water content and density are two soil properties that are mutually related to each other by the soil's grain density, and both represent the relative abundance of the water phase in the soil system. Since the resistivity of a soil sample is generally higher than the resistivity of its pore water, it is expected that soils with higher water content have lower resistivity. If it is also assumed that the soil is fully saturated, resistivity is expected to be directly proportional to the soil's density. The figure below supports to some extent the conjecture relative to water content, although there is a significant lack of information in the range between 40 Ω m and 10 Ω m.



Byneset (NTNU)
 Leira (Multiconsult)
 Smørgrav (NGI)
 Dragvoll (NTNU)

Figure 7-5: Density and water content versus resistivity

The correlation is not very strong, which suggests that water content is not very high in the hierarchy of the factors influencing resistivity. A very similar picture is portrayed by plotting resistivity versus density, but the scatter in this case is even larger and it does not provide much additional information.

7.2.4. Grain size distribution and clay content

Grain size distribution is an important factor to take into consideration. Different typical resistivity values characterize different soils classified according to their grain size distribution, making electrical resistivity a useful tool for interpreting the subsurface layering. Furthermore, it was previously discussed how the conductive properties of soil change with the conductive properties of pore water depending on the electrical characteristics of the solid grains, which are a direct consequence of their size.



Figure 7-6: Relation between clay fraction and soil resistivity

Although the amount of clay particles contained in a soil are known to a have an influence on resistivity, a direct correlation is very difficult to recognize from Figure 7-6 for several reasons. Mineralogy is independent of the other parameters to which resistivity has been correlated to previously, and it is difficult to account for their effects. Soil at Smørgrav for instance is fatter than the lean clays of the Sør-Trøndelag region, and it has relatively high salt content. In Figure 7-6 it might appear as if resistivity actually tended to lower values as the clay fraction becomes larger, but it is not actually possible to distinguish the contribution of salinity from the contribution of the conductive soil particles.

7.2.5. Comments

The correlations presented in the previous paragraphs indicate that the factors hereby considered all contribute to the final bulk resistivity of a soil. It is also evident that the salinity of the pore water is the factor with the greatest influence, at least until the threshold value of 1 g/l is reached. Below that limit, salinity loses its predominant role in determining resistivity. Correlating directly the physical properties to resistivity does not give enough information to explain which one of them becomes the most significant. From a mathematical point of view, this translates into finding a formulation that allows accounting for the relative importance of all the variables of the equation. It seems reasonable to conjecture though that no specific parameter becomes significantly more important than the others. What appears to be the case at very low salinities is that water content, density (structure of the voids), clay fraction and salt content itself are equally important, and if any these are equal in two samples, it is the combination of the others that decides which of the two samples will have higher resistivity. The predominant role of salinity probably overshadows the effect of other soil properties when the pore water is very conductive, but the same processes might occur in those conditions as well.

The most likely source of uncertainty or error in the correlations above is the limited amount of data. As it was pointed out, the lack of samples with resistivity below 40 Ω m and produces a wide gap in the charts. Furthermore, data from Smørgrav gives suspiciously low resistivity values, and the behavior of that soil might be somehow extreme. It would be therefore interesting to include data from sites where it is known that the clay is unleached, in order to see how those data would fit in the correlations.

7.3. Correlation between resistivity and geotechnical properties

Given the discussion on the effects of pore water chemistry on the structure of fine grained soils, it is reasonable to suppose that a soil's strength and its stiffness are related to its resistivity. Both undrained shear strength and resistivity are "phenomenological" parameters, meaning that they express the effect of a combination of different physical properties of the soil. From an engineering point of view, it is probably more important to understand how resistivity relates to parameters that can be used in geotechnical practice rather than understanding the processes at the micro-scale that determine soil resistivity.

The available data though are only enough in order to try to find a correlation with undrained shear strength, both undisturbed and remolded. The considerations introduced throughout Chapter 2 induce to expecting a stronger relation between resistivity and remolded shear strength rather than undisturbed shear strength because of the role of dissolved electrolytes during reflocculation after remolding. This is actually visible in Figure 7-7, but the chart also shows that there is no unique way of determining soil strength based on resistivity alone: the point representing the stiff clay layer in Leira, in fact, is characterized by resistivity typical of leached clays.



Byneset (NTNU) + Leira (Multiconsult) + Smørgrav (NGI) + Dragvoll (NTNU)

Figure 7-7: Relation between shear strength from falling cone test and soil resistivity

The effect of pore water resistivity on shear strength is even more evident, and the link between pore water resistivity and remolded shear strength is the strongest among those considered in this section. In Figure 7-8, the vertical axis on the right chart has been limited to 6 kPa and the one on the left side has been limited to 60 kPa, in order to show more clearly what is happening below those limits. Only the sample from the stiff clay layer from Leira is not represented. The correlation with undisturbed shear strength appears to be improved as well, but it is still weaker than the other one.



Byneset (NTNU)
 Leira (Multiconsult)
 Smørgrav (NGI)
 Dragvoll (NTNU)

Figure 7-8: Relation between shear strength from falling cone test and pore water resistivity



Byneset (NTNU)
 Leira (Multiconsult)
 Smørgrav (NGI)
 Dragvoll (NTNU)

Figure 7-9: Relation between shear strength from falling cone test and salt content per unit mass of soil

The two figures above are particularly appropriate to emphasize how low the strength of the clay at Smørgrav is compared to its conductive properties. In Figure 7-8, the chart on the left shows that this clay is just as strong as strong as other clays with much lower salt content, and the figure on the right show that neither the remolded shear strength benefits from a higher salinity. The strong effect that temperature has on water resistivity should not be ignored, and therefore it is probably more significant to compare shear strength to salt content per unit weight of soil, but despite the efforts it is difficult to recognize any pattern Figure 7-9.

7.4. Correlation between resistivity and CPTU parameters

CPTU soundings are widely used to interpret subsurface layering based on the values measured in tip resistance, pore pressure, side friction and their mutual proportions. Resistivity can also be used as an investigative tool in addition to the parameters listed above, and in some cases it can provide important information on the soil type and its behavior. The potential of such a tool in identifying possible layers of leached marine clay has been proven in previous circumstances, but it is still unclear whether resistivity can contribute to determining the presence of highly sensitive or quick clay. There is consensus on the fact that resistivity measurements alone cannot succeed in this task, but they can be used to add some information to those given for instance by dimensionless parameters such as those used by Robertson (1990) for his classification charts (Q, B_q , R_f). In this section, the data from the soundings at Byneset, Leira, Dragvoll and Smørgrav are going to be integrated to those from Snåsa presented in the fall semester project.

The charts shown in the following pages feature both soils that are known to be quick or highly sensitive clays, with remolded undrained shear strength lower than 1 kPa, and other soil types: quick and sensitive clays are plotted as points with yellow fill and thicker borders. Points without colored fill represent the whole soil masses, "sampled" every half meter depth irrespective of soil type. Some of these points have proven not to be sensitive clays, while others have characteristics very close to those of the sensitive clays, but their mechanical properties could not be verified and their behavior can only be presumed.

7.4.1. Q, B_q and R_f

The charts seen in Figure 7-10 are intended to show the values of normalized tip resistance, pore pressure ratio and normalized side friction corresponding to the parts in Robertson's charts (1990) designated as sensitive, fine grained soils (1). Plots that include the complete range of calculated values are given in Appendix C. It is possible to see that there is fairly good agreement between the normalized parameters calculated for the current data and the values reported by Robertson, and the samples from quick and highly sensitive clay appear right in the middle of the range of resistivity values expected for those soil types, with the exception of the samples from Smørgrav. In the case of this site the layers that exhibit Q and B_q values expected for quick clay are actually those with higher salt content and lower sensitivity (excluding the dry crust), and resistivity is very low compared to the other sites. Unfortunately the data from Snåsa could not be verified by laboratory analyses, but if any of the points with resistivity higher than 80 Ω m would turn out to be representing quick clay with salinity comparable to the one at Dragvoll or Leira or slightly higher, then they would actually have a relatively high resistivity. This could imply that resistivity versus these normalized CPTU parameters correlations are only valid when site-specific, which is reasonable considering that the processes that the clay deposits have undergone during and after their formation are more likely to be similar.

Again, it is very difficult to recognize any clear pattern in the charts of Figure 7-10, and those that appear as trends are not unique.





Figure 7-10: Resistivity versus normalized CPTU parameters used in Robertson (1990) Q, B_q, R_f

7.4.2. "Effective" tip resistance q_e

 q_e was presented in Paragraph 5.3 as a parameter introduced by Fellenius and Eslami (2000) with the name of "effective" tip resistance since a pore pressure is subtracted to a stress. As the authors care to stress though, the term effective here is not used with the common meaning as in "effective stress", since pore pressure values measured during CPTUs are a direct function of the location of their measurement (Fellenius and Eslami, 2000). q_e is defined as

$$q_E = q_t - u_2 \qquad Equation 5-7$$

which means that sand layers are expected to have significantly higher q_e than clay layers, and generally non-sensitive clays have higher q_e than sensitive ones. Although q_e is still measured in kPa, to some extent it still accounts for depth since the pore pressure build up is dependent on depth.



Figure 7-11: Resistivity versus "effective" tip resistance q_e

Comparing Figure 7-11 with the top two plots of Figure 7-10, it look as if the points representing quick clay actually have smaller q_e values than the other ones, but some of the points that are known to belong to the stiff clay layer at Leira (data from Multiconsult) have similar q_e as some of the quick clay points. Resistivity values in this case can be used to distinguish the two layers from each other, but if it were not known that the points with resistivity around 80 Ω m belonging to that series are actually associated to a stiff clay layer, interpreting them would have been difficult. It should be pointed out though that the difference between the results of the CPTUs carried out by NTNU and Multiconsult at Leira is quite important, and the data obtained by NTNU seem to be more consistent with the other data sets. The chart that shows the complete range of calculated values is given in Appendix C.

7.4.3. Classification charts: Robertson (1990), Fellenius and Eslami (1997)

Classification charts are used to estimate the behavior of the soils investigated with CPTU soundings. Several authors have proposed charts that take into consideration different parameters related to pore pressure response and side friction, but in this context only those developed by Robertson (1990) and by Fellenius and Eslami (1997) are going to be used in order to assess the value of the additional information that resistivity offers. Points from the current sites and the sites involved in the fall semester project were plotted according to a color scale after being sorted by resistivity, in intervals of 10 Ω m between 0 Ω m and 110 Ω m. All points with resistivity higher than this last value have been plotted using the same symbol.

The first classification method hereby considered is the one suggested by Robertson (1990), introduced in Paragraph 5.3. Figure 7-12 below shows the plot based on normalized side friction on the left, and the one based on pore pressure ratio on the right. Soil types associated to the numbered areas are given in Figure 5-3.



Robertson (1990) classification charts

Figure 7-12: Soil classification charts based on Robertson (1990) and resistivity scale (right).

Almost all the points with resistivity lower than 110 Ω m appear in either the field representing sensitive clays (1) or the field representing clays (3). It is worth noticing that the points that are plotted as sensitive clays in the chart on the left are generally not the same as those plotted in the corresponding area in the chart on the right, but this is not uncommon. Many of the points that are known to represent quick and highly sensitive clay, furthermore, are not featured in field number 1. The chart developed by Fellenius and Eslami (1997), shown in Figure 7-13 and in Figure 5-4, gives a similar picture of the situation, but the graph is divided into a smaller number of sections and it is simpler to interpret. The symbols relative to the chart on the left are the same as those of Figure

7-10 and Figure 7-11, while the color scale for the chart on the right is the same as the one of Figure 7-12. Soil types associated to the different areas are given in Figure 5-4.





Figure 7-13: Soil classification chart based on Fellenius and Eslami (1997).

In Figure 7-13 all of the soils known to be quick clays are plotted in the bottom left section, which corresponds to sensitive/collapsible clays and silts, but there are also points from less sensitive clays that are plotted in that sector. Nevertheless, in the figure on the right hand side, it is possible to see that the points that appear in the bottom left sector span the entire resistivity range which is generally associated to marine clays, both unleached and leached. The points moreover are scattered and do not form any apparent trend which allows to distinguish sensitive clays from quick clays. The difference between these two similar but yet different soil types is not highlight by the CPTU parameters, neither the dimensionless ones nor the ones used in Figure 7-13. As explained in Chapter 2, the conditions and the physical properties of very sensitive clays and quick clays are substantially the same, and as the results of the R-CPTU soundings present in this work show quite clearly, the differences that determine whether leached clay exhibits quick behavior or not are not reflected in resistivity measurements.

8. Discussion

It is not always possible to perform chemical analyses on the pore water of soil samples, but it is more common to measure its conductance or conductivity on small amounts of interstitial fluid in order to assess their salinity. Modern electronic devices are able to measure very low conductivity values, but older analog equipment as the conductivity meter in the geotechnical laboratory at NTNU might present some inaccuracies. Based on the results of chemical analyses, which yielded both salinity and conductivity of the samples, it is found that the ratio between electrical conductivity (in ms/m) and salinity (in mg/l) was approximately 8-8,3. These factors were found to be valid for clays from the Trondheim area, and they should be used cautiously in clays with noticeably different charcteristics.

The results of the correlations presented throughout Paragraph 7.2 seem to indicate that water content is the single physical property that most influences bulk resistivity after salinity, which is reasonable considering the importance of the conductivity of the liquid phases. As in the case of sands, it might be meaningful in clays as well to correlate resistivity to the volume of water in the voids (assuming 100% soil saturation) rather than to its weight. When soil and pore water resistivity rather than bulk resistivity to be related to remolded shear strength, whilst undisturbed shear strength is affected to a much smaller degree by either of these parameters. It is not possible however to deduce soil sensitivity based on only bulk or water resistivity.

The hypothesis of the existence of one single factor that was able to explain the parallel trends that appeared in the charts relating normalized CPTU parameters to resistivity, conjectured in the semester project and constituting the starting point of the present work, has been disproved quite confidently. The correlations that appear in Paragraph 7.2 indicate that below the threshold salinity value of 1 g/l of pore water, or alternatively 0,3 g/kg of soil, salt content loses its predominance as the factor most influential in determining resistivity in marine clays. Hence it is most likely that it is rather a combination of different soil properties and in situ measuring conditions that can explain the disposition of the data in the normalized CPTU parameters versus resistivity plots. The role of the fraction of clay particles could not be thoroughly verified since it was not possible to distinguish the contribution of salinity from the contribution of clay to the determination of the soil's bulk resistivity. On a wider perspective, this is true for all the entities that were correlated to resistivity. At the present state, it is thus quite reasonable to exclude that resistivity can directly and uniquely be correlated neither to CPTU measurements that are able to give back geotechnical parameters that can be used in design practice.

Generally speaking resistivity can still be used as an additional tool to interpret the soil types occurring in the subsurface, but it looks as if its utility is limited only to some favorable conditions, as for instance locating well-defined interfaces and abrupt transition zones between soil types with noticeably different characteristics. Where the transitions are smoother as in the case of Byneset, or where the properties of two adjacent layers are not very dissimilar as in the case of Smørgrav, hardly any difference is reflected into the resistivity plots. The case of Smørgrav, where quick clay displayed resistivity values as low as 3 Ω m, also indicates that the conventional resistivity interval associated to leached clays should probably be widened, an in such case there would be a greater

overlap between the range of values characteristic for unleached and leached marine clays. Moreover, the classification charts and other previous plots suggest that some very sensitive clay might have resistivity higher than 100 Ω m (see data from Snåsa).

In the classification charts by Robertson (1990) where the points are plotted according to resistivity, the soil types agree in most cases with the resistivity values expected for that soil type. This is especially true for the chart that considers pore pressure ratio instead of normalized side friction. Nevertheless it seems that the classification chart by Fellenius and Eslami (1997) has a better accuracy in locating soils in their correct sector, but unfortunately there is a substantial lack of data representing unleached clays, which are more interesting to compare to leached clay rather than sandy soils. With unleached clays available for a direct comparison, more light could be shed on unclear aspects regarding the boundaries of the resistivity intervals and the correlation between physical and geotechnical properties and resistivity.

9. Conclusion and future work

The purpose of this work was to study the physical and geotechnical characteristics of marine clays and relate them to their electrical features, taking into consideration the properties of the soil's liquid phase as well as those of its solid fraction. For this purpose, R-CPTUs were carried out in boreholes close to where the analyzed samples were retrieved.

Problems with NTNU's equipment were highlighted during the current field work. Hence, the very first issue that NTNU should address as to continue this field of research in a reliable way is to get the conductivity module rectified and properly calibrated. The modified calibration factors found in Paragraph 6.6 give an approximation of the actual resistivity values in the soil, amplifying varitions that could actually be significantly smaller. The modified factors though could still be helpful in trying to trace trends in the soil mass.

Given the minor additional effort needed in order to perform R-CPTUs instead of classic CPTUs, they should become part of the standard routine in geotechnical investigations. Even if the potentiality of these information has not been completely understood yet, building up a database can be useful for future research. It would be useful to acquire more data from sites with unleached marine clay and sites where there is a transition from this soil type to leached clay. A comparison with resistivity measurements in clays of non-marine origin would also be beneficial.

As long as laboratory investigations are concerned, common routine investigations, grain size distribution and pore water salinity measurements are deemed to be sufficient for the purposes of the research topic. The results obtained show that pore water salinity is not the controlling factor controlling resistivity when salinity itself is very low, but it was not possible to indicate what parameter replaced it: the relative importance of the parameters included in the circumstances was found to be challenging to evaluate. Data from oedometer tests could also be included, so that the influence of overconsolidation, especially on CPTU parameters, can be investigated. Because of the cost of extracting a sufficient amount of interstitial fluid from soil samples, both in terms of resources and in terms of time, it could be more efficient to get accurate measurements of pore water conductivity by other means in order to obtain the amount of total dissolved salts. Anyway, chemical analysis are still needed to verify whether the proportionality factor of aound 8 between electrical conductivity and TDS holds for a wider range of salinity and for clays with different characteristics. In general, in order to fully understand the mechanisms that control resistivity in soils it is vital to include also soil mineralogy and pore water chemistry in the analysis of soil's physical properties.

The use of CPTU data has little margins for improvement, but as of today resistivity can be used mainly to distinguish soils with quite different behavior and characteristics. Nevertheless it would be interesting to find or propose classification charts different from those included in this study, based on derived parameters that are more prone to highlighting differences in soils behaving like sensitive clays. In that case, resistivity measurements might turn out to be more useful for geotechnical applications.

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A. Field Investigations

a. Byneset H1101

- RCPTU measurements (q_t, u_2, f_s, ρ)
- Derived parameters (q_n, q_e, Q, B_q, R_f)

Coordinates	N 7030140 (ca.)
(UTM Zone 32, Euref89)	E 557004 (ca.)
Performed by	NTNU
Date	22.10.2012



Figure A-1: Byneset; q_t , u_2 , f_s , resistivity and q_n (net tip resistance) plotted versus depth.



Figure A-2: Byneset; Q, B_q , R_f and q_e (effective cone resistance) plotted versus depth.



Figure A-3: Byneset; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)

b. Dragvoll D1, D3, D4

- RCPTU measurements (q_t, u_2, f_s, ρ)
- Derived parameters (q_n, q_e, Q, B_q, R_f)

Borehole		D1	D3	D4
Coordinates	Ν	7031319.127	7031326 (ca.)	7031323 (ca.)
(UTM Zone 32, Euref89)	Е	573273.861	573264 (ca.)	573267 (ca.)
Performed by		NTNU	NTNU	NTNU
Date		10.04.2013	07.05.2013	07.05.2013



Figure A-4: Dragvoll, boreholes D1, D3 and D4; q_{t} , u_{2} , f_{s} , resistivity and q_{n} (net tip resistance) plotted versus depth.



Figure A-5: Dragvoll, boreholes D1, D3 and D4; Q, B_q , R_f and q_e (effective cone resistance) plotted versus depth.



Figure A-6: Dragvoll, borehole D1; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)



Figure A-7: Dragvoll, borehole D3; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)



Figure A-8: Dragvoll, borehole D4; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)

c. Leira L17

- RCPTU measurements (q_t, u_2, f_s, ρ)
- Derived parameters (q_n, q_e, Q, B_q, R_f)

Borehole		L17	L17
Coordinates	Ν	7029222 (ca.)	7029222 (ca.)
(UTM Zone 32, Euref89)	Е	570122 (ca.)	570122 (ca.)
Performed by		Multiconsult	NTNU
Date		12.11.2012	21.05.2013



Figure A-9: Leira, Multiconsult and NTNU soundings; q_{b} , u_{2} , f_{s} , resistivity and q_{n} (net tip resistance) plotted versus depth.



Figure A-10: Leira, Multiconsult and NTNU soundings; Q, B_q , R_f and q_e (effective cone resistance) plotted versus depth.



Figure A-11: Leira, sounding by Multiconsult; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)



Figure A-12: Leira, sounding by NTNU; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)

d. Smørgrav H505

- RCPTU measurements (q_t, u_2, f_s, ρ)
- Derived parameters (q_n, q_e, Q, B_q, R_f)

Coordinates	N 6622441.85
(UTM Zone 32, Euref89)	E 549498.82
Performed by	NGI
Date	06.11.2008



Figure A-13: Smørgrav; q_b , u_2 , f_s , resistivity and q_n (net tip resistance) plotted versus depth.



Figure A-14: Smørgrav; Q, B_q , R_f and q_e (effective cone resistance) plotted versus depth.



Figure A-15: Smørgrav; Soil classification after Robertson (1990)

- 1. Sensitive, fine grained
- 2. Organic soils Peats
- 3. Clays Clay to silty clay
- 4. Silt mixtures Clayey silt to silty clay
- 5. Sand mixtures Silty sand to sandy silt
- 6. Sands Clean sand to silty sand
- 7. Gravelly sand to sand
- 8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
- 9. Very stiff, fine grained (heavily overconsolidated or cemented)

B. Laboratory testing

a. Byneset H1101

- Routine investigations
- Grain size distribution
- Oedometer
- Summary charts

Coordinates	N 7030140 (ca.)
(UTM Zone 32, Euref89)	E 557004 (ca.)
Performed by	NTNU
Date	22.10.2012

Ro	utin	e in	V	estiga	tic	ons										
Loca	tion			Esp				0	perator			Je	eremy King			
Boreh	nole			1101				D	ate sampli	ing		30).10.12			
Depth	1			3,0-3,8		m		D	ate openir	ıg		3	1.10.12			
Grou	nd wate	er		1		m		G	rain dens	ity fr	om pycr	ometer				
Lengt	th of sa	mple, l	L	79		cm		М	ass pycno	mete	r+water	14	47,43			g
Volui	ne of sa	ample,														
23,2*	L			1832,8		cm ³		Μ	ass pycn.	+wate	er+sampl	e 15	52,93			g
Mass	cylinde	er														
w/san	nple			5019,8		g		Te	otal dry m	ass		3	10,33			g
Mass	empty	cylind	er	1734,3		g		M	ass cup			30	02,81			g
Mass	sample	,		3285,5		g	2	M	ass dry			7,	52			g
Densi	ity	1.		1,79		g/cr	ns	G	rain densi	ty		3,	72			g/cm³
Speci	fic weig	ght		17,59		kN/	m ³		• .•		D /					
Samp	ble sub		n			Gene		classif	ication		Routin	e paran	neters	0	4	0/
3	/	wate	r co	ontent, W_1		Silty C			1		Plastici	ty index	, PI T	8,4	+	%
/	12	Dens	ity s	small ring,	ρ	Isolat	ea s	alt poc	kets		Liquid	Index, L	1	19	9,3	%
12	1/	Fallin	ng c	one, VI		Some	gra	ivel an	d snell pa	rts	Porosit	y, n		38	,9 42	
1/	28	UCS	1	CAU224							Void ra	itio, e		1,4	43	0/
28	39	Wata	«S I	, CAU334							Saturat	ion		10	0,98	% ~/l
39 40	40	Fallir		one ∇^2							PW Co	nductivi	tv	Ζ,.	2	g/I mS
45	56	Treal	$\frac{1g}{cs}$ 2	CAU350		Fallir	וס כ	one			UCS	nuucuvi	ty.			mo
58	66	Oedo	met	ter		Samp	Sample		Sr	St	Force		3		Su	
		Grair	n de	nsity, grair	ı	I III	-									
66	68	size c	listr	ibution		nr.		kPa	kPa		Kg	Kg %			kPa	
		Fallir	ng c	one, ∇3												
68	73	wp -	wl			1		25,5	1,8	14	15		2,5		30,92	
73	74	Wate	r co	ontent, w ₃		2		38,7	2,4	16						
74	78	Salt	1	1		3		37,6	2,3	16						
Wate	er conte	ent		w1	W2	2	w?	3	wl	W	р	Densit	y small ring	1		1
Cup r	nr.			108	12	.4	39)	111	57	7				Ring	Cup
Total	mass w	vet	g	98,57	51	,75	71	,48	39,97	30),36	Ring/c	up nr.		II	74
Total	Total mass dry g 73,55					5,7	56	5,19	35,29	29	9,17	Tot ma	iss wet	g	91,52	
Mass water g 25,02					8,0	05	15	5,29	4,68	1,	19	Tot ma	iss dry	g		125,6
Mass cup g 21,89					24	,07	22	2,91	22,57	24	1,98	Mass r	ing/cup	g	31,08	86,03
Masse dry sample g 51,66 1					19	9,63	33	3,28	12,72	4,	19	Mass v	vet sample	g	60,44	60,44
												Mass c	Iry sample	g	39,56	39,56
Water	r contei	nt		48,4	41	,0	45	5,9	36,8	28	3,4	Volum	e (cm ³)		34,4	34,4
			11,0						Density (g/cm ³)			1,76				

Ro	utin	e ir	V	estiga	tio	ons										
Loca	tion			Esp				0	perator			Je	remy King			
Borel	nole			1101				D	ate sampli	ing		30	0.10.12			
Depth	1			4,0-4,8		m		D	ate openir	ıg		06	5.11.12			
Grou	nd wate	er		1		m		G	rain dens	ity fr	om pycr	ometer				
Leng	th of sa	mple, l	[_	79,4		cm		М	ass pycno	omete	r+water	14	8,78			g
Volu	ne of sa	ample,														
23,2*	L			1842,1		cm ³	3	Μ	ass pycn.	+wate	er+sampl	e 15	6,81			g
Mass	cylinde	er						_								
w/sar	nple			5107,3		g		Te	otal dry m	ass		12	23,38			g
Mass	empty	cylind	er	1715,7		g		M	ass cup			11	.0,88			g
Mass	sample	•		3391,6		g		M	ass dry			12	2,50			g
Densi	ity			1,84		g/c1	m ³	G	rain densi	ty		2,	80			g/cm ³
Speci	fic wei	ght		18,06		kN/	m ³		<u> </u>		-					
Samp	ole sub	divisio	n			Gene	ral	classif	ication		Routin	e param	eters			
2	4	Wate	r cc	ontent, w_1		Silty	clay				Plastici	ty index.	, PI	7,)	%
4	10	Dens	ity s	small ring,	ρ	Some	silt	layers	5		Liquid Index, LI				8,2	%
10	15	Falliı	ng c	one, ∇1		Many	she	ell part	S		Porosit	y, n		53	,3	
15	26	UCS		~							Void ra	itio, e		1,	1	
26	37	Treal	cs 1	, CAU430							Saturat	ion		10	0,9	%
37	38	Wate	r cc	ontent, w_2							Salt co	ntent		1,)	g/l
38	43	Fallii grain	ng c siz	one V2, e distr.							PW Co	nductivi	y			mS
43	50	Oedo	me	ter		Falliı	lling cor				UCS		•			
50	60	Treal	cs 2	, CAU455		Samp	le	Su	Sr	St	Force		3		Su	
60	63	Salt				nr.		kPa	kPa		Kg		%		kPa	
		Falliı	ng c	one ∇3,												
63	68	grain	der	nsity		1		33,3	1,8	19	17,5		2,0		36,26	
68	72	wl - v	vр			2		48,2	6,1	8						
72	74	Wate	r co	ontent, w ₃		3		47,3	2,4	20						
Wate	er conte	ent		w1	w2	2	w.	3	wl	W	р	Densit	y small ring			
Cup r	nr.			60	22	28	54	ŀ	239	22	27				Ring	Cup
Total	mass w	vet	g	125,32	10	5,00	13	33,90	59,62	40	0,10	Ring/c	up nr.		Π	74
Total	mass d	ry	93,43	83	,39	10)4,40	50,44	37	7,35	Tot ma	ss wet	g	94,94		
Mass	Mass water g 31,89					,61	29	9,52	9,18	2,	75	Tot ma	lss dry	g		131,02
Mass	cup g 21,97 2				27	,03	25	5,22	22,77	26	5,83	Mass r	ing/cup	g	31,08	86,03
Mass	e dry sa	ample g 71,46 5				5,36	79	9,17	27,67	10),52	Mass v	vet sample	g	63,86	63,86
												Mass d	ry sample	g	44,99	44,99
Wate	r contei	nt	44,7	38	3,3	37	7,3	33,2	26	5,1	Volum	e (cm ³)		34,4	34,4	
Water content 44,7												Density (g/cm ³)			1,856	

Ro	utin	e in	V	estiga	tic	ons										
Loca	tion			Esp				0	perator			Je	remy King			
Borel	nole			1101				Da	ate sampli	ing		30	0.10.12			
Depth	1			5,0-5,8		m		Da	ate openir	ıg		08	8.11.12			
Grou	nd wate	er		1		m		G	rain dens	sity fi	rom pycr	ometer				
Leng	th of sa	mple, l	[]	79,2		cm		М	ass pycno	omete	er+water	14	18,93			g
Volu	me of s	ample,														
23,2*	Ľ			1837,4		cm ³	6	Μ	ass pycn.	+wat	er+sampl	e 16	51,94			g
Mass	cylinde	er														
w/sar	nple			5183,9		g		To	otal dry m	ass		32	23,16			g
Mass	empty	cylind	er	1726,9		g		M	ass cup			30)2,81			g
Mass	sample	•		3457,0		g		M	ass dry			20),35			g
Densi	ity			1,88		g/cr	n³	G	rain densi	ty		2,	77			g/cm ³
Speci	fic wei	ght		18,46		kN/	m³				T					
Sam	ole sub	divisio	n			Gene	ral	classif	ication		Routin	e paran	neters	1		
3,5	5	Wate	r co	ontent, w ₁		Silty of	clay	7			Plastici	ty index	, PI	5,	4	%
5	10	Dens	ity s	small ring,	ρ	Some	silt	layers			Liquid	I	14	-3,8	%	
10	15	Fallir	ng c	one, ⊽1		Single	e gr	avel gi	ains		Porosity, n			50	,4	
15	26	UCS									Void ratio, e			1,0		
26	37	Treal	cs 1	, CIU535							Saturat	ion		10	1,1	%
37	39	Wate	r co	ontent, w ₂							Salt con	ntent		0,	9	g/l
		Fallin	ng c	one $\nabla 2$,												
20	11	Griar	1 S1Z	e distr.								nduativi				mC
39	44 51	Orali		iisity		E-ll'						naucuvi	ly			1115
51	62	Traal				Falli		Su	S.	C+	Eoroa				C 11	
62	66	Solt	15 2	, CAUJ0J		nr	ic	b La barrow		SL	Ka		3		b b b b	
66	71	Fallir		one $\nabla 3$		ш. 1		кга 43.5	кга 3.4	13	13		⁷⁰		26.2	
71	73	W- W	ig c	0110, VJ		2		43,3	2.6	17	15		4,5		20,2	
73	77	Wate	r co	ntent wa		3		47.6	2,0	17						
Wate	r confe	nt		w1	w	2	w	3	2,0 wl	w	n	Densit	v small ring			
Cup r	nr.			238	21	.6	10)4	60	1	<u>р</u> 11	Densie	<u>, ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,</u>		Ring	Cup
Total	mass v	vet	g	85,79	96	5,07	13	3,18	59,15	4.	3,21	Ring/c	up nr.		II	110,88
Total	mass d	ss dry g 70,28 7				,37	10)3,34	49,63	3	8,57	Tot ma	iss wet	g	96,26	
Mass	Mass water g 15,51				18	3,70	29	9,84	9,52	4,	,64	Tot ma	iss dry	g		158,19
Mass	Iass cup g 28,01 2				26	5,80	22	2,03	21,97	22	2,57	Mass r	ing/cup	g	31,08	110,88
Mass	e dry sa	mple	g	42,27),57	81	,31	27,66	10	5,00	Mass v	vet sample	g	65,18		
												Mass d	lry sample	g	47,31	47,31
Wate	r contei	content 36,7					36	5,7	34,4	29	9,0	Volum	e (cm ³)		34,4	34,4
Water content 36,7						,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,						Densit	$y (g/cm^3)$		1,89	

Ro	utin	e ir	V	estiga	tic	ons										
Loca	tion			Esp				0	perator			Je	remy King			
Borel	nole			1101				Da	ate sampli	ing		30).10.12			
Depth	1			6,0-6,8		m		Da	ate openir	ng		09	9.11.12			
Grou	nd wate	er		1		m		G	rain dens	ity fi	rom pycr	nometer				
Lengt	th of sa	mple, l	Ĺ	79,7		cm		М	ass pycno	mete	r+water	14	18,93			g
Volu	me of s	ample,														
23,2*	L			1849		cm ³	5	Μ	ass pycn.	+wat	er+sampl	e 10	51,94			g
Mass	cylinde	er														
w/sar	nple			5244,6		g		To	otal dry m	ass		32	23,16			g
Mass	empty	cylind	er	1729,2		g		Μ	ass cup			30	02,81			g
Mass	sample	•		3515,4		g		Μ	ass dry			20),35			g
Densi	ity			1,90		g/cı	m³	G	ain densi	ty		2,	77			g/cm ³
Speci	fic wei	ght		18,65		kN/	′m³				T					
Samp	ole sub	divisio	n			Gene	ral	classif	ication		Routin	e paran	eters			
3	5	Wate	r co	ontent, w ₁		Silty	Ity clay					ty index	, PI	6,	51	%
5	10	Dens	ity s	small ring,	ρ	Some	silt	layers			Liquid Index, LI			15	4,4	%
10	15	Fallir	ng c	one ⊽1		Single	e gra	avel gr	ains		Porosity, n			48	,83	
15	26	UCS									Void ratio, e			0,	95	
26	37	Treal	cs 1	, CAU630							Saturat	ion		99	,56	%
37	38	Wate	r co	ontent, w ₂							Salt con	ntent		0,	5	g/l
		Fallir	ng c	one ∇2,												
• •		grain	der	nsity, grain												~
38	43	size c	lıstr								PW Co	nductivi	ty			mS
43	50	Oedo	met	ter		Fallir	ng c	one		a	UCS					
50	61	Treal	xs 2	, CAU655		Samp	le	Su	Sr	St	Force		3		Su	
61	66	Fallir	ng c	one V3		nr.		kPa	kPa		Kg		%		kPa	
66	70	Salt				1		45,0	5,4	8	14		12		26,0	
70	73	W _P - 7	WL			2		54,4	3,9	14					_	
73	74	Wate	r co	ontent, w_3		3		38,9	2,7	14						
Wate	er conte	ent		w1	W.	2	W.	3	WI 219	W Of	p	Densit	y small ring	1	Dina	Corr
Cup r	ır.			4/	32	. 40	22		218	2.	30	Diverte			Ring	Cup
Total	al mass wet g 99,93					2,42	84	+,80) (7	49,23	44	+,21	Ring/C	up nr.	~	II 07.10	110,88
Total mass dry g 79,86 Mass water g 20.07					/3	,44 . 09	09	7,67	42,91	4	J,40	T ot ma	iss wet	g	97,10	150.94
Mass water g 20,07					10	0,98	15	0,19 7 17	0,32	3,	81 1 C1	T OU Ma	iss dry	g	21.09	159,84
Mass	Mass cup g 22,23 2					0,08	27	,17 50	22,35	24	+,01	Mass r	ing/cup	g	51,08	110,88
Iviass	Masse dry sample g 57,63 52					.,30	42	2,50	20,56	1:	0,19	IVIASS V	vet sample	g	00,02	19.00
Wet	Western 24.0 2					. 4	25	. 7	20.7	-	4 1	IVIASS C	a (am ³)	g	24.4	48,90
wate	r contei	IC	<u> </u>	34,8	52	2,4 35		,/	30,7	24	+,1	volum	$e(cm^3)$		34,4	34,4
Water content 34,8											D		y (g/cm ⁻)		1,919	

Ro	utin	e in	V	estiga	tic	ons										
Loca	tion			Esp				O	perator			Je	remy King			
Borel	nole			1101				Da	ate sampli	ng		30	0.10.12			
Depth	ı			7,0-7,8		m		Da	ate openin	ıg		09	9.11.12			
Grou	nd wate	er		1		m		G	rain dens	ity fi	rom pycn	ometer				•
Lengt	th of sa	mple, l	L	79,4		cm		Μ	ass pycno	mete	r+water	14	48,47			g
Volu	me of s	ample,														
23,2*	L			1842,08	3	cm ³	5	Μ	ass pycn	+wate	er+sampl	e 10	51,33			g
Mass	cylinde	er														
w/san	nple			5194,9		g		To	otal dry m	ass		12	27,91			g
Mass	empty	cylind	er			g		M	ass cup			10	07,36			g
Mass	sample	•				g		M	ass dry			20),55			g
Densi	ity	1.				g/ci	m ³	Gr	ain densit	ty		2,	67			g/cm ³
Speci	fic wei	ght				kN/	m ³	1 .	• .•							
Samp	ole sub		n			Gene	ral (classif	ication		Routin	e paran	neters	4	0.40/	0/
4	5	Wate	r co	$\frac{11}{11}$		Silty	$\frac{clay}{1}$	1			Plastici	ty index	, PI T	4,	04%	%
5	9	Dens	ity s	small ring,	ρ	Relati	ivel	y home	ogeneous		Liquid	1	30	03%	%	
9	14	Fallin	$\frac{1}{1}$	one VI		Some	san	d and	gravel gra	uns	Porosity	y, n		44	,31	
14	24	Geoc	hen	nistry		At ce	ntre	of san	nple		Void ra			0,	80	0/
24	35	Ireal	<u>s</u>								Saturati	ion		10	07,8	%
35	36	Wate	r co	ontent, w_2							Salt con	ntent		0,	6	g/l
36	40	Grain	ig c i de	nsity							PW Co	nductivi	tv			mS
40	48	Oedo	me	ter		Fallir	alling con					nuuctivi	t y			IIID
48	59	Treal				Samp	le U	Su	Sr	St	Force		8		Su	
59	63	Fallir	19 C	one ∇3		nr.	10	kPa	kPa	51	Kg		%		kPa	
63	65	W1 - V	- <u>0</u> -			1		24.3	1.9	13	8				••	
65	66	Wate	r co	ontent. w ₃		2		34.8	2.5	15						
66	72	Salt,	grai	in size dist	r.	3		23,7	2,1	12						
72	78	Mine	ralc	ogi				,	,							
Wate	er conte	ent		w1	w	2	w	3	wl	w	p	Densit	y small ring			
Cup r	ır.			24,33	1,8	87	13	,23	24,33	1,	.87		• •		Ring	Cup
Total	mass v	vet	g	34,83	2,4	47	14	,83	34,83	2,	47	Ring/c	up nr.		II	64
Total	mass d	ass dry g 23,70					11	,55	23,70	2,	10	Tot ma	iss wet	g	99,03	
Mass water g 24,33					1,8	87	13	,23	24,33	1,	87	Tot ma	iss dry	g		74,93
Mass	Mass cup g 34,83 2					47	14	,83	34,83	2,	47	Mass r	ing/cup	g	31,08	23,74
Mass	e dry sa	e dry sample g 23,70 2					11	,55	23,70	2,	10	Mass v	vet sample	g	67,95	67,95
												Mass c	lry sample	g	51,19	51,19
Water	r contei	nt		33,4 %	34	,8 %	37	,1 %	26,9 %	22	2,9 %	Volum	e (cm ³)		34,4	34,4
Water content 33,4 %												Densit	$y (g/cm^3)$		1,98	

Ro	utin	e in	V	estiga	tio	ons										
Loca	tion			Esp				0	perator			Je	remy King			
Boreh	nole			1101				D	ate sampli	ng		30	0.10.12			
Depth	ı			8,0-8,8		m		D	ate openin	ıg		1().11.12			
Grou	nd wate	r		1		m		G	rain dens	ity fr	om pycr	ometer				
Lengt	th of sa	mple, I		79,8		cm		Μ	lass pycno	mete	r+water	14	48,35			g
Volu	ne of sa	ample,														
23,2*	L			1851,36	5	cm ³	3	Μ	lass pycn	+wate	er+sampl	e 16	63,67			g
Mass	cylinde	er														
w/san	nple			5234,5		g		Te	otal dry m	ass		23	34,74			g
Mass	empty	cylind	er	1739,3		g		Μ	lass cup			21	10,53			g
Mass	sample	•		3495,2		g		Μ	lass dry			24	4,21			g
Densi	ity			1,89		g/cr	m³	G	rain densi	ty		2,	72			g/cm ³
Speci	fic wei	ght		18,52		kN/	′m³				1					
Samp	ole sub	divisio	n			Gene	ral	classif	fication		Routin	e paran	neters	1		
0	5	Mine	ralc	ogi		Silty	clay	r			Plastici	ty index	, PI	7,	21%	%
5	6	Wate	r co	ontent, w ₁		Relati	ivel	y hom	ogeneous		Liquid	Index, L	ľ	19	3%	%
6	11	Dens	ity s	samll ring		Some	gra	vel, sł	nells		Porosit	y, n		48	,70	
11	15	Fallir	ng c	one, ∇1		Layer	ing	at 8,6			Void ra	tio, e		0,	95	
15	26	Treal	KS .								Saturat	ion		10	2,6	%
26	31	Fallir	ng c	one ∇2							Salt con	ntent		0,	5	g/l
31	32	Wate	r co	ontent, w ₂							PW Co	nductivi	ty			mS
32	40	Oedo	met	ter		Falling of		one		1	UCS					
40	51	Treal	KS			Sample		Su	Sr	St	Force		3		Su	
51	56	Salt,	grai	in density p)S	nr.		kPa	kPa		Kg		%		kPa	
56	61	Geoc	hen	nistry		1		65,7	2,4	28						
61	64	w _L - v	NP			2		68,0	2,8	26						
64	69	Fallir	ng c	one ∇3		3		36,9	1,7	24						
69	70	Wate	r co	ontent, w ₃		4		35,4	1,4	26						
70	74	Fallir	ng c	one, ∇4												
74	79	Geoc	hen	nistry	1											
Wate	er conte	ent		w1	W.	2	w:	3	wl	W	р	Densit	y small ring			1
Cup r	nr.			219	24	2	49)	241	67	7				Ring	Cup
Total	mass w	wet g 79,12				2,89	97	,32	65,59	43	3,79	Ring/c	up nr.		II	57
Total	mass d	nass dry g 64,22),67	78	3,61	56,09	39	9,91	Tot ma	iss wet	g	96,68	
Mass	ass water g 14,9				12	2,22	18	3,71	9,5	3,	88	Tot ma	ass dry	g		73,04
Mass	Mass cup g 23,88 2				27	,57	25	5,48	24,06	22	2,63	Mass r	ing/cup	g	31,08	24,98
Mass	e dry sa	ry sample g 40,34 3				8,1	53	3,13	32,03	17	7,28	Mass v	vet sample	g	65,6	65,6
												Mass d	Iry sample	g	48,06	48,06
Water	r conter	content 36,9 %					35	5,2 %	29,7 %	22	2,5 %	Volum	e (cm ³)		34,4	34,4
												Density (g/cm ³)			1,91	

Ro	utin	e in	V	estiga	tic	ons										
Loca	tion			Esp				O	perator			Je	eremy King			
Boreh	nole			1101				Da	te sampli	ng		2	5.11.12			
Depth	ı			9,0-9,8		m		Da	ate openin	g		1	1.01.13			
Grou	nd wate	er		1		m		G	rain dens	ity fr	om pycr	ometer				
Lengt	th of sa	mple, l		79,3		cm		Μ	ass pycno	mete	r+water	14	48,35			g
Volur	ne of sa	ample,														
23,2*	L			1839,76	5	cm ³	•	Μ	ass pycn	⊦wate	er+sampl	e 10	53,19			g
Mass	cylinde	er														
w/san	nple					g		To	otal dry m	ass		1.	32,28			g
Mass	empty	cylind	er	1439,2		g		M	ass cup			10	08,85			g
Mass	sample	•				g		M	ass dry			2.	3,43			g
Densi	ity					g/cr	n³	Gı	ain densit	ty		2,	73			g/cm ³
Speci	fic wei	ght				kN/	m³									
Samp	ole sub	divisio	n			Gene	ral (classif	ication		Routin	e paran	neters	-		
0	9	Mine	ralc	ogy		Silty	clay				Plasticity index, PI			3		%
9	10	Wate	r co	ontent, w ₁		Relati	ively	y homo	ogeneous		Liquid	Index, L	I	41	4	%
10	15	Dens	ity s	small ring,	ρ	Some	gra	vel, sh	ells		Porosity, n			51	,04	%
15	20	Fallir	ng c	one, ∇1							Void ratio, e			1,	04	
20	31	Treal	KS .								Saturat	ion		10	3,19	%
31	32	Wate	r co	ontent, w ₂							Salt con	ntent		0,	5	g/l
32	36	Fallir	ng c	one, ∇2							PW Co	nductivi	ty			mS
36	44	Oedo	met	ter		Falling		one	1 1		UCS					
44	55	Treal	KS .			Samp	Sample		Sr	St	Force		3		Su	
	50	Fallir	ng c	one $\nabla 3$,				1.0	1.D			V. O/			1.5	
55	59	grain	der	isity ps		nr.		kPa	kPa	16	Kg	<u>×g</u> %			kPa	
59	61	W _L -V	N _P			1		21,7	0,5	46						
61	65	Salt,	grai	n size dist	r.	2		35,6	1,3	27						
65	66	Wate	r co	$\frac{1}{1}$		3		30,6	1	32						
66	/8	Geoc	hen	nistry												
Wate	er conte	ent		w1	w	2	w?	3	wl	W	D	Densi	v small ring			
Cup n	nr.			233	24	7	24	.5	54	30)		,8		Ring	Cup
Total	mass w	vet	g	89.59	69	0.57	79	.43	73	70).7	Ring/c	up nr.		II	238
Total	al mass wet g 89,59				57	,e . '.5	66	.84	63.65	62	2,44	Tot ma	ass wet	g	95.5	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$				12	2.07	12	.59	9,35	8.	26	Tot ma	ass dry	o g	,0	73,95	
Mass water g 17,38 1 Mass cup g 27,17 2				22	.91	27	.31	25,22	22	2,91	Mass r	ing/cup	g	31,08	28,01	
Masse	s cup $g 27,17 2$ se dry sample $g 45.04 3$				34	.59	39	.53	38,43	39	9,53	Mass	vet sample	g	64,42	64,42
		r	0	- ,	-	/		/				Mass of	lry sample	g	45,94	45,94
Water	r conter	content 38.6 %					31	,8 %	24,3 %	20),9 %	Volum	$1e (cm^3)$	0	34,4	34,4
Water content				-							Density (g/cm ³)		$y (g/cm^3)$		1,87	

Ro	utin	e in	V	estiga	tic	ons											
Loca	tion			Esp				O	Operator			Je	Jeremy King				
Borehole			1101				Da	Date sampling			2	26.11.12					
Depth 10,0-			10,0-10	,8	m		Da	Date opening				2	1.01.13				
Grou	nd wate	er		1		m			Grain density from pycnometer								
Lengt	th of sa	mple, I		80		cm		M	ass pyc	nome	etei	r+water	1	48,35			g
Volui	ne of s	ample,															
23,2*L			1856		cm ³		M	ass pyc	n.+w	ate	er+sample 156,71		56,71			g	
Mass	cylinde	er						_									
w/san	nple			5324		g		To	otal dry	mass	3		1	19,5			g
Mass	empty	cylinde	er	1744,8		g		M	ass cup				1	06,1			g
Mass	sample	•		3579,2		g		Ma	ass dry	•			1	3,4			g
Densi	ity	1.		1,93		g/cr	n ³	Gr	ain den	isity			2	,66			g/cm ³
Speci	fic wei	$\frac{ght}{1}$		18,92		kN/	m ³										
Samp	ole sub	divisio	n			Gene	ral c	classif	ication			Routin	e paran	neters		0.0	0/
0	6	Mine	ralo	ogy		Silty						Plasticity index, PI		, PI	3,92		%
6	/	Water content, w ₁				Some	Some damages			Liquid Index, LI		314		%			
7	11	Denisty small ring, ρ			ρ	Distu	rbed	at bot	h ends			Porosity, n		44,1		%	
11	15	Falling cone, ∇1							void ratio, e		0,79		0/				
15	26	Treaks							Saturation		107,5		%				
26	35	Oedometer								Salt con	ntent		0,	6	g/l		
35	39	Falling cone, $\nabla 2$												mS			
39	40	Water content, w_2			Failing cone			C.				1		0			
40	51	Treaks			Samp	le	Su	Sr	St		Force		3		Su		
51	50	Salt,	grai	n size dist	r.	nr.		кРа 26.4	KPa	1.00	<u>,</u>	Kg		%		кРа	
50	59 62	$W_L - V_L$	W _P			2		36,4	0,4	105	۶ ۱						
59	03	Faint	ig c	one v4		2		30,2	0,4	101	L						
03	04	w ate	r co	ontent, W_3		3	_		0,4								
64	68	Grain	ig e i dei	nsity os		4		23.4	0.8	28							
68	79	Mine	ralo	ov				23,1	0,0	20							
00	12	101111C	iuio	6)													
Wate	er conte	ent		w1	w2	2	w3	3	wl		wŗ)	Densi	y small ring			
Cup nr.		62	23	5	59		113 61						Ring	Cup			
Total mass wet g		73,61	70	,85	87	,1	62,01		34	,8	Ring/c	up nr.		II	104		
Total mass dry g		60,79	59	,4	72	,69	54,29)	33	,05	Tot ma	ass wet	g	98,83			
Mass water g		12,82	11	,45	14	,41	7,72		1,	75	Tot ma	ass dry	g		73,1		
Mass cup g		22,17	26	,23	25	,41	22,57	7	24	,48	Mass	ring/cup	g	31,08	22		
Mass	e dry sa	mple	g	38,62	33	,17	47	,28	31,72	2	8,:	57	Mass	wet sample	g	67,75	67,8
											Mass of	iry sample	g	51,11	51,1		
Water	r contei	nt		33,2 %	34	,5 %	30	,5 %	24,3	%	20	,4 %	Volun	$me(cm^3)$		34,4	34,4
											Densit	$y (g/cm^3)$		1,97			

Location	Byneset	Depth	3,60
Borehole	H1101	Clay	39,3%



Location	Byneset	Depth	4,60
Borehole	H1101	Clay	33,1%



Location	Byneset	Depth	5,60
Borehole	H1101	Clay	33,3%



Location	Byneset	Depth	6,60
Borehole	H1101	Clay	30,3%



Location	Byneset	Depth	7,60
Borehole	H1101	Clay	30,3%



Location	Byneset	Depth	8,60
Borehole	H1101	Clay	31,4%



Location	Byneset	Depth	9,60
Borehole	H1101	Clay	29,3%



Location	Byneset	Depth	10,60
Borehole	H1101	Clay	29,7%





Figure B-1: Byneset, summary of laboratory results (shear strength, water content, specific weight)


Figure B-2: Byneset, summary of laboratory results (clay fraction, salt concentration, overconsolidation ratio)

b. Dragvoll D1

- Routine investigations
- Grain size distribution
- Oedometer
- Summary charts

Borehole		D1	D3	D4
Coordinates	Ν	7031319.127	7031326 (ca.)	7031323 (ca.)
(UTM Zone 32, Euref89)	Е	573273.861	573264 (ca.)	573267 (ca.)
Performed by		NTNU	NTNU	NTNU
Date		10.04.2013	07.05.2013	07.05.2013

Ro	utin	e in	V	estiga	tio	ons										
Loca	tion			Dragvo	11			0	perator			K	arl Fredrik M	loe		
Boreh	nole			D1				Da	ate sampli	ng		29	9/11/12			
Depth	ı			2,0-2,8		m		Da	ate openin	ıg		03	3/12/12			
Grou	nd wate	r				m		G	rain dens	ity f	rom pycı	nometer				
Lengt	th of sa	mple, l		78,9		cm		М	ass pycno	mete	er+water	14	18,35			g
Volu	ne of sa	ample,														
23,2*	L			1830,48	3	cm ³	3	Μ	ass pycn	+wat	er+sampl	e 29	92,96			g
Mass	cylinde	er														
w/san	nple			5198,2		g		To	otal dry m	ass		27	79,81			g
Mass	empty	cylind	er	1749,2		g		Μ	ass cup			13	3,15			g
Mass	sample	•		3449		g		Μ	ass dry			2,	67			g
Densi	ity			1,88		g/cı	m³	Gı	ain densi	ty		29	92,96			g/cm ³
Speci	fic wei	ght		18,48		kN/	′m³				-					
Samp	ole sub	divisio	n			Gene	ral	classif	ication		Routin	e paran	eters	1		
5	7	Wate	r co	ntent, w ₁		Clay					Plastici	ty index	, PI	7,	20%	
10	15	Dens	ity s	small ring,	ρ	Relati	ively	y homo	ogeneous		Liquid	Index, L	Ι	22	3,39%	
15	17	Grair	n de	nsity, ρ _s		Some	san	d and	gravel		Porosit	y, n		48	3,11%	
17	19	Grair distri	ı siz buti	e on	71						Void ra	ntio e		0	93	
20	25	Fallir	וס ה	one $\nabla 1$							Saturat	ion		10)7 69%	
25	37	UCS	150	0110, 11	71						Salt co	ntent		10	11,0270	σ/l
37	39	Wate	r co	ontent wa							PW Co	nductivi	tv			mS
39	52	Chen	nistr	v		Fallir	1 σ C	one				iladetivi	- 9			IIIG
52	57	Fallir		one $\nabla 2$		Samp	le	Su	Sr	St	Force		8		Su	
57	69	Rese	rve			nr.		kPa	kPa	21	Kg		%		kPa	
69	72	w ₁ /v	v			1		21.8	0.65	7	7		3		14 36	
66	68	Wate	r co	ntent. w ₃		2		14.7	0.91	, 16			0		1,00	
Wate	er conte	ent		w1	W	2	wâ	3	wl	W	/p	Densit	y small ring			
Cup r	nr.			49	69)	63		216	2					Ring	Cup
Total	mass w	vet	g	93,06	11	5,36	10	4,19	72,5	3	1,52	Ring/c	up nr.		II	227
Total	mass d	ry	g	74,29	92	2,14	81	,42	62,55	2	9,77	Tot ma	iss wet	g	96,87	
Mass	water		g	18,77	23	3,22	22	,77	9,95	1	,75	Tot ma	iss dry	g		74,44
Mass	cup		g	25,48	22	2,39	22	,1	26,8	2	1,29	Mass r	ing/cup	g	31,08	26,83
Mass	e dry sa	mple	g	48,81	69	9,75	59	,32	35,75	8	,48	Mass v	vet sample	g	65,79	65,79
												Mass d	lry sample	g	47,61	47,61
Water	r conter	nt		38,5 %	33	3,3 %	38	,4 %	27,8 %	2	0,6 %	Volum	e (cm³)		34,4	34,4
												Densit	$y (g/cm^3)$		1,91	1,38

Ro	utin	e in	V	estiga	tic	ons											
Locat	tion			Dragvol	11			(Operator	•			Ka	arl Fredrik M	loe		
Boreh	nole				1			Ι	Date sam	plin	g				2	9/11/12	
Depth	ı			3,0-3,8		m		Ι	Date oper	ning					0	3/12/12	
Grour	nd wate	er				m		(Frain de	nsit	y fr	om pycr	ometer				
Lengt	h of sa	mple, I			80,2	cm		Ν	Aass pyc	nom	neter	r+water				148,35	g
Volur	ne of s	ample,															
23,2*	L			186	0,64	cm ³	3	Ν	Aass pyc	n.+v	vate	er+sampl	e			154,57	g
Mass	cylinde	er															
w/san	nple			49	47,6	j g		Г	Total dry	mas	SS					311,94	g
Mass	empty	cylinde	er	14	04,4	g		N	Aass cup							301,88	g
Mass	sample	•		35	43,2	g		N	Aass dry							10,06	g
Densi	ty				1,90) g/c1	m³	(Brain den	sity						2,63	g/cm ³
Speci	fic wei	ght		1	8,68	kN/	m ³										
Samp	ole sub	divisio	n			Gene	ral	classi	ification			Routin	e param	eters	1		
5	7	Wate	r co	ntent, w_1		Clay						Plastici	ty index,	PI	1	0,94%	
10	15	Dens	ity s	mall ring,	ρ	Relati	ivel	y hon	nogeneou	18		Liquid	Index, L	[16	55,24%	
15	17	Grain	ı dei	nsity, ρ _s		Some	sar	nd and	ł gravel			Porosit	y, n		-	50,34%	
17	19	distri	ı sız buti	e on	74							Void ra	tio, e			1,01	
20	25	Fallir	ng co	one. ∇1	71							Saturat	ion		11	9.74%	
25	37	UCS	-8 -	,								Salt co	ntent			,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	g/]
37	39	Wate	r co	ntent w ₂								PW Co	nductivit	v			mS
39	52	Chen	nistr	v		Fallir	ng c	one				UCS	nauenvii	5			
52	57	Fallir	ng co	one. $\nabla 2$		Samp	le	Su	Sr	St		Force		3		Su	
57	69	Resei	ve	,		nr.		kPa	kPa			Kg		%		kPa	
69	72	w1 / w	Vn				1	32.7	7 2,1		7	8	14		2		29,01
66	68	Wate	r co	ntent, w ₃			2	42,4	4 1,5		28						,
Wate	r conte	ent		w1	w2	2	W.	3	wl		wj	p	Densit	y small ring		1	
Cup n	nr.			64		208		52	2	37		22				Ring	Cup
Total	mass v	vet	g	113,44	1	09,03	1	30,27	7 80),4		36,37	Ring/c	up nr.		II	202
Total	mass d	ry	g	88		84,93	1	00,84	4 66,	95		34,44	Tot ma	ss wet	g	97,1	
Mass	water		g	25,44		24,1		29,43	3 13,	45		1,93	Tot ma	ss dry	g		67,76
Mass	cup		g	22,1		25,71		26,3	3 25,	51		25,47	Mass r	ing/cup	g	31,08	22,89
Masse	e dry sa	mple	g	65,9		59,22		74,54	4 41,	44		8,97	Mass w	vet sample	g	66,02	66,02
													Mass d	ry sample	g	44,87	44,87
Water	r contei	ent 38,6 % 4		40	0,7 %	3	9,5 %	32,5	%		21,5 %	Volum	e (cm ³)		34,4	34,4	
		ontent 38,6 %											Densit	$y (g/cm^3)$		1,92	1,30

Ro	utin	e ir	V	estiga	tio	ons											
Loca	tion			Dragvo	11			0	perator	•			K	arl Fredrik M	loe		
Borel	nole			1				D	ate samp	oling	g		29	9/11/12			
Depth	1			4,0-4,8		m		D	ate open	ing			03	3/12/12			
Grou	nd wate	er				m		G	rain de	nsit	y fr	om pycr	nometer				
Leng	th of sa	mple, l	[]	78,8		cm		Μ	lass pyci	nom	ete	r+water	14	18,35			g
Volu	ne of s	ample,															
23,2*	L			1828,16	5	cm ³	3	Μ	lass pyci	n.+v	vate	er+sampl	e 15	57,55			g
Mass	cylinde	er															
w/sar	nple			5090,7		g		Te	otal dry	mas	S		29	94,38			g
Mass	empty	cylind	er	1792,7		g		Μ	lass cup				27	79,81			g
Mass	sample	•		3298		g		Μ	lass dry				14	1,57			g
Densi	ity			1,80		g/c1	m³	G	rain den	sity			2,	71			g/cm ³
Speci	fic wei	ght		17,70		kN/	′m³					1					
Samp	ole sub	divisio	n			Gene	ral	classif	fication			Routin	e paran	eters			
5	7	Wate	r co	ontent, w ₁		Clay						Plastici	ty index	, PI -	6,	69%	
10	15	Dens	ity s	small ring,	ρ	Relat	ivel	y hom	ogeneou	IS		Liquid	Index, L	I	28	34,57%	
15	17	Grain	ı de	nsity, ρ _s		Some	e san	d and	gravel			Porosit	y, n		48	3,78%	
17	19	Grair distri	ı siz buti	.on								Void ra	tio, e		0.	95	
20	25	Falliı	ng c	one, ∇1	n 1e, ∇1							Saturat	ion		10)5.99%	
25	37	UCS	0	, -	≥, ∇1							Salt co	ntent			- ,	g/l
37	39	Wate	r co	ontent. w ₂								PW Co	nductivi	tv			mS
39	52	Chen	nisti	v		Falliı	ng c	one				UCS		· J	1		
52	57	Falliı	ng c	one, $\nabla 2$		Samp	le	Su	Sr	St		Force		З		Su	
57	69	Rese	rve			nr.		kPa	kPa			Kg		%		kPa	
69	72	w ₁ / v	Vp			1		14,9	0,69	22		7,3		4		14,82	
66	68	Wate	rco	ontent, w ₃		2		10,2	0,32	32	,						
Wate	er conte	ent		w1	W	2	w.	3	wl		W	р	Densit	y small ring			
Cup r	nr.			113	59)	44		211		7	-				Ring	Cup
Total	mass v	vet	g	102,65	98	3,71	11	2,55	75,78		47	7,49	Ring/c	up nr.		II	55
Total	mass d	ry	g	79,22	77	7,7	88	,89	65,44		44	1,76	Tot ma	iss wet	g	97,06	90,28
Mass	water	-	g	23,43	21	,01	23	,66	10,34		2,	73	Tot ma	iss dry	g		72,14
Mass	cup		g	22,57	25	5,41	25	,71	27,58		31	,52	Mass r	ing/cup	g	31,08	24,33
Mass	e dry sa	mple	g	56,65	52	2,29	63	,18	37,86		13	3,24	Mass v	vet sample	g	65,98	65,95
							1						Mass d	lry sample	g	47,81	47,81
Wate	r contei	nt		41,4 %	40),2 %	37	',4 %	27,3 9	%	20),6 %	Volum	e (cm ³)		34,4	34,4
													Densit	$y (g/cm^3)$		1,92	1,39

Ro	utin	e in	V	estiga	tic	ons											
Loca	tion			Dragvol	11			0	perator				Ka	arl Fredrik M	loe		
Boreh	nole				1			D	ate sam	oling					2	9/11/12	
Depth	ı			5,0-5,8		m		D	ate oper	ing					04	4/12/12	
Grou	nd wate	er				m		G	rain de	nsity	fr	om pycn	ometer				
Lengt	h of sa	mple, I	_		80,7	cm		Ν	lass pyci	nome	etei	r+water				148,35	g
Volur	ne of s	ample,															
23,2*	L			187	2,24	cm ³	3	N	lass pyci	n.+w	ate	er+sampl	e			154,9	g
Mass	cylinde	er															
w/san	nple			50	04,8	g		Т	otal dry	mass	5					312,39	g
Mass	empty	cylinde	er	15	45,7	g		Ν	lass cup							301,88	g
Mass	sample	•		34	59,1	g		Ν	lass dry							10,51	g
Densi	ty				1,85	g/ci	m³	G	rain den	sity						2,65	g/cm ³
Speci	fic wei	ght		1	8,12	kN/	′m³										
Samp	ole sub	divisio	n			Gene	ral	classi	fication			Routin	e param	eters	1		
5	7	Wate	r co	ntent, w ₁		Clay						Plastici	ty index,	PI		4,74%	
10	15	Dens	ity s	small ring,	ρ	Relati	ivel	y hom	ogeneou	IS		Liquid	Index, L	[41	9,59%	
15	17	Grain	dei	nsity, ρ _s		Distu	rbec	1 at bo	oth ends,	at 30)	Porosit	y, n		4	7,13%	
17	19	Grain distri	i siz buti	e on		And	at 57	7 cm				Void ra	tio e			0.89	
20	25	Fallir	ouci	one $\nabla 1$		7 ma t					_	Saturati	ion		11	1 99%	
25	37	UCS	50	0110, 11							_	Salt cor	ntent			1,7770	o/]
37	39	Wate	r co	ntent. w ₂								PW Co	nductivit	v			mS
39	52	Chen	nistr	v		Fallir	ıø c	one				UCS		.)			
52	57	Fallir	ig co	one, $\nabla 2$		Samp	le	Su	Sr	St		Force		3		Su	
57	69	Reser	ve			nr.		kPa	kPa			Kg		%		kPa	
69	72	w1 / w	/p				1	10,1	0,1	10	1		2		2,5		4,12
66	68	Wate	r co	ntent, w ₃			2	4,1	0,1	4	1						
Wate	r conte	ent		w1	w2	2	W.	3	wl		wp	0	Densit	y small ring		•	
Cup n	ır.			228		221		234	2	31		11				Ring	Cup
Total	mass v	vet	g	127,63	1	31,97	1	29,02	86,	36		44,58	Ring/cu	up nr.		II	210
Total	mass d	ry	g	100,38		99,94		99,3	74,	42		41,95	Tot ma	ss wet	g	98,06	88,99
Mass	water		g	27,25		32,03		29,72	11,	94		2,63	Tot ma	ss dry	g		70,47
Mass	cup		g	27,03		25,96		26,23	27,	06		29,1	Mass ri	ing/cup	g	31,08	22,2
Masse	e dry sa	mple	g	73,35	,	73,98		73,07	47,	36		12,85	Mass w	et sample	g	66,98	66,79
													Mass d	ry sample	g	48,27	48,27
Water	r contei	nt		37,2 %	43	3,3 %	4	0,7 %	25,2	%		20,5 %	Volum	e (cm ³)		34,4	34,4
	r content 37,2 %												Density	$y(g/cm^3)$		1,95	1,40

Ro	utin	e ir	v	estiga	ti	ons											
Loca	tion			Dragvo	11			0	perator	1			K	arl Fredrik M	loe		
Boreł	nole			1				Da	ate samp	oling	g		29	0/11/12			
Depth	1			6,0-6,8		m		Da	ate open	ing			04	/12/12			
Grou	nd wate	er				m		G	rain de	nsit	y fr	om pycr	ometer				•
Lengt	th of sa	mple, l	Ĺ	80,3		cm		М	ass pyci	nom	lete	r+water	14	8,35			g
Volu	ne of s	ample,															
23,2*	L			1862,96	5	cm ³	3	Μ	ass pyci	n.+v	vate	er+sampl	e 15	58,25			g
Mass	cylinde	er															
w/san	nple			5006,7		g		To	otal dry	mas	S		22	27,09			g
Mass	empty	cylind	er	1485,5		g		Μ	ass cup				21	1,42			g
Mass	sample	•		3521,2		g		M	ass dry				15	5,67			g
Densi	ity			1,89		g/c1	m³	Gı	ain den	sity			2,	72			g/cm ³
Speci	fic wei	ght		18,54		kN/	′m³										
Samp	ole sub	divisio	n			Gene	ral	classif	ication			Routin	e paran	eters	-		
18	20	Wate	er co	ontent, w1		Clay						Plastici	ty index.	, PI	3,	00%	
20	25	Dens	ity :	small ring,	ρ	Quick	ζ.					Liquid	Index, L	I	56	50,75%	
25	30	Falliı	ng c	one, ∇1								Porosit	y, n		51	,29%	
30	32	Grain	ı de	nsity, ps	y, ps							Void ra	itio, e		1,	05	
22	24	Grain	ı siz	ze	nt w?							G ()			10	4 210/	
32	34	distri	buti	ion	ent, w2							Saturat	ion		10	94,31%	. /1
35	3/	Wate	er co	ontent, w2	n ent, w2							Salt con	ntent				g/l
37	49	UCS		80								PW Co	nductivi	ty			mS
49	54	Fallin	$\frac{\log c}{\frac{1}{2}}$	one, V2		Falli	$\frac{1}{1}$	one	0	.						0	
54	66	Chen	nisti	ry		Samp	le	Su	Sr	St		Force		3		Su	
66	70	wl –	wp			nr.		kPa	kPa		,	Kg -		%		kPa	
70	72	Wate	er co	ontent, w3		1		7,5	0,1	15	,	5		3		10,25	
XX 7 4			<u> </u>	1		2		6,5	0,1	65			D 4				
wate	er conte	ent	-	W1	W.	2	W3	<u>, , , , , , , , , , , , , , , , , , , </u>	WI 45		W	p	Densit	y small ring	1	Dina	Curr
Cup r	ır.			240	01	5 21	12	5 <u>5</u> 11	45		15)	Dingla			King	
Total	mass v	vet	g	124,88	12	25,51	13	5,11	92,25		44	+,/0	King/C	up nr.	a	II 05.47	104 86.21
Mass	mass u	1 y	g	96,05	97	7,05	10	4	19,57		42	2,45	Tot ma	as dry	g	95,47	67.54
Mass	water		g	20,85	21	1 1 9	20	,+ 57	12,00		2, 20	55) 5	Tot ma	iss ury	g	21.09	22.03
Mass	cup	mnla	g	22,98	72	+,40	27	,57	25,29		11	1,5	Mass I	ung/cup	g	51,00	64.28
IVIASS	e ury sa	unpie	g	15,07	12	,57	19	,14	50,28		11	1,93	Mass d	ry somple	g	45 51	45.51
Wata	r oont-			2570/	25	7 / 0/	25	0.0/	22.50)/.	10) 5 0/	Weber	a (cm ³)	g	43,31	43,31
w ater	conte	IL	-	55,1 %	31	,4 %	- 33	, 7 %	22,3 %	/0	15	<i>,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	Darrali	$e(cm^3)$		34,4 1.97	34,4
													Densit	y (g/cm ⁻)		1,87	1,32

Ro	utin	e ir	IV	estiga	tic	ons											
Loca	tion			Dragvol	11			0	perator				A Ei	lberto Monta de Helle	fia/	Гonje	
Boreh	nole			1				Da	ate sam	oling	5		15	5/04/13			
Depth	ı			8-8,80		m		Da	ate oper	ing	<u>.</u>		18	3/04/13			
Grou	nd wate	r				m		G	rain de	nsity	y fr	om pycn	ometer				
Lengt	h of sa	mple, l	L	79,3		cm		Μ	ass pyci	nom	etei	r+water	14	8,93			g
Volur	ne of sa	ample,															
23,2*	L			1839,76	5	cm ³	6	Μ	ass pyci	n.+w	vate	er+sampl	e 15	59,27			g
Mass	cylinde	er															
w/san	nple			5049,6		g		To	otal dry	mas	S		22	28,72			g
Mass	empty	cylind	er	1456,7		g		M	ass cup				21	2,7			g
Mass	sample	;		3592,9		g		M	ass dry				16	5,02			g
Densi	ty			1,95		g/cr	n ³	Gı	ain den	sity			2,	82			g/cm ³
Speci	fic wei	ght		19,16		kN/	m ³		• .•								
Samp	ole sub	livisio	n			Gene	ral c	classif	ication			Routin	e param	eters		201	
0	5	X				Clay						Plastici	ty index.	, PI	5,	93%	
5	10	Wate	$\frac{r}{c}$	ontent, wl		Quick	C					Liquid	Index, L	1	32	7,20%	
7	12	Dens	ity	small ring,	ρ							Porosit	y, n		49	,26%	
12	17	Falli	ng c	cone, VI							Void ra	t10, e		0,9)/ 1.050/		
1/	28	UCS	1									Saturati	lon		10	4,25%	. /1
28	40	Geoc	chen	nistry	stry							Salt con	itent		0	<i>C</i> 1	g/l
40	42	Wate	er co	$\nabla n tent, W2$		T -112-						PW Co	nductivi	ty	0	64	mS
42	47	Fain	ng c	$\frac{1}{1}$		Faint	$\frac{1}{1}$	one	C	C4		UCS Earra				C.,	
47	52	Salt,	wp	- WI		Samp	le	Su	Sr	St		Force		3		Su	
52	71	size o	listr	ribution	1	nr.		kPa	kPa			Kg		%		kPa	
71	73	Wate	er co	ontent, w3		1		14,9	0,1	14	9	2,2		1		4,60	
73	78	Х				2		12,7	0,1	12	7						
Wate	r conte	ent		w1	w	2	w3	3	wl		wp	0	Densit	y small ring		•	
Cup n	ır.			62	22	7	10	8	49		14					Ring	Cup
Total	mass w	vet	g	132,3	11	8,38	14	6,35	60,89		30),15	Ring/c	up nr.		II	
Total	mass d	ry	g	102,03	96	,17	11	5,52	54,79		29	,15	Tot ma	ss wet	g	96,5	
Mass	water		g	30,27	22	,21	30	,83	6,1		1		Tot ma	lss dry	g		155,65
Mass	cup		g	22,17	26	,83	21	,89	25,48		22	2,43	Mass r	ing/cup	g	31,08	108,25
Masse	e dry sa	mple	g	79,86	69	,34	93	,63	29,31		6,	72	Mass v	vet sample	g	65,42	65,42
													Mass d	ry sample	g	47,4	47,4
Water	r contei	nt		37,9 %	32	.,0 %	32	,9 %	20,8 9	%	14	,9 %	Volum	e (cm ³)		34,4	34,4
													Densit	$y (g/cm^3)$		1,90	1,38

<th colspa<="" th=""><th>Ro</th><th>utin</th><th>e ir</th><th>IV</th><th>estiga</th><th>tio</th><th>ons</th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th></th>	<th>Ro</th> <th>utin</th> <th>e ir</th> <th>IV</th> <th>estiga</th> <th>tio</th> <th>ons</th> <th></th>	Ro	utin	e ir	IV	estiga	tio	ons											
Bore-ber IV9-9.80mm <td colspace<<="" td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>A</td><td>lberto Monta</td><td>fia/</td><td>Гonje</td><td></td></td>	<td></td> <td>A</td> <td>lberto Monta</td> <td>fia/</td> <td>Гonje</td> <td></td>														A	lberto Monta	fia/	Гonje	
Borehole I I Date sample I State sample IS 04/13 IS 04/13 IS 04/13 Cround W P 0ate opening IS 04/13 IS 04/13 IS 04/13 Ground wat N N Grain density inversion density inversin density inversion densindensity inversin densi	Locat	tion			Dragvol	11			O	perator	•			Ei	de Helle				
Depti m Date openior IR/04/13 IR/04/13 <th< td=""><td>Boreh</td><td>nole</td><td></td><td></td><td>1</td><td></td><td></td><td></td><td>Da</td><td>ite samp</td><td>oling</td><td>5</td><td></td><td>15</td><td>5/04/13</td><td></td><td></td><td></td></th<>	Boreh	nole			1				Da	ite samp	oling	5		15	5/04/13				
<table-container>Ground water in any interval of sample.mGrain density From provent unterval of sample.Length of sample.78,9CnMass pronound any interval of sample.183,04cm³Mass pronound any interval of sample.19,44gMass value in any interval of sample.183,04cm³Mass pronound any interval of sample.159,44gMass value interval of sample.525,37gValue interval of sample.159,44gMass value interval of sample.525,37gValue interval of sample.28,47gMass value interval of sample.17,93g/Cm³Grain value interval of sample.28,47gMass value interval of sample.19,37g/Cm³Grain value interval of sample.17,03gg/Cm³71219,37g/Cm³Grain value interval of sample.11,04711,04711,04711,0471217Falling value interval of sample.Falling value interval of sample.19,04719,04719,04719,0471344UCGrain value interval of sample.Sample.Sample.10,04710,04710,04710,04710,04714Grain value interval of sample.Sample.Sample.Sample.Sample.10,047<td>Depth</td><td>1</td><td></td><td></td><td>9-9,80</td><td></td><td>m</td><td></td><td>Da</td><td>ite open</td><td>ing</td><td></td><td></td><td>18</td><td>3/04/13</td><td></td><td></td><td></td></table-container>	Depth	1			9-9,80		m		Da	ite open	ing			18	3/04/13				
Length of sample, L 78,9 cm Mass pycnemet+water 148,47 g g 3.2 °L 1830,48 cm ³ Mass pycnewet+sample 159,44 g 3.2 °L 1830,48 cm ³ Mass pycnewet+sample 159,44 g Mass pycnewet+se 525.7 g Total dry mass 22×4.9 g Mass pycnewet+se 525.7 g Total dry mass 22×4.9 g Mass pycnewet+se 1728,7 g Mass pycnewet+se 21,146 g Mass pycnewet+se 1728,7 g Mass pycnewet+se 21,146 g Second 8 KN/M E 11,46 g Second 8 KN/M E 12,80	Grou	nd wate	r				m		Gı	ain de	nsity	y fr	om pycn	ometer					
	Lengt	h of sa	mple,	L	78,9		cm		Ma	ass pyci	nom	eter	r+water	14	18,47			g	
	Volur	ne of sa	ample,		1000.40														
$ \begin{array}{c c c c c c c } \ \begin{tabular}{c c c c } \ \begin{tabular}{c c c c c c } \ \begin{tabular}{c c c c c c c c } \ \begin{tabular}{c c c c c c c c c c c c c c c c c c c $	23,2*	L			1830,48	\$	cm ³		Ma	ass pyci	n.+v	vate	er+sampl	e 15	9,44			g	
	Mass w/san	cynnae	er		52537		g		То	tal dry	mag	c		22	98 /0			a	
	Mass	empty	cylind	er	1728.7		g		M		mas	3		21	1 /6			5 g	
	Mass	sample	c ynno		3525		σ		M	ass dry				17	1,40			5 o	
	Densi	tv	, 		1.93		g/cr	m ³	Gr	ain den	sitv			2	,05 81			s g/cm ³	
	Speci	fic wei	ght		18.89		kN/	m ³		uni uch	Shty			,				g/em	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Samp	le sub	divisio	n	,		Gene	ral (classifi	ication			Routin	e param	eters				
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	0	5	Х				Clay						Plastici	ty index.	PI	2,	30%		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	5	7	Wate	er co	ontent, w1		Quick	5					Liquid	Index, L	I	58	1,23%		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	7	12	Dens	sity	small ring,	ρ							Porosit	y, n		47	,41%		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	12	17	Falli	ng c	one, ⊽1								Void ra	tio, e		0,9) 0		
$ \begin{array}{ c c c c c c c c c c } \hline \begin matrix $	17	22	Salt	1									Saturati	ion		10	3,69%		
2233size distributionSalt contentSalt content $[g/]$ 3344UCSVCSPW Conductivity $0,75$ mS4246Water content, w2Falling cone, $\nabla 2$ SampleSuSrStForce ε SuSu5156Salt 2, wp, wlnr.kPakPaKg%kPakPa5673Geochemistry115,20,11524,34 $8,73$ 7375Water content, w3215,20,11524,34 $*$ 7375Water content, w3215,20,11524.3 M $*$ K 7578XVV115,20,1152 M M V V V Value content, w3215,20,1152 M V V V V Value content, w3215,20,1152 M V V V V Value content, w3215,20,1152 V			Grai	n de	nsity, grair	1													
3344UCSPW Conductivity $0,75$ mS4246Water content, w2Falling cone, $\nabla 2$ SampleSuSrStForce ϵ SuSu5156Salt 2, wp, w1nr.kPakPaKg $\%$ $\%$ kPa5673Geochemistry115,20,11524,34 k 8,737375Water content, w3215,20,11524,34 k 8,737578XVIVvaluevaluevaluevaluevalueWater content, w3215,20,1152Valuevaluevaluevalue7578XVVvaluevaluevaluevaluevaluevaluevaluevaluevaluevalueGanda Kater content, w3215,20,1152Valuevalue <t< td=""><td>22</td><td>33</td><td>size</td><td>distı</td><td>ribution</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Salt cor</td><td>ntent</td><td></td><td></td><td></td><td>g/l</td></t<>	22	33	size	distı	ribution								Salt cor	ntent				g/l	
42 46 Water content, w2 Falling conc, ∇2 Sample Su Sr St Force $ε$ Su 51 56 Salt 2, wp,wl nr. kPa kPa Kg % kPa kPa 56 73 Geochemistry 1 15,2 0,1 152 4,3 4 8,73 73 75 Water content, w3 2 15,2 0,1 152 4,3 4 8,73 75 78 X 2 15,2 0,1 152 4. 7 1 15,2 15,2 1 15,2 1 15,2 4,3 4 8,73 75 78 X 15,2 0,1 15,2 1<	33	44	UCS										PW Co	nductivi	ty	0,	75	mS	
46 51 Falling cone, $\nabla 2$ Sample Su Sr St Force ϵ Su 51 56 Salt 2, \forall , \forall , \forall , \forall nr. kPa kPa kg % % kPa 56 73 Geochemistry 1 15,2 0,1 152 4,3 4 8,73 73 75 Water content, w3 2 15,2 0,1 152 4,3 4 8,73 75 78 X 15,2 0,1 152 - 1 152 - 1 152 - 1 1 152 1 152 - 1 - - 1 - - 1 - - 1 - - 1 -	42	46	Wate	er co	ontent, w2		Fallir	ng co	one	•	1		UCS		I		_		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	46	51	Falli	ng c	cone, ∇2		Samp	le	Su	Sr	St		Force		3		Su		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	51	56	Salt	2, w	p,wl		nr.		kPa	kPa			Kg		%		kPa		
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	56	73	Geod	chen	nistry		1		15,2	0,1	15	2	4,3		4		8,73		
75 78 X w1 w2 w3 w1 wp Density small ring Cup nr. 219 203 212 221 3 Image: Cup nr. Ring Cup Total mass wet g 128,72 140,22 114,21 62,4 36,54 Ring/cup nr. Image: Cup Image: Cup Total mass dry g 102 110,75 91,91 56,11 35,2 Tot mass wet g 97,58 88,95 Mass water g 26,72 29,47 22,3 6,29 1,34 Tot mass dry g 97,58 88,95 Mass cup g 23,88 26,64 25,96 27,78 Mass ring/cup g 31,08 22,57 Mass dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 64,51 66,38 Mass dry sample g 49,13 49,13 49,13 49,13	73	75	Wate	er co	ontent, w3		2		15,2	0,1	15	2							
Water content w1 w2 w3 w1 wp Density small ring Cup nr. 219 203 212 221 3 Image: Cup nr. Ring Cup Total mass wet g 128,72 140,22 114,21 62,4 36,54 Ring/cup nr. II 113 Total mass dry g 102 110,75 91,91 56,11 35,2 Tot mass wet g 97,58 88,95 Mass water g 26,72 29,47 22,3 6,29 1,34 Tot mass dry g 71,7 Mass cup g 23,88 26,64 25,96 27,78 Mass ring/cup g 31,08 22,57 Masse dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 66,5 66,38 mass dry sample g 78,12 84,11 65,95 30,15 7,42 Mass dry sample g 49,13 49,13	75	78	Х		1	1								r					
Cup nr.2192032122213RingCupTotal mass wetg128,72140,22114,2162,436,54Ring/cup nr.II113Total mass dryg102110,7591,9156,1135,2Tot mass wetg97,5888,95Mass waterg26,7229,4722,36,291,34Tot mass dryg71,7Mass cupg23,8826,6425,9625,9627,78Mass ring/cupg31,0822,57Masse dry sampleg78,1284,1165,9530,157,42Mass wet sampleg69,566,38Image: dry sampleg11111111Image: dry sampleg78,1284,11111111Image: dry sampleg78,1284,111 <td>Wate</td> <td>r conte</td> <td>ent</td> <td></td> <td>w1</td> <td>W.</td> <td>2</td> <td>w3</td> <td>3</td> <td>wl</td> <td></td> <td>W</td> <td>0</td> <td>Densit</td> <td>y small ring</td> <td></td> <td></td> <td>~</td>	Wate	r conte	ent		w1	W.	2	w3	3	wl		W	0	Densit	y small ring			~	
Total mass wetg128,72140,22114,2162,436,54Ring/cup nr.III113Total mass dryg102110,7591,9156,1135,2Tot mass wetg97,5888,95Mass waterg26,7229,4722,36,291,34Tot mass dryg71,7Mass cupg23,8826,6425,9625,9627,78Mass ring/cupg31,0822,57Masse dry sampleg78,1284,1165,9530,157,42Mass wet sampleg66,566,38Image: transition of the state of	Cup n	ır.		_	219	20)3	21	2	221		3		D : (Ring	Cup	
Total mass dry g 102 110,75 91,91 56,11 35,2 Tot mass wet g 97,58 88,95 Mass water g 26,72 29,47 22,3 6,29 1,34 Tot mass dry g 71,7 Mass cup g 23,88 26,64 25,96 25,96 27,78 Mass ring/cup g 31,08 22,57 Masse dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 66,5 66,38 Mass dry sample g 49,13 49,13	Total	mass w	vet	g	128,72	14	0,22	11	4,21	62,4		36	0,54 . 0	Ring/c	up nr.		11	113	
Mass water g 26,72 29,47 22,3 6,29 1,34 Tot mass dry g 71,7 Mass cup g 23,88 26,64 25,96 25,96 27,78 Mass ring/cup g 31,08 22,57 Masse dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 66,5 66,38 L L L L L Mass dry sample g 49,13 49,13	I otal	mass d	ry	g	102	11	0,75	91	,91	56,11		30	0,2 24	T ot ma	ss wet	g	97,58	88,95	
Mass cup g 25,88 26,04 25,96 27,78 Mass fing/cup g 51,08 22,57 Masse dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 66,5 66,38 Image: dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 49,13 Image: dry sample g 49,13 49,13 49,13 49,13 49,13	Mass	water		g	26,72	25	,47	22	,3	6,29		1,.	34 79	1 ot ma	iss dry	g	21.09	/1,/	
Masse dry sample g 78,12 84,11 65,95 30,15 7,42 Mass wet sample g 60,5 60,58 Imass dry sample g 49,13 <td>Mass</td> <td>cup</td> <td></td> <td>g</td> <td>23,88</td> <td>20</td> <td>0,64</td> <td>25</td> <td>,96</td> <td>25,96</td> <td></td> <td>21</td> <td>7,78 42</td> <td>Mass r</td> <td>ing/cup</td> <td>g</td> <td>31,08</td> <td>22,57</td>	Mass	cup		g	23,88	20	0,64	25	,96	25,96		21	7,78 42	Mass r	ing/cup	g	31,08	22,57	
Mass dry sample g 49,13 49,13	Masse	e ary sa	unpie	g	/8,12	84	,11	03	,90	30,15		1,4	+2	Mass V		g	40.12	40.12	
Water content $24.2.0\%$ $25.0.0\%$ $22.9.0\%$ $20.0.0\%$ $19.1.0\%$ Values (cm3) 24.4 24.4	Wata	. oontoo	. t	-	24.2.0/	25	C 0/	22	Q 0/	20.04)/.	10	2 1 0/	Webwe	ry sample	g	49,15	49,13	
water content $54,2$ % $53,0$ % $20,9$ % $18,1$ % volume (cm ²) $54,4$ <	w ater	conter	n	-	34,2 %	32	9,0 %	33	,0 %	20,9 9	/0	18	9,1 %0	Density	$(\alpha/\alpha m^3)$		34,4 1 02	54,4 1.42	

Ro	utin	e in	IV	estiga	tic	ons											
				T									A	lberto Monta	fia/I	Helene	
Loca	tion			Dragvol	11			0	perator	•			K	ornbrekke			
Boreh	ıole			1				D	ate samj	oling			15	5/04/13			
Depth	1			10-10,8		m		D	ate oper	ning			16	5/04/13			
Grou	nd wate	r				m		G	rain de	nsity	fr	om pycn	ometer				
Lengt	th of sa	mple, I	L	79		cm		Μ	lass pyc	nome	eter	r+water	14	48,35			g
Volur	me of sa	ample,															1
23,2*	L			1832,8		cm ³		Μ	ass pyci	n.+w	ate	r+sample	e 16	55,71			g
Mass	cylinde	r		5460.4				T	1 . 1 .				20	00 74			
w/san	nple	. 1 1		5469,4		g		10	otal dry	mass	,		32	22,74			g
Mass	empty	cylinde	er	1819,92	<u></u>	g			ass cup				29	15,26 7.49			g
Mass	sample	;		3649,48	•	g			ass ary				21	72			g
Densi	ity	. 1. 4		1,99		g/cr	n ³	G	rain den	sity			2,	12			g/cm ³
Speci	lic weig	gnt divicio	<u></u>	19,55		Cono	m ³	alaccif	Figurian			Doutin	0 D 0 P 0 P	otorg			
0		X X				Clay		1185511				Plastici	ty index	DI	31	28%	
2	12	Geoc	han	<u> </u>		Ouicl						Liquid	Index I	, 1 1 T	15	6 56%	
12	12	w1	nen	.1.		Quick	<u> </u>					Porosit		1	45	52%	
12	20	S1										Void ra	y, n		45	,5270 84	
20	25	X										Saturati	ion		10) , 12 74%	
26	31	ρ										Salt cor	ntent		10	2,7470	g/l
31	36	∇1									_	PW Co	nductivi	ty	0.	75	mS
36	45	Ødo				Fallir	ig ce	one			_	UCS		<u> </u>			
45	46	w2				Samp	le	Su	Sr	St		Force		3		Su	
46	57	UCS				nr.		kPa	kPa			Kg		%		kPa	
57	62	∇2				1		14,9	0,1	149)	6		3,5		12,24	
62	71	K, ps	i.			2		12,7	0,1	127	7						
71	75	S2, w	/l, w	vp													
75	78	w3															
Wate	r conte	ent		w1	w.	2	w3	3	wl		wp)	Densit	y small ring			
Cup r	ır.			200	68	}	49	1	108		3					Ring	Cup
Total	mass w	vet	g	158,19	83	3,74	11	4,4	63,26	1	36	,64	Ring/c	up nr.		Π	53
Total	mass d	ry	g	127,49	69	9,84	92	,28	56,45		35	,39	Tot ma	iss wet	g	100,33	
Mass	water		g	30,7	13	3,9	22	,12	6,81		1,2	25	Tot ma	ıss dry	g		75,77
Mass	cup		g	27,47	24	,09	25	,48	21,89	1	27	,78	Mass r	ing/cup	g	31,08	22,93
Masse	e dry sa	umple	g	100,02	45	5,75	66	,8	34,56	1	7,6	51	Mass v	vet sample	g	69,25	69,25
ļ													Mass d	lry sample	g	52,84	52,84
Water	r contei	nt		30,7 %	30),4 %	33	,1 %	19,7 9	%	16	,4 %	Volum	e (cm ³)		34,4	34,4
							l						Densit	$y (g/cm^3)$		2,01	1,54

Location	Dragvoll	Depth	2,18
Borehole	D1	Clay	32,2%



Location	Dragvoll	Depth	3,18
Borehole	D1	Clay	28,4%



Location	Dragvoll	Depth	4,18
Borehole	D1	Clay	35,2%



Location	Dragvoll	Depth	5,18
Borehole	D1	Clay	36,7%



Location	Dragvoll	Depth	6,33
Borehole	D1	Clay	32,4%



Location	Dragvoll	Depth	8,14
Borehole	D1	Clay	48,8%



Location	Dragvoll	Depth	8,60
Borehole	D1	Clay	43,7%



Location	Dragvoll	Depth	9,27
Borehole	D1	Clay	45,0%



Location	Dragvoll	Depth	10,65
Borehole	D1	Clay	31,4%



Location	Dragvoll	σ' _{v0}	104kPa	m	21,8
Borehole	D1	σ'.	120kPa	$\mathbf{M}_{\mathbf{NC}}$	4 MPa
Depth	10,14	OCR	1,15		



Figure B-3: Dragvoll, stress-strain plot from oedometer and oedometer modulus M



Figure B-4: Dragvoll, summary of laboratory results (shear strength, water content, overconsolidation ratio)



Figure B-5: Dragvoll, summary of laboratory results (clay fraction, salt concentration)

c. Leira L17

- Laboratory analysis
- Grain size distribution
- Summary charts

Borehole		L17	L17
Coordinates	Ν	7029222 (ca.)	7029222 (ca.)
(UTM Zone 32, Euref89)	Е	570122 (ca.)	570122 (ca.)
Performed by		Multiconsult	NTNU
Date		12.11.2012	21.05.2013

Ro	utin	le i	n	V	estiga	tio	ons											
Loca	tion				Leira				0	perator	•			A	lberto Monta	fia		
Boreh	nole				17				Da	ate sam	pling	5		ch	leck			
Depth	ı				15,2		m		Da	ate oper	ning			05	5/02/2013			
Grou	nd wate	er					m		G	rain de	nsity	/ fr	om pycnometer					
Lengt	h of sa	mple	, L				cm		М	ass pyc	nome	ometer+water			148,35			
Volu	ne of s	ampl	e,															
23,2*	L						cm ³ Mass pycn.+wate					er+sampl	e 17	70,75			g	
Mass	cylinde	er																
w/san	nple						g Total dry mass						24	6,35			g	
Mass	empty	cylir	ide	r			g Mass cup							21	2,49			g
Mass	sample	•					g	2	M	Mass dry 33,86								g
Densi	ty c: ·	1.					g/cr	n°	G									g/cm ³
Speci	fic wei	ght	•				KN/	m³	1				D (*					
Samp	ole sub	divis	10N	1			Gene	ral	classif	ication			Routin	e param	neters	4	20/	
							Clay		.:				Plastici	ty index,	, PI	4,	5%	
							Very sensitive						Porosity n				9%	
							Some sand						Void ratio e					
													Volu ra	luo, e				
												_	Salurat	ntont				g/l
														nductivit	\$7	0	65	g/1
							Ealling cone					UCS					IIIS	
							Samp	lg U le	Su	u Sr			Force		8		Su	
							nr	10	kPa	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			Ka		<u> </u>		kPa	
							1		hi u	1.4			118		70		ini u	
							-			-,.								
Wate	r conte	ent			w1	W.	2	w?	3	wl		wr	0	Densit	y small ring			
Cup r	ır.																Ring	Cup
Total	mass v	vet		g	135,03					89,13		30),69	Ring/c	up nr.			
Total	mass d	ry		g	120,58					85,15		29	,22	Tot ma	ss wet	g		
Mass	water			g	63,37					66,6		20),66	Tot ma	ss dry	g		
Mass	cup			g	57,2					18,6		8,6	6	Mass r	ing/cup	g		
Mass	e dry sa	mpl	e	g	14,5					4,0		1,5	5	Mass v	vet sample	g		
														Mass d	ry sample	g		
Water content				25%					21%		17	'%	Volum	e (cm ³)				
														Densit	$y (g/cm^3)$			

Ro	utir	e :	in	V	estiga	tio	ons											
Loca	tion				Leira				C	Operator				A	lberto Monta	fia		
Borel	nole				17				Γ	Date samp	oling	5		ch	leck			
Depth	ı				17,25		m		Ľ	Date open	ing			05	5/02/2013			
Grou	nd wate	er					m		6	Grain density from pycnom				ometer	ometer			
Leng	th of sa	mpl	e, L				cm		Ν	Aass pyci	cnometer+water			14	148,35			
Volu	ne of s	amp	ole,															
23,2*	L						cm ³ Mass pycn.+wa					vate	er+sampl	e 15	52,93			g
Mass	cylind	er																
w/sar	nple						g Total dry mass						22	21,94			g	
Mass	empty	cyli	nde	r			g Mass cup						21	4,54			g	
Mass	sample	e					g Mass dry							7,	4			g
Densi	ity						g/cr	n ³ Grain density 2,62									g/cm ³	
Speci	fic wei	ght					kN/	m ³	<u> </u>									
Samp	ole sub	divis	SIOI	1			Gene	ral	classi	ification			Routin	e param	eters		70/	
							Clay		•,•				Plastici	ty index,	, PI	4,	/%	
							Very	sens	sitive				Liquid Index, LI 2: Porosity n				2%	
							Some sand						Porosit	Void ratio e				
													Void ra	tio, e				
													Saturat	ion				. /1
													Salt con	ntent		0	00	g/l
																	,80	mS
							Fallir	1g c	one	e v Gr (t Force					C	
							Samp	le	Su 1-Do		St		Force		8	Su 1-Da		
							nr.		KPa 21		80		кg		%	kPa		
							1		51	0,4	80							
Wate	r cont	ent			w1	w	2	w	3	w/1		11/1	n	Densit	v small ring			
Cupr	r cont	ciit			vv 1	vv.	4	w.	5	W1		w	P	Densit	y sinan ring	[Ring	Cup
Total	mass v	vet		σ	139.47					83.95		33	3 71	Ring/c	un nr		Ring	Cup
Total	mass d	lrv		5 0	122.47					79.81		32	2.51	Tot ma	ss wet	σ		
Mass	water			D g	63.75					60.79		25	5.47	Tot ma	ss drv	g		
Mass	cup			в g	58.7					19.0		7.0	0	Mass r	ing/cup	g		
Mass	e dry sa	ampl	le	g	17.0					4.1		1.	2	Mass v	vet sample	g		
		- P -	-	0	- 7 -					,-		- ,.		Mass d	ry sample	g		
Wate	r conte	nt			29%					22%		17	1%	Volum	e (cm ³)			1
water content													Densit	Density (g/cm ³)				

Ro	utin	le i	in	V	estiga	tio	ons											
Loca	tion				Leira				Ol	perator	•			A	lberto Monta	fia		
Boreh	nole				17				Da	te sam	oling			ch	leck			
Depth	ı				21,60		m		Da	te oper	ing			05	5/02/2013			
Grou	nd wate	er					m		Gi	rain de	nsity	fro	om pycnometer					
Lengt	th of sa	mple	e, L				cm		Ma	Mass pycnometer+water			14	148,78				
Volu	ne of s	ampl	le,							17								
23,2*	L						cm ³ Mass				n.+wa	ater	r+sampl	e 15	57,18			g
Mass	cylinde	er																
w/san	nple		1				g Total dry mass							30	04,21			g
Mass	empty	cylir	nde	r			g Mass cup							29	91,26			g
Mass	sample						g	2	Ma	ass dry	•.			12	2,95			g
Densi	r ·	1.					g/cr	n°	Gr	Grain density 2,85								g/cm ³
Speci	fic wei	gnt	•				KIN/	m ³	-1*e				D		4			
Samp	ble sub	aivis	sion				Gene	ral	classin	Ication		_	Diastiai	e param	DI	6	20/	
							Somo	000	rea ma	torial		_	Liquid	Indox I	, FI T	19	J%0	
							Some	00	u se ma	uenai		+	Dorosit		070			
													Void ratio, e					
													Saturati	ino, c				
												-	Salt cor	ntent				σ/l
													PW Co	nductivi	tv	1 ()	mS
							Falling cone						UCS					ing
							Samp	le	Su	u Sr S			Force	3		Su		
							nr.	-	kPa	Pa kPa			Кя		%		kPa	
							1		23,0	0,2	115		0					
Wate	r conte	ent			w1	W.	2	w?	3	wl		wp)	Densit	y small ring			
Cup r	nr.																Ring	Cup
Total	mass v	vet		g	197,6					126		32,	,48	Ring/c	up nr.			
Total	mass d	ry		g	168,9					114,3	9	30,	,93	Tot ma	iss wet	g		
Mass	water			g	66,6					63,75		21,	,78	Tot ma	iss dry	g		
Mass	cup			g	102,3					50,6		9,2		Mass r	ing/cup	g		
Mass	e dry sa	mpl	e	g	28,7					11,6		1,6	;	Mass v	vet sample	g		
														Mass d	lry sample	g		
Water	r conte	nt			28%					23%		179	%	Volum	e (cm ³)			
		_									_		Densit	$y (g/cm^3)$				

Ro	utir	le	in	V	estiga	tio	ons											
Loca	tion				Leira				0	perator				A	lberto Monta	fia		
Borel	nole				17				D	ate sam	oling	g		ch	leck			
Depth	ı				23,3		m		D	ate oper	ing			06	5/02/2013			
Grou	nd wate	er					m		G	rain de	nsity	y fr	om pycr	ometer	ometer			
Leng	th of sa	mpl	le, L	_			cm		Μ	Mass pycnometer+water			148,78				g	
Volu	ne of s	amp	ole,							17								
23,2*	L						cm ³ Mass pycn.+wate					er+sampl	+sample 155,05				g	
Mass	cylind	er																
w/sar	nple						g Total dry mass						22	22,32			g	
Mass	empty	cyli	inde	er			g Mass cup							21	.2,7			g
Mass	sample	e					g	g Mass dry						9,	62			g
Densi	ity						g/ci	n ³	-3 Grain density 2,87									g/cm ³
Speci	fic wei	ght					kN/	m ³		Q8 / 8								
Samp	ole sub	divi	SIO	n			Gene	ral	classi	fication			Routin	e param	eters		70/	
							Clay			1			Plastici	$\frac{1}{1}$ ty index,	, PI	3,	/%	
							Some	coa	arse m	aterial			Porosity n				22%	
													Porosit	y, n				
													Void ra	itio, e				
													Saturat	ion				. /1
													Salt col			0	0	g/I
							Falls			۵			PW CO	nauctivii	ly	0,	9	ms
							Fain		one	e Sa			Eorce		c		C.,	
							Samp	le	Su kDo	I = Sr = St			Force	<u>٤</u> ٥⁄		Su IrDo		
							111. 1		кга	NF a			Кg		%		кга	
							1			0,5								
Wate	r cont	ent			w1	w	2	w	3	wl		WI	n	Densit	v small ring			
Cup r	nr.	ciit					_		5				2	Densie	,		Ring	Cup
Total	mass v	vet		g	122.08					88.33		30).48	Ring/c	up nr.		Tung	
Total	mass d	lrv		g	109.05					84.13		29	0.22	Tot ma	ss wet	g		
Mass	water	5		g	63,75					63,75		21	,78	Tot ma	ss dry	g		
Mass	cup			g	45,3					20,4		7,	4	Mass r	ing/cup	g		
Mass	e dry sa	amp	le	g	13,0					4,2		1,	3	Mass v	vet sample	g		
	2	1		5								,		Mass d	ry sample	g		1
Water content				29%					21%		17	1%	Volum	e (cm ³)				
water content												Dens		Density (g/cm ³)				

Ro	utin	e	in	V	estiga	tio	ons											
Loca	tion				Leira				O	perator				A	lberto Monta	fia		
Borel	nole				17				Da	ite samj	oling			ch	leck			
Depth	1				25,5		m		Da	te oper	ing			06	5/02/2013			
Grou	nd wate	er					m		Gi	rain de	nsity	fr	om pycn	nometer				
Leng	th of sa	mpl	e, L	,			cm		M	ass pyc	nome	eter	+water	14	8,93			g
Volu	ne of s	amp	ole,															
23,2*	L						cm ³		M	ass pyci	n.+w	ate	r+sampl	e 15	56,47			g
Mass	cylinde	er													0.65			
w/sar	nple	1.					g		To	otal dry	mass	3		31	2,67			g
Mass	empty	cylı	nde	r			g		Ma	ass cup				30	0,98			g
Mass	sample	•					g	2	Ma	$\frac{1}{1}$	•,			1	.,69			g
Densi	rty	. 1. 4					g/cr	n ³	Gr	ain den	sity			2,	82			g/cm ³
Speci	fic wei	gnt	~ ! ~ -				KIN/	m ³	alaarif				Dantin					
Samp	bie sub		SIO	1			Clay	rai	ciassii				Diactici	e paran	DI	1	20/	
							Some	<u> </u>	arca ma	torial			Liquid	Index I	, FI T	4,2	10%	
							Some	00		uertai			Porosit		1	20	1 /0	
													Void ra	tio e				
													Saturati	on				
												Salt cor	ntent				g/]	
													PW Co	nductivi	v	0.9	95	mS
							Fallir	ng c	one				UCS		- J	•,•	-	
							Samp	le	Su	Sr	St		Force		3		Su	
							nr.		kPa	kPa			Kg		%		kPa	
							1		32	0,37	88							
Wate	er conte	ent			w1	W.	2	w?	3	wl		wŗ)	Densit	y small ring			
Cup r	nr.																Ring	Cup
Total	mass v	vet		g	109,25					73,39		31	,28	Ring/c	up nr.			
Total	mass d	ry		g	99,92					65,36		29	,93	Tot ma	lss wet	g		
Mass	water			g	63,37					26,3		21	,29	Tot ma	lss dry	g		
Mass	cup			g	36,6					39,1		8,6	5	Mass r	ing/cup	g		
Mass	e dry sa	ampl	le	g	9,3					8,0		1,4	4	Mass v	vet sample	g		
												Mass dry sample g						
Wate	r conte	nt			26%					21%		16	%	Volum	e (cm ³)			
														Densit	$y (g/cm^3)$			

Ro	utin	le i	in	V	estiga	tio	ons											
Loca	tion				Leira				0	perator	•			А	lberto Monta	fia		
Boreł	nole				17				D	ate sam	oling	g		cł	neck			
Depth	1				27,7		m		D	ate oper	ing	-		00	5/02/2013			
Grou	nd wate	er					m		G	rain de	nsity	y fr	om pycr	nometer	neter			
Leng	th of sa	mple	e, L				cm		Μ	Mass pycnometer+water 148,78					g			
Volu	me of s	amp	le,															
23,2*	L						cm ³	•	Μ	lass pyci	n.+v	vate	er+sampl	e 10	53,31			g
Mass	cylind	er							-									
w/sar	nple	1.	1				g		T	otal dry	mas	s		23	34,04			g
Mass	empty	cylii	nde	r			g		M	lass cup				2.	11,46			g
Mass	sample	9					g	. 2	M	lass dry				22	2,58			g
Densi		. 1. 4					g/cr	n ³	G	rain den	sity			2,	80			g/cm ³
Speci	lic wei	gnt J::					KIN/	m ³	alaasii	C			Dartin					
Samp	bie sub		5101	1			Clay	rai	ciassii				Diastici	e paran	DI	5	70/	
							Some	<u> </u>	area m	atorial			Liquid	Index I	, F1 T	$\frac{3}{23}$	8%	
							Some	00		ateriai			Porosit	nucz, L	1	2.	10 /0	
													Void ra	y, II Itio e				
													Saturat	ion				
													Salt co	ntent				o/1
													PW Co	nductivi	tv	0.	85	mS
							Fallir	ng c	one				UCS		- ,	о,		
							Samp	le	Su	Sr	St		Force		3		Su	
							nr.		kPa	kPa			Kg		%		kPa	
							1		24,3	0,25	99)						
Wate	er conte	ent			w1	W	2	w.	3	wl		W	р	Densit	y small ring			
Cup r	ır.																Ring	Cup
Total	mass v	vet		g	113,4					44,3		30),45	Ring/c	up nr.			
Total	mass d	lry		g	102,88					41,3		29	9,29	Tot ma	iss wet	g		
Mass	water			g	66,6					27,11		21	,78	Tot ma	ıss dry	g		
Mass	cup			g	36,3					14,2		7,	5	Mass r	ing/cup	g		
Mass	e dry sa	ampl	e	g	10,5					3,0		1,	2	Mass wet sample g				
												Mass dry sample g						
Wate	r conte	nt			29%					21%		15	5%	Volum	e (cm ³)			
														Densit	$y (g/cm^3)$			

Ro	utin	le i	in	V	estiga	tio	ons											
Loca	tion				Leira				0	perator	•			A	lberto Monta	fia		
Boreh	nole				17				D	ate samj	oling	g		ch	eck			
Depth	ı				29,3		m		D	ate oper	ing			08	8/02/2013			
Grou	nd wate	er					m		G	rain de	nsit	y fr	om pycr	ometer				
Lengt	h of sa	mple	e, L	,			cm		Μ	Mass pycnometer+water 148,93					g			
Volui	ne of s	amp	le,															
23,2*	L						cm ³	•	Μ	lass pyci	n.+v	vate	er+sampl	e 15	58,15			g
Mass	cylind	er							-									
w/san	nple	1.	1				g			otal dry	mas	s		22	26,93			g
Mass	empty	cylii	nde	r			g		M	lass cup				21	2,7			g
Mass	sample	9					g	. 2	M	lass dry				14	,23			g
Densi	ty C	. 1. 4					g/cr	m ³	G	rain den	sity			2,	84			g/cm ³
Speci	lic wei	gnt a::/					KIN/	m ²	alaasi	Fination			Doutin		otora			
Samp	ne sub		5101	1			Clay	rai	classi				Diastici	ty index	DI	4	70/	
							Some	005	area m	atorial			Liquid	Index I	r I	4,	30/	
							Some	00		ateriai			Porosit		L	1.5	570	
													Void ra	tio e				
													Saturat	ino, c				
													Salt co	ntent				o/1
													PW Co	nductivit	v	0.9	9	mS
							Fallir	ng c	one				UCS		.)	•,	-	ing
							Samp	le	Su	Sr	St		Force		3		Su	
							nr.		kPa	kPa			Kg		%		kPa	
							1			0,32			0					
Wate	r cont	ent			w1	W	2	w.	3	wl		W	р	Densit	y small ring			
Cup r	ır.																Ring	Cup
Total	mass v	vet		g	87,88					70,2		30),06	Ring/c	up nr.			
Total	mass d	lry		g	80,55					62,77		28	3,85	Tot ma	ss wet	g		
Mass	water			g	48,87					26,8		21	,29	Tot ma	ss dry	g		
Mass	cup			g	31,7					36,0		7,	6	Mass r	ing/cup	g		
Mass	e dry sa	ampl	le	g	7,3					7,4		1,	2	Mass v	vet sample	g		
														Mass d	ry sample	g		
Water	r conte	nt			29%					21%		16% Volume (cm ³)						
														Densit	$y (g/cm^3)$			

Ro	utin	e ir	IV	estiga	ti	ons											
Loca	tion			Leira				0	perator	•			A	lberto Monta	fia		
Boreł	nole			17				D	- ate samj	oling	g		ch	leck			
Depth	1			31,2		m		D	ate oper	ing	-		08	3/02/2013			
Grou	nd wate	er				m		G	rain de	nsity	y fr	om pycr	ometer				•
Leng	th of sa	mple,	L			cm		Μ	lass pyci	nom	leter	r+water	14	8,78			g
Volu	ne of s	ample,	,														
23,2*	L					cm ³	3	Μ	lass pyci	n.+v	vate	er+sampl	e 16	55,15			g
Mass	cylinde	er												< # 0			
w/sar	nple	1. 1	1			g		T	otal dry	mas	S		31	.6,58			g
Mass	empty	cylind	er			g		M	lass cup				29	,58			g
Mass	sample					g		M	lass dry				23)			g
Densi	c	. 1. 4					m ³	G	rain den	sity			2,	90			g/cm³
Speci	lic wei	gnt Ji-Jaia				KIN/	m	ala asii	Plac 41 am			Dartin					
Samp	bie sub		n			Clau	ral	classi				Dlastici	e paran	DI	5	50/	
						Some	COS	rso m	atorial			Liquid	Index I	, FI T	5,	570	
						Slight	tly d	lriad	ateriai			Porosit		1			
						Singin	uy u	ineu				Void ra	y, II				
												Saturat	ion				
											Salt co	ntent				σ/]	
												PW Co	nductivi	v	0.	7	mS
						Fallir	ng c	one				UCS		- J	•,		
						Samp	le	Su	Sr	St		Force		3		Su	
						nr.		kPa	kPa			Kg		%		kPa	
						1		31,7	1,2	26	;						
Wate	er conte	ent		w1	W	2	wâ	3	wl		wj	р	Densit	y small ring			
Cup r	nr.															Ring	Cup
Total	mass v	vet	g						83,6		28	3,6	Ring/c	up nr.			
Total	mass d	ry	g						80,12		27	,47	Tot ma	ss wet	g		
Mass	water		g						66,18		21	,66	Tot ma	ss dry	g		
Mass	cup		g						13,9		5,	8	Mass r	ing/cup	g		
Mass	e dry sa	mple	g						3,5		1,	1	Mass wet sample g				
											Mass dry sample g						
Wate	r conte	nt							25%		19	9%	Volum	e (cm ³)			
													Densit	y (g/cm ³)			

Ro	utin	e i	nv	76	estigat	tio	ons											
Loca	tion				Leira				0	perator	,			A	lberto Monta	fia		
Borel	nole				17				Da	te sam	oling			ch	leck			
Depth	ı				33,5		m		Da	ate oper	ing			08	3/02/2013			
Grou	nd wate	er					m		G	rain de	nsity	fr	om pycn	ometer				
Leng	th of sa	mple,	L				cm		Μ	ass pyci	nome	eter	+water	14	18,93			g
Volu	ne of s	ample	,															
23,2*	L						cm ³		Μ	ass pyci	n.+w	ate	r+sampl	e 15	54,51			g
Mass	cylinde	er							-						0.00			
w/sar	nple	1.	1				g		To	otal dry	mass	3		21	9,09			g
Mass	empty	cyline	ler				g		M	ass cup				21	.0,53			g
Mass	sample	•					g	2	M	ass dry	•,			8,	56			g
Densi	rty	. 1. (g/cr	n ³	G	ain den	sity			2,	87			g/cm³
Speci	lic wei	gnt J:::					KIN/	m ⁹	alaasif	ication		-	Doutin					
Samp	bie sub	aivisi	on				Clay	rai	ciassii	Ication			Diactici	e paran	DI	6	20/	
							Some	<u> </u>	rsa m	torial			Liquid	Index I	, FI T	0,.	2 70	
							Slight	tu d	ried	uerrar			Porosit		1			
						blightly und				Void ra	tio e							
													Saturati	ino, c				
												Salt cor	ntent				σ/]	
													PW Co	nductivi	v	0.9)	mS
							Fallir	ng c	one				UCS		- J	•,•	-	
							Samp	le	Su	Sr	St		Force		3		Su	
							nr.		kPa	kPa			Kg		%		kPa	
							1			1,2								
Wate	er conte	ent			w1	w	2	w	3	wl		wŗ)	Densit	y small ring			
Cup r	nr.																Ring	Cup
Total	mass v	vet	8	5						93,24		33	,95	Ring/c	up nr.			
Total	mass d	ry	g	5						88,4		32	,78	Tot ma	ss wet	g		
Mass	water		g	5						66,6		25	,47	Tot ma	lss dry	g		
Mass	cup		g	5						21,8		7,3	3	Mass r	ing/cup	g		
Mass	e dry sa	mple	g	5						4,8		1,2	2	Mass wet sample g				
												Mass dry sample g						
Wate	r contei	nt								22%		16	%	Volum	e (cm ³)			
														Densit	y (g/cm³)			

Location	Leira	Depth	15,2
Borehole	L17	Clay	31,3%



Location	Leira	Depth	17,25
Borehole	L17	Clay	33,1%



Location	Leira	Depth	21,6
Borehole	L17	Clay	35,3%



Location	Leira	Depth	23,3
Borehole	L17	Clay	34,8%



Location	Leira	Depth	25,5
Borehole	L17	Clay	31,7%



Location	Leira	Depth	27,7
Borehole	L17	Clay	38,4%



Location	Leira	Depth	29,3
Borehole	L17	Clay	29,1%



Location	Leira	Depth	31,2
Borehole	L17	Clay	40,4%



Location	Leira	Depth	33,5
Borehole	L17	Clay	33,2%





Figure B-6: Leira, summary of laboratory results (shear strength, water content, overconsolidation ratio)



Figure B-7: Leira, summary of laboratory results (clay fraction, salt concentration)

C. Correlations


Figure C-1: Resistivity plotted versus normalized tip resistance Q, all sites



Figure C-2: Resistivity plotted versus pore pressure ratio B_q , all sites



Figure C-3: Resistivity plotted versus normalized side friction R_{f} , all sites



Figure C-4: Resistivity plotted versus "effective" tip resistance q_e , all sites

D. Pore water salinity and conductivity

Table D-1: Pore water salinity, in mg/l, calculated with the factors of Table 7-1.

Byneset	Depth (m)	3,75	4,6	5,65	6,7	7,7	8,55		9,65	10,55	
	Salt (mg/l)	2200	1000	900	500	600	600		500	600	
	Source*	Geo	Geo	Geo	Geo	Geo	Geo		Geo	Geo	
	Depth (m)					7,2	8,6	8,75	9,7		
	Salt (mg/l)					838	958	981	1867		
	Source*					UiO	UiO	UiO	UiO		
Dragvoll	Depth (m)	2,45	3,45	4,45	5,45	6,6	8,35		9,6	10,05	
	Salt (mg/l)	729	649	587	500	352	912		838	866	
	Source	NTNU	NTNU	NTNU	NTNU	NTNU	UiO		UiO	UiO	
	Depth (m)						8,47	9,17	9,5	10,15	10,7
	Salt (mg/l)						750	880	880	750	880
	Source*						Geo	Geo	Geo	Geo	Geo
	Depth (m)	11,4	15,2	17,25	21,6	23,3	25,5	27,7	29,3	31,2	33,5
Leira	Salt (mg/l)	540	720	890	1110	1000	1050	950	1000	780	1000
	Source*	Geo	Geo	Geo	Geo	Geo	Geo	Geo	Geo	Geo	Geo
Smørgrav	Depth (m)	2,25	3,25	4,2	5,6	6,6	8,7	9,45	10,5	11,5	
	Salt (mg/l)	200	600	900	1500	1800	2300	2100	2100	3000	
	Source*	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	
	Depth (m)	12,5	13,45	14,3	15,5	16,4	17,5	18,5	19,45	20,5	
	Salt (mg/l)	4000	5000	5800	7000	8000	8500	9000	10000	10000	
	Source*	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	

* Geo=NTNU Geotech. lab; UiO=OsloUniversity Dpt. of Geosciences; NTNU=NTNU Dpt. of Chemistry

Byneset	Depth (m)	3,75	4,6	5,65	6,7	7,7	8,55		9,65	10,55	
	EC(mS/m)	272	125	113	63	75	75		63	75	
	Source*	Geo	Geo	Geo	Geo	Geo	Geo		Geo	Geo	
	Depth (m)					7,2	8,6	8,75	9,7		
	EC(mS/m)					105	119	122	242		
	Source*					UiO	UiO	UiO	UiO		
	Depth (m)	2,45	3,45	4,45	5,45	6,6	8,35		9,6	10,05	
Dragvoll	EC(mS/m)	92	78	71	60	42	110		101	104	
	Source	NTNU	NTNU	NTNU	NTNU	NTNU	UiO		UiO	UiO	
	Depth (m)						8,47	9,17	9,5	10,15	10,7
	EC(mS/m)						90	106	106	90	106
	Source*						Geo	Geo	Geo	Geo	Geo
	Depth (m)	11,4	15,2	17,25	21,6	23,3	25,5	27,7	29,3	31,2	33,5
Leira	EC(mS/m)	66	88	109	135	122	128	116	122	95	122
	Source*	Geo	Geo	Geo	Geo	Geo	Geo	Geo	Geo	Geo	Geo
Smørgrav	Depth (m)	2,25	3,25	4,2	5,6	6,6	8,7	9,45	10,5	11,5	
	EC(mS/m)	25	75	113	188	225	284	259	259	366	
	Source*	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	
	Depth (m)	12,5	13,45	14,3	15,5	16,4	17,5	18,5	19,45	20,5	
	EC(mS/m)	482	595	682	805	920	966	1011	1111	1111	
	Source*	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	NGI	

Table D-2: Pore water conductivity at 25°C, in mS/m, calculated with the factors of Table 7-1.

* Geo=NTNU Geotech. lab; UiO=OsloUniversity Dpt. of Geosciences; NTNU=NTNU Dpt. of Chemistry

Byneset	Depth (m)	3,75	4,6	5,65	6,7	7,2	7,7	8,6	8,75	9,7	10,55
	Temperature (°C)	9,8	9,1	8,7	8	8	7,8	7,3	7,3	7,2	6,9
	EC(mS/m)	193	88	78	42	71	50	80	81	160	41
	Resistivity (Ωm)	5,2	11,5	12,9	23,6	14,0	19,8	12,6	12,4	6,2	24,4
	Depth (m)	2,45	3,45	4,45	5,45	6,6	8,35		9,6	10,05	
	<i>Temperature</i> ($^{\circ}C$)	6,2	5,7	5,3	5,3	5,7	6,2		6,3	6,3	
	EC(mS/m)	59	50	44	38	27	70		65	67	
Drogvoll	Resistivity (Ωm)	16,9	20,1	22,6	26,6	37,2	14,2		15,4	14,9	
Dragvon	Depth (m)						8,47	9,17	9,5	10,15	10,7
	Temperature (°C)						6,1	6,2	6,2	6,3	6,4
	EC(mS/m)						58	68	68	68	69
	Resistivity (Ωm)						17,3	14,7	14,7	14,7	14,6
	Depth (m)	11,4	15,2	17,25	21,6	23,3	25,5	27,7	29,3	31,2	33,5
Laina	Temperature (°C)	8,4	8,1	7,6	7,4	7,3	7,3	7,3	7,2	7,1	7,1
Lella	EC(mS/m)	45	60	73	90	81	85	77	81	63	81
	Resistivity (Ωm)	22,2	16,8	13,8	11,1	12,4	11,8	13,0	12,4	15,9	12,4
	Depth (m)	2,25	3,25	4,2	5,6	6,6	8,7	9,45	10,5	11,5	
Smørgrav	Temperature (°C)	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5	
	<i>EC (mS/m)</i>	17	50	75	125	150	190	173	173	244	
	Resistivity (Ωm)	59,9	20,0	13,3	8,0	6,7	5,3	5,8	5,8	4,1	
	Depth (m)	12,5	13,45	14,3	15,5	16,4	17,5	18,5	19,45	20,5	
	<i>Temperature</i> ($^{\circ}C$)	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5	
	<i>EC (mS/m)</i>	322	397	455	537	614	645	675	742	742	
	Resistivity (Ωm)	3,1	2,5	2,2	1,9	1,6	1,6	1,5	1,3	1,3	

Table D-3: Pore water conductivity in mS/m and resistivity in Ω m at specified temperature