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A Laboratory Study of Salt Diffusion and its Effect on Electrical Resistivity and Sensitivity in Quick Clay

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Abstract:

Electrical resistivity measurements as a geophysical method have become increasingly popular as a supplement to geotechnical field investigations over the last years. The main use for this method is to uncover the possibility of quick clay occurrences. Since low salt content indicates sensitive clay, resistivity profiles can give an image of potential quick clay deposits, as there is a strong relation between resistivity and salinity.

This aim of this study was to perform a laboratory experiment to verify the relation between salinity and resistivity in clay, and maybe get a broader understanding of the diffusion front of the salt. Index testing was preformed to compare the influence of salinity on the geotechnical parameters. An introduction to quick clay and the use of resistivity as geophysical measuring method is included to be able to evaluate and understand the laboratory experiment.

The laboratory set-up consisted of three 54 mm cylinders of quick clay coupled up to two tubes at each end, which worked as water reservoirs. One of the cylinders had tubes filled with water and the two others with different salt concentrations. Each cylinder had a number of electrodes, which made it possible to measure the change in voltage for each cylinder at a chosen time throughout the experiment. When the data was processed, the results of the average resistivity between the electrodes could give an indication of the diffusion front of the ions. It was performed index testing on one of the cylinders after 38 days to see how the salt had affected the clay.

The results indicate a strong relation between salt and resistivity and the change in geotechnical parameters. As the clay is applied more salt, the resistivity decreases. It is noticed an increase in disturbed and undisturbed shear strength with increasing ion diffusion front. The water content did not change noticeably, which coincided with earlier studies. When the salt reached a concentration front of approximately 0,5 g/L, it influenced the clay in such a way that it was more suitable for construction purposes.

Keywords:

1. Quick clay
2. Resistivity
3. Geophysics
4. Salinity

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PREFACE

This master thesis is done as part of the M.Sc. program for civil and geotechnical engineering at the Norwegian University of Science and Technology (NTNU). The work is carried out during the spring semester of 2016. The aim of the study was to perform a laboratory experiment to verify the relation between salinity and resistivity in clay, and maybe get a broader understanding of the diffusion front of the salt.

The experiment is a pilot project, which makes the process as important as the results. The decision of the laboratory set-up was time consuming, and limitations due cost and time made it difficult to get an ideal set-up. I have learned a great deal about the pre-phase process, and how much time it takes to come up possible ways to perform an experiment to retrieve some valuable results, and that many things may go wrong along the way.

I would like to thank Professor Gustav Grimstad, my supervisor, who has helped me with structuring and understanding how to go forward with my master thesis, with helping me defining and building my set-up, as well as being in contact with the borers and external companies to get my cylinders. Professor Gudmund R. Eiksund, who has come with useful input concerning the set-up and output data. Dr. Rolf Sandven at Multiconsult as a consultant, who has given me insight in how Multiconsult work with resistivity in the field and what type of problems they face with respect to resistivity. Dr. Inger-Lise Solberg, who has helped me gather information on the topic. Ph.D. Tonje Eide Helle, who has helped me with understanding how to design the laboratory set up based on what I wanted to achieve, and for the useful information based on earlier studies from the area, as well as teaching me how to perform salt measurements. M.Sc. Ingelin Gjengedal by sharing her master thesis, and knowledge concerning the topic. Head Engineer Per Østensen, who has helped me with the laboratory set up with making the electrical apparatus and program to retrieve the resistivity values. I would never have finished without his help. And at last my parents and my brother, for supporting me.

Trondheim, 10.06.2016

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SUMMARY

Resistivity measurements as a geophysical method have become increasingly popular as a supplement to geotechnical field investigations over the last years. The main use for this method is to uncover the possibility of quick clay occurrences. Since low salt content indicates sensitive clay, resistivity profiles can give an image of potential quick clay deposits, as there is a strong relation between resistivity and salinity.

To get a greater grasp of the relation between salt and resistivity a laboratory experiment was invented by introducing a marine clay to a brine. The laboratory set-up consisted of three 54 mm cylinders that were coupled up to two tubes at each end, which worked as water reservoirs. One of the cylinders had tubes filled with water and the two others with different salt concentrations. Each cylinder had a number of electrodes, which were coupled up to a voltmeter and a power source. The change in voltage between the electrodes were measured for each cylinder at a chosen times throughout the experiment, which then was compared to the results from the other cylinders. By having many electrodes perforating the clay, the resistivity along intervals in the clay could be found. An exact set-up like this is not known to have been performed before, but the results are comparable to earlier studies concerning resistivity measurements in quick clay due to salt exposure.

An introduction to the physical properties of quick clay and the use of resistivity as a geophysical measuring method are necessary to understand the theory behind the experiment. The relation between quick clay and resistivity is defined by their characteristics. Quick clay is defined by its internal structure, the formation and physical properties according to defined standards. Further, the characterization of the resistivity is based on basic physical laws, and the relation to water, salinity and changes in temperature, porosity etc. A brief description of resistivity used in the field, are included.

It was performed index testing of one of the cylinders after 38 days to see how the salt had affected the clay. The cylinder was divided into 16 parts for index testing. The results from the cylinder indicated a strong relation between salt and resistivity and changes in the geotechnical parameters. As the clay was applied more salt, the resistivity decreased. It is noticed an increase in remoulded and undisturbed shear strength with increasing ion diffusion front. The plasticity limit was expected not to change, but there were found an increasing plasticity limit when the salt content was increased. This is thought to be due to the plasticity limit being found after retrieving the salt content, which was found after centrifuging the water and stirring it back into

the clay. This could have altered the properties of the clay. The water content did not change noticeably, which coincided with earlier studies.

The average salt values for the samples at the bottom part of the clay cylinder were compared to the average length of the sample, which is considered to be the measured effective diffusion length. The measured and effective calculated diffusion length for the samples and its respectively salt content, shows that they correspond quite well, despite all simplifications made to be able to relate these values.

The trendline for the resistivity and salt, based on different clays in the earlier study by Long, is a bit higher than for the resistivity values retrieved from this experiment (Long et al., 2012). Some of the values does however correspond quite well, and any deviation may be caused by local variations or errors such as temperature, water content, clay content, porosity etc.

One can however conclude that the salt do decrease the resistivity, which with a high enough concentration front of approximately 0,5 g/L influence the clay in such a way that it is more suitable for construction purposes. The cost of such a procedure in the field is very high and also a very time-consuming proses (Helle, 2013). It will however be of interest to improve the ground conditions in many cases, such as in highly populated areas, mainly because the value of a secure and buildable ground may exceed the downside of the high costs related to the development.

SAMMENDRAG

Resistivitetsmålinger som en geofysisk metode har blitt mer populært å benytte seg av i geotekniske feltundersøkelser de siste årene. Hensikten med denne metoden er å detektere kvikkleire. Siden lavt saltinnhold indikerer sensitiv leire, kan man ved hjelp av resistivitetsprofiler gi et bilde av potensielle kvikkleireforekomster, da det er en sterk sammenheng mellom resistivitet og saltinnhold.

For å forstå relasjonen mellom salt og resistivitet, har det blitt oppfunnet og utført et laboratorieeksperiment ved a introdusere en marin leire til en saltløsning. Laboratorieforsøket besto av tre 54-mm sylindere som var oppkoblet til to rør som fungerte som vannreservoar. En av sylinderne hadde rør fylt med vann, og de andre to med ulik saltkonsentrasjon. Hver sylinder hadde et sett med elektroder, som var oppkoblet til et voltmeter og en strømkilde. Endringen i volt mellom elektrodene ble målt for hver sylinder etter en gitt tid gjennom hele forsøket, som la et sammenligningsgrunnlag for alle sylinderne. Ved å ha flere elektrodepunkter kunne man finne resistiviteten i intervaller langs med leira. Denne måten å utføre et eksperiment på er ikke kjent for å ha blitt utført tidligere, men resultatene er sammenlignbare med andre forsøk hvor kvikkleire er introdusert for saltløsninger.

Denne master oppgaven gir en introduksjon til de fysiske egenskapene til kvikkleire og bruken av resistivitetsmålinger som en geofysisk metode. Relasjonen mellom kvikkleire og resistivitet er definert av leiras karakteristikk. Kvikkleire er definert av indre struktur, formasjon og fysiske egenskaper i henhold til definerte standarder. Videre kan man karakterisere kvikkleire basert på fysiske lover, relasjon til vann, saltinnhold og endringer i temperatur, porøsitet osv. En rask gjennomgang av resistivitet og bruken av dette i felt er gjennomgått.

Det ble utført indekstesting på en av sylinderne etter 38 dager for å se hvordan saltet hadde påvirket leira. Leira ble inndelt i 16 biter under indekstesingen. Resultatene indikerer en sterk sammenheng mellom salt og resistivitet, og en endring i de geotekniske parameterne. Det viste seg at da leira ble usatt for mer salt sank resistiviteten. Det er registrert en økning i uomrørt og omrørt skjærstyrke med økende diffusjonsfront. Plastisitetsgrensen er forventet å ikke enders, men det ble funnet en økende plastisitetsgrense for økende mengde salt. Dette skyldes trolig at plastisitetsgrensen ble funnet etter saltinnholdet. Dette betyr at plastisitetsgrensen ble funnet etter at leira hadde blitt sentrifugert og vannet var rørt tilbake i leira, som kan ha endret leiras egenskaper. Vanninnholdet endret seg ikke nevneverdig, som samsvarer godt med tidligere studier.

Gjennomsnittsverdiene for salt fra prøvene fra den nedre delen av leirsylinderen er sammenlignet med gjennomsnittlig lengde av hver prøve, som er antatt å være den målte effektive diffusjonslengen. Den målte og beregnede effektive diffusjonslengden for prøvene og deres respektive saltinnhold, viser at disse verdiene samsvarer godt, på tross av alle nødvendige forenklinger for å finne resultatene.

Trendlinjen for resistiviteten og salt fra ulike leirer i det tidligere studiet av Long, er noe høyere enn for resistivitetsverdiene fra eksperimentet (Long et al., 2012). Noen av verdiene samsvarer imidlertidig ganske godt, og avvikene kan skyldes lokale variasjoner og feilkilder som f.eks. temperatur, vanninnhold, leirinnhold, porøsitet og lignende.

Man kan imidlertidig konkludere med at salt øker resistiviteten, som ved en høy nok konsentrasjonsfront på omtrent 0,5 g/L påvirker leira på en måte som gjøre den mer egnet for utbygging. Kostnaden for en slik prosedyre i felt er veldig høy og tidkrevende prosess (Helle, 2013). Mange steder vil det være interesse for å forbedre grunnforholdene, slik som i høyt befolkede områder, hovedsakelig fordi verdien av en trygg grunn, overgår ulempen av de høye kostnadene relatert til utbyggingen.

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CHAPTER 1

1 INTRODUCTION

Due to the danger related to the presence of quick clay, it is necessary to detect and find the boundaries to the areas where the quick clay is located. When overloaded, the quick clay can form avalanches and slides with large extent. This is a danger to the environment, and can cause fatalities and large destruction, if it occur. To avoid such unfortunate incidents there is a huge interest in locating these areas, making it possible to prevent such an outcome.

Today there are many methods used to identify and secure the areas where there is quick clay. This thesis will focus on electrical resistivity measurements, and how this can be used to identify and locate quick clay. A laboratory study is performed to illustrate the relation between resistivity and salinity in clay.

To get a greater grasp of the relation between salt and resistivity a laboratory experiment was invented by introducing marine clay to a brine. The laboratory experiment could give a broader understanding of the diffusion front of the salt. Index testing will be performed to compare the influence of salinity on the geotechnical parameters. The index tests needs to be included to be able to verify if the clay is quick or not.

1.1 BACKGROUND

The background of this master thesis is the NIFS-report (Naturfare, Infrastruktur, Flom og Skred), which translated to English means Danger in nature, Infrastructure, Flooding and Avalanches. One of the subjects of this report is brittle clay, which in many cases can be hard to detect, or that different surveys give different results for the sensitivity. Due to these ambiguous results, resistivity measurements as a geophysical method has become increasingly popular as a supplement to geotechnical field investigations over the last years.

The increase in population forces construction in unfavorable areas where quick clay may be located. The development areas may be city centers, larger road sections or large infrastructure projects. This creates challenges with respect to the geophysical and geotechnical measurement methods used to identify quick clay. Due to the extents of these projects, it is costly to identify and define the areas existing of quick clay. If it is possible to reduce the number of surveys, large amount of money can be saved. This will not only be beneficially for the companies responsible for building these roads and infrastructure, but it could also have a huge positive impact on the societies where quick clay deposits are common.

1.2 PROBLEM FORMULATION

How is resistivity used to detect quick clay and brittle clay, and how can a laboratory study be made to get a relation between resistivity and salinity when introducing a clay to a brine?

1.3 OBJECTIVES

The objective of this study is to make a laboratory study that could give a broader understanding of the relation between resistivity and salinity when introducing a clay to a brine. To be able to do that it is necessary to learn more about quick clay, and how resistivity measurements are used to locate quick clay deposits.

1.4 LIMITATIONS

The thesis is limited to a short literature study of quick clay and resistivity methods, which is necessary to understand the laboratory set-up and its results. This means that different programs for resistivity calculations are not included, the use of different arrays are not discussed (For further information concerning arrays see my project thesis (Øveraas, 2015)). The thesis is limited to a short introduction to 2D-, an 3D resistivity methods.

For the laboratory set-up some limitations due to time and cost are inevitable. The number of cylinders are decided based on minimizing cost and time, whilst at the same time getting necessary comparable results. One part from each cylinder has been index tested, to get a comparable basis when studying the results. Since this top part of the cylinder is most likely a disturbed one, results from Ph.D. student Tonje Eide Helle have been used to get values that are more accurate. Since the set-up is an original one, it has been time consuming to decide how the setup should be performed to be able to get the data needed for comparing the geotechnical parameters. There have also been limitations concerning the ability to get the right type and number of cylinders due to the lack of borers at the university. The cost of ordering cylinders from an external company is high, so it was preferable to use internal labor at NTNU if possible. Oedometer and triaxial testing have not been performed due to the lack of cylinders and to limit the extent of the project, but could be found for the site from (Helle et al., 2015). The index testing is limited to testing of water content, salt content, undisturbed and disturbed shear strength, and plasticity limit.

The theory applied to predict the diffusion of the salt is limited to Fick's 2. Law, and looked upon as a 1D problem. The input concentration is assumed constant, even though it is not the reality because the ions move into the clay, and the water may evaporate.

1.5 TERMINOLOGY

Since geotechnics and electro science originally are two separate fields, the symbols for the different quantities may sometimes overlap. This means that when talking about clay and soil ρ(rho) is the symbol of density, and when talking of electrical currents ρ is the symbol of resistivity. The same applies for the vertical stresses, which in geotechnics are termed σ. In electrical science, σ is termed conductance. Each chapter is clearly divided in its respectable field, and if the other field is mentioned, the symbols are explained to avoid confusion. Resistivity in this context is meant as electrical resistivity, which is the terminology that will be used throughout the thesis. When discussing diffusion front, length etc. it is meant as the effective self-diffusion of the salt.

CHAPTER 2

2 QUICK CLAY

2.1 PARAMETERS TO IDENTIFY QUICK CLAY

The following parameters are commonly used to identify quick clay.

2.1.1 Classification

There are many ways to classify soil, where one of the most common is based on particle size. Since soil is deposits of grains with different sizes, there is never a perfect homogeneous soil in nature, but there will be different fractions of different particle sizes. To know what is meant when one talk about different types of soil, it has to be classified, to avoid misunderstandings. The Norwegian way of this classification is illustrated in Table 2-1nbased on the table from (NGF, 1982a).

As seen from Table 2-1 clay is defined as minerals with size equal to or less than 2μm. To classify a material as clay, the clay content of the material has to be larger than 30 % (NGF, 1982a).

Table 2-1 The fractions and grain sizes that classify soil

Fraction		**Grain size**
Coarse Classification	Fine classification	[mm]
Boulder and Rock		
	Large Boulder	>630
	Boulder	200-630
	Rock	63-200
Gravel		2.0-63
	Coarse gravel	20-63
	Medium gravel	6.3-20
	Fine gravel	2.0-6.3
Sand		0.063-2.0
	Coarse sand	0.63-2.0
	Medium sand	0.2-0.63
	Fine sand	0.063-0.2
Clay		≤0.002

2.1.2 Sensitivity

The effect of disturbance in clay is called sensitivity. Sensitivity is defined as the ratio between the undisturbed and undrained remolded shear strength of a sample (NGF, 1982a),

$$S_t = \frac{c_u}{c_{ur}}$$

(2-1)

where, S_t is the sensitivity (-), c_u is the undisturbed shear strength in kN/m^2, c_{ur} is the undrained remolded shear strength in kN/m^2.

Since the undisturbed clay per definition has to be undrained to be undisturbed, the literature refer c_u as either undrained or undisturbed shear strength. Also undrained remolded shear strength is often shorted to remolded shear strength.

When the remolded shear strength is equal or less than 0,5 kN/m^2 and the sensitivity is equal or larger than 30 it is defined as quick clay (NGF, 1982a). In many contexts quick clay is mentioned together with brittle clays, which is defined as clay with remolded shear strength less than 2 kN/m^2 (NVE, 2014).

2.1.3 Water content

The water content is normally given as a percentage of the dried mass. Regular Norwegian clays has a water content of 20-40 %, which is an important parameter when it comes to clay (Emdal, 2006).

$$w = \frac{m_w}{m_s}\%$$

(2-2)

Where, w (%) is the water content, m_w (g) is the mass of water, m_s (g) is the mass of solid material

2.1.4 Plasticity index

As cited by (Emdal, 2006) plasticity index and liquidity index was first defined by Attenberg in 1913, and is why these limits are referred to as Attenberg limits. Plasticity is defined by (NGF, 1982a) as "a property of a soil consistent of fine material to change its mechanical behavior when the water content changes". This is the water content where the material is no longer able to form without jointing. The plasticity index is necessary to find the liquidity index, which could give an indication if the clay is quick or not. The plasticity index is given by (NGF, 1982a) as

$$I_p = w_L - w_p$$

(2-3)

Where, I_p is the plasticity index (%), w_L (%) is the liquid limit, w_p (%) is the plasticity limit (see appendix for more information concerning the limits.)

2.1.5 Liquidity index

The liquidity index is given by (NGF, 1982a) as “the numerical difference between the natural water content and the plasticity limit, given as a percentage of I_L.” It is the limit where the material changes from a plastic to liquid state.

$$I_L = 100\ \% \ \frac{w - w_p}{I_P}$$

(2-4)

If the liquidity index is less than the water content it indicates that the clay is quick (Solberg, 2010). This means that when disturbed, the quick clay turns into liquid. This property is highly unwanted, and may cause huge damages to the surroundings, if it occurs. Laboratory testing is therefore necessary to determine if the clay is quick or not.

2.1.6 Activity

The activity of a clay is dependent of the clay content in a clay and the plasticity index. If a material consist of small particles, rather than large particles, the total surface is larger, hence the ability to bind water is larger (Emdal, 2006). This ability is defined by (Skempton, 1984) as colloid activity

$$Activity = \frac{I_P}{clay\ fraction}$$

(2-5)

Table 2-2 by (Skempton, 1984) defines activity in clay as either inactive, normal or active clay.

Table 2-2 Table made based on (Skempton, 1984)

Activity in clays	
Classification	**Activity**
Inactive Clays	<0.75
Normal Clays	0.75-1.25
Active Clay	1.25

2.1.7 Porosity

When minerals are deposited in fresh water, the minerals will form a relatively compact structure, with little porosity. Porosity is defined by (NGF, 1982a) as :

$$n = \frac{V_P}{V_T}\ 100\ \%$$

(2-6)

Where, *n* (%) is the porosity, V_P (cm^3) is the volume of pores, V_T (cm^3) is the total volume

For further information concerning porosity and different types of porosity at a micro structural level of clay see (Fukue et al., 1999).

2.2 THE CLAY STRUCTURE

2.2.1 The ice age and todays marine boundary

Quick clay is related to the last ice age and the change of the marine boundary. To understand the structure of the Norwegian quick clay, and how it became the structure it is today, one has to go back to the Pleistocene time, which is our most recent glacial period. As a result of the massive glaciers that covered most part of Norway, the underlying rock eroded and were exposed to physical and chemical weathering. As the glaciers grew larger and larger, they pushed the underlying rock in front of the glacier, molding it into what is known as moraine. This glacial deposit consist of a variety of sizes of rock, also clay minerals. As a result of the increasing temperature the glaciers withdrew and today the glaciers are only present in the more elevated areas of Norway. The weight of the overlaying ice forced the underlying rock to set. This happened over a long period, and as a counter-effect of these settlements, the rock began to elevate when the glaciers where gone.

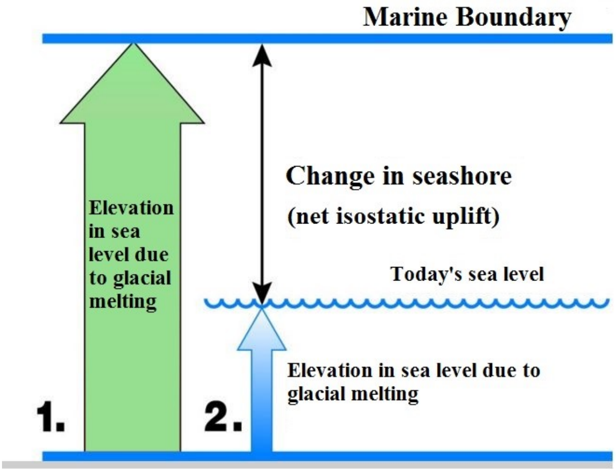


Figure 2-1 Picture from Harald Sveian (NGU) explaining change in marine boundary due to the influences from glaciers.

The elevations due to this phenomenon is registered even today (Kartverket, 2015). This is particular interesting in the coastal area. Figure 2-1 illustrates the change in marine boundary due to the isostatic uplift and the melting of the glaciers. The land that was former under seawater, which is no longer covered with saltwater, might still contain salt when not leached. These salt ions in the clay is part of its structure and helps the clay maintaining its strength. As long as the salt remains in the pore water, the strength is maintained, but the seawater level has sunken and the salt in the clay structure can be leached. When this happens, the clay loses its former strength and we refer to it as quick clay. To identify the quick clay there are national maps where the marine boundary is shown. These maps indicates where quick clay could be located.

When the clay loses its strength, it causes a threat to the surroundings because it can cause avalanches, landslides, destroy larger areas, and in worst case take human lives. All the clay that is located under the marine boundary, which is the clay that has been located under seawater at a time due to the glaciers, is in danger of being quick. These areas has to be examined/investigated to ensure that it is no presence of quick clay. Areas that do consist of quick clay have to be investigated further according to (NVE, 2014) and either prove to buildable (possible to build on), or not.

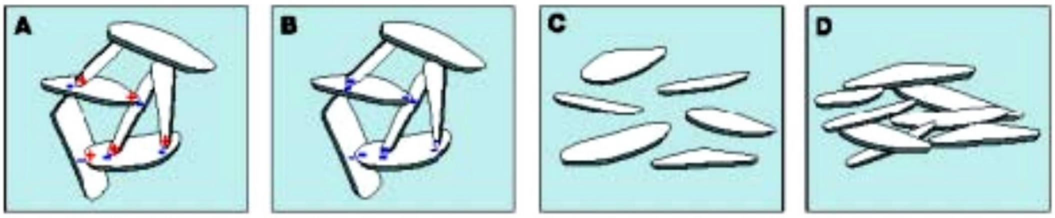
2.2.2 The clay minerals

The sedimentation of soil and crushed rock caused by glaciers and river transportation, gave a variety of minerals dependent on the composition of the bedrock. Clay minerals will therefore consist of different compounds, which may have an effect on the transportation of salt, due to the different charges and attraction forces that the clay may possess.

2.2.3 The clay structure

The internal structure of clay will be dependent on many factors, but one that is very important with respect to it being quick or not is the content of salt. As opposed to the compact structure that fresh water makes, saltwater will make a structure with relatively higher porosity. The porosity, the volume of pores of the total volume of a given sample, will be decisive for the flow of water. If the material has a large porosity, there are many or large pores, and the water can easily flow through the sample. This applies as long as the pores are connected. If the porosity is little to none, the water will have trouble to travel though the material. The relatively high porosity will occur due the charge of the ions that are present in the water. Note that clay is relatively compact compared to deposits of larger grains, even though it is a difference between the porosity of clay deposits in fresh and salt water.

If the water is filled with ions, the tension between the minerals will force a structure with more space between the clay minerals than for the clay minerals deposited in fresh water. This open structure will occur when clay minerals are deposited in saltwater (Sveian, 2002). This is not a problem until the salt leaches out of the clay, and the structure collapses. When it does collapse, it turns into a thinly liquid that flows out of proportions and can turn into a landslide.



Leire med saltholdig porevann
Tiltrekkende krefter mellom partiklenes kanter og flater. Små frastøtende krefter mellom flatene. Flakformige korn i en åpen, men stabil kornstrektur.

Kvikkleire før ras
Ingen eller små frastøtende krefter mellom kanter og flater. Større frastøtende krefter mellom flatene. Åpen og ustabil kornstruktur

Kvikkleire under ras
Kollaps av kornstruktur. Overskudd av vann. Tyntflytende leirsuppe.

Omrørt leire etter ras
Tettere og mer stabil kornstruktur

Figure 2-2 The figure is from (Sveian, 2002) showing different stages of clay.

Figure 2-2 shows four different stages of the quick clay (Sveian, 2002). Stage A shows clay with pore-water containing salt, where the attracting and rejecting forces creates an open but stable structure. Stage B shows quick clay before a landslide, where the rejecting forces are minor or none existent. This creates an open and unstable structure. Stage C shows the collapsing of the grain structure, which happens during a landslide. The excess of water makes the material into a thinly liquid. Stage D shows the disturbed clay after a landslide, which has a more dens and stable structure, than during sliding.

Clay is not very permeable and it will in some places take hundreds of years until the salt is fully leached (Solberg, 2010). However, since the permeability in soils in nature is inhomogeneous, there could be formed layers or areas with more permeability than others. This will result in higher leaching of salt in these areas, which could result in quick clay deposits. This will likely occur close to where the water flow is the largest; layers of permeable material like sand, at the bedrock or at the surface (Solberg, 2010).

2.2.4 Electrical double layer

One may divide the clay particle layers in two, where the inner layer is called the stern layer, and outer layer the diffuse layer as shown in Figure 2-3. The inner stern layer is consistent, whilst the outer diffuse layer exchange ions with the surroundings (Sciences, 2012). The stern layer has the opposite charge than the particle surface, which makes the ions want to stick to the particle. The ions in the diffuse layer is both attracted by the charged surface and rejected by the stern layer, which will affect the thickness of the layer depending on the concentration of the solution. A high concentration will give a thinner layer due to the presence of more ions. A leached clay will however result in a larger diffuse layer which will increase the space between the clay particles. This may both affect the strength of the clay and the sensitivity.

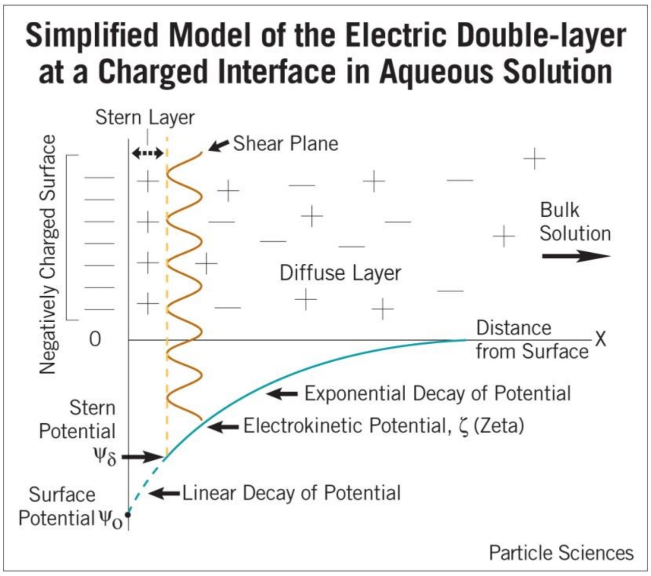


Figure 2-3 Simplified model of the electric double-layer at a charges interface in Aqueous Solution (Sciences, 2012)

If the soil is exposed to a strong electrolyte such as KCl, the cations will be attracted to the negative charged surface of the clay particles, causing a movement of ions within the double-layer when applying a voltage difference across a section of the soil. The effect of the movement of the fluid inside the diffused double layer is called electro osmosis. The ions presents in the pore water is also affected by the applied voltage, where the cations moves towards the cathode and the anions towards the anode. This effect is called ionic migration or electro-migration. The movement of larger particles, electrophoresis, will not be further discussed in this thesis (Vane and Zang, 1997).

2.2.5 Chemical weathering

Chemical weathering is the breaking down and reformation of minerals, which results in changes in the mechanical strength (Løken, 1968). The chemical weathering could be caused by changes due to polluted rainwater that leaches the clay or changes the pore chemistry, such as pH and ionic composition. From (Løken, 1968) it appears that the chemical weathering could proceed if the clay is stored in oxidizing environment, which will affect the geotechnical parameters. Chemical weathering might be caused due to changes in temperature, pressure, water and/or access to oxygen. This affect could occur if the clay is stored in the laboratory for too long.

2.2.6 The effect of leaching

There have been performed different studies to verify the effect of leaching in clay. The increase in sensitivity, decrease in shear strength and the change in the Attenberg's limits have been graphically illustrated in Figure 2-4 (Bjerrum, 1954). As seen in Figure 2-4 the properties stays more or less the same until the salt concentration of 15 g/l is reached. After this point, the properties of the clay changes except for the water content which stays the same. Note that an old way to present the remolded shear strength is in t/m^2. The relation between t/m^2 and kPa is a factor of 10, which gives a 0,1t/m^2=1kPa (Tirant, 1979).

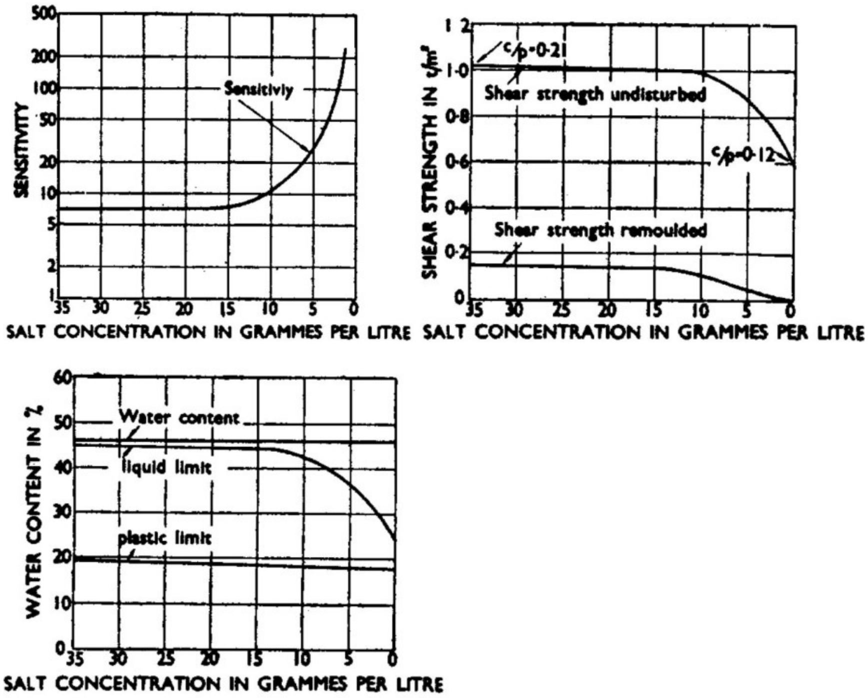


Figure 2-4 Changes in properties of a normally consolidated marine clay when leached by fresh water (Bjerrum, 1954).

2.2.7 The effect of different type of salt

Salts are defined by (Joesten et al., 2006) as “ionic compounds composed of cations from a base and the anion from an a acid”. Cations are the ions with positive charge and anions are the ions with negative charge. Salt in this thesis is meant is different types of chloride compounds. There is further an interest in what type of cation that the salt consist of, since the anion in each case will be chloride.

Table 2-3 shows the ion composition of seawater, which makes it clear that sodium is the main cation contributor in a solution for sea water (Sverdrup et al., 1942). This is why one might refer to sodium chloride when talking about seawater. A leached clay will have an ion composition with far less ions, as the one described in Table 2-3. Note that this means roughly means a salt content of around 3,4%.

Table 2-3 Ions in salt water based on (Sverdrup et al., 1942).

MAJOR CONSITITUENTS OF SEA WATER	
Ion	**g/l**
Cl^-	18,97
SO_4^{2-}	2,64
Na^+	10,50
K^+	0,38
Mg^{2+}	1,28
Ca^{2+}	0,41
Total ca.	34,3

A report from NGI (Norwegian geological survey) from 1969 addresses the interest in finding the change in the properties of marine clays when adding different types of salts to the clay (Løken et al., 1967). In this particular study different chlorides was tested: $NaCl$, KCl, $MgCl_2$, $CaCl_2$, $FeCl_2$, $FeCl_3$ and $AlCl_3$. It concludes that from this experiment the effect on the Attenberg limits could be ranged depended on the cations as follows, were sodium gives the least effect:

$Na^+ < Fe_{gel} \leq Fe^{2+} \leq Mg^{2+} = Ca^{2+} < Fe^{3+} < Al^{3+} = K^+ \leq Al_{gel}$

When ranging the cations with respect to increasing shear strength the report got the results as follows for specimens stored for 26 days:
$Fe_{gel} < Na^+ = Mg^{2+} < Ca^{2+} = Al_{gel} < K^+ < Fe^{2+} < Fe^{3+} < Al^{3+}$

The remolded shear strength can be illustrated with respect to the normality (molarity/valence of cation) for the different cations as shown in Figure 2-5 from (Moum et al., 1968). Note that the remolded shear strength is give in t/m^2, which is a tenth of a kPa ($0{,}1t/m^2=1kPa$). As seen in Figure 2-5 the increase in concentration of the solution increases the remolded shear strength. Aluminum is the cation that gives the greatest increase in remolded shear strength, when increasing the concentration. Since the solubility for aluminum is not as good as for potassium, this makes potassium more suitable when dealing with solutions. Potassium is easily dissolved and easy to come by, which makes a chloride compound of this element suitable to use if the intended outcome is to increase shear strength and get a noticeable effect on the Attenberg limits.

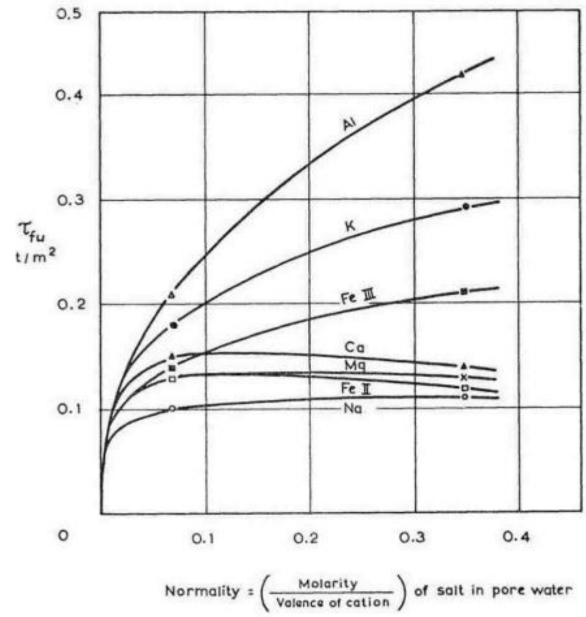


Figure 2-5 Effects of different salts as chlorides on remolded undrained shear strength (Moum et al., 1968).

2.2.8 Landslides due to quick clay deposits

The reason why it is important to locate quick clay is to prevent collapse, and destruction when doing constructional work. As long as the geometry of the quick clay is left intact and the clay is not applied any loadings, the clay is stable (Solberg, 2010). As soon as external forces are applied, the factor of safety is reduced. External forces can be high discharges of water, such as heavy rainfall or melting of snow, which will increase the ground water level. The increase of water pressure will reduce the effective stresses, hence a reduction in shear strength, which may cause collapsing. Additional loading such as buildings or infrastructural work could overload the maximal bearing capacity and lead to failure. The most common natural cause may be the erosion in creeks and rivers. Unloading at the foot of a slope or loading at the top of a slope may also cause sliding (Solberg, 2010).

CHAPTER 3

3 THEORY

3.1 RESISTIVITY

To understand resistivity in soils, and the methods used to find it, it is necessary to include basic rules from physics to explain how resistivity works. This chapter will include these laws and clarify how resistivity can be used to indicate what type of material the soil consist of.

3.1.1 Ohm's law

In 1829 George Simon Ohm found a linear connection between the electrical current and the resistance in a conducting wire, which he introduced as the potential difference across the wire. It is today known as Ohm's law. Ohm's law is defined by (Lowrie, 2007):

$$V = IR$$

(3-1)

Where, V = Potential difference [Volt], I = Electrical current [Ampere], R = Resistance [Ohm (Ω)]

3.1.1.1 Resistance

The resistance is the opposite of conductance and is defined by following equation(Lowrie, 2007)

$$R = \rho \frac{L}{A}$$

(3-2)

Where, R = Resistance [Ω], ρ = Resistivity [Ωm], L = Length [m], A = Cross-section area [m^2]

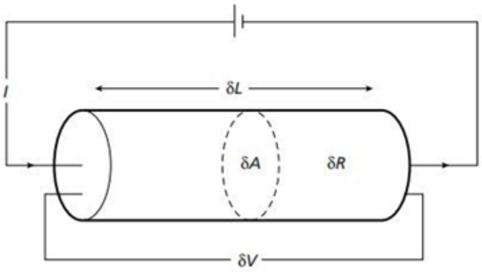


Figure 3-1 The parameters for defining resistivity from (Kearey, 2002)

3.1.1.2 Resistivity

Figure 3-1 shows the parameters used to define resistivity. The small delta, δ, accounts for a change along the sample between the ending and start value. Resistivity is defined by (Lowrie, 2007) as "a physical property of the material of the conductor, which expresses its ability to oppose a flow of charge". In other words, the resistivity is the material property of the resistance, and can tell us something about the material, which can help us classify it. When substituting R from equation (3-2) with equation (3-2):

$$\rho = R\frac{A}{L} = \frac{V}{I}\frac{A}{L}$$

(3-3)

The conductivity is expressed as the inverse of the resistivity (Kearey, 2002)

$$\sigma = \frac{1}{\rho}$$

(3-4)

Where, σ is the conductivity in (1/Ωm = Siemens/m)

If we relate these laws to a material such as soil after adding an electrical current through a specific part of the soil, it will give an idea of how good the soil conducts electricity. To put this information into use, it is necessary to look at different types of soil and classify them by how they resist flow; their resistivity. Earth is a relatively isolating materiel compared to clay. This is due to the clay minerals, which have a better conductivity than earth grains (Dahlin, 2001). The resistivity in groundwater differ from as low as 0,05 Ωm when it contains salt to more than 1000 Ωm for water originating from glaciers (Reynolds, 2011).

The current flow in soil related to electrical resistivity in soils, the expression for the apparent resistivity, the geometrical factor, different types of electrode arrays such as Wenner, Schlumberger and Dipole-Dipole, and a comparison of the different arrays are elaborated in my project thesis (Øveraas, 2015).

3.2 WATER TRANSPORT

3.2.1 Permeability

The degree of permeability is a part in deciding how fast the water travels through the soil. It will be easier for the water to flow through the material if it has a larger permeability. Even though clay is known to have a little permeability, there may be some inhomogeneities such as layers of silt or sand that can transport water faster, and carry the ions out of that part of the clay. This can cause reduced strength is this particularly areas. The permeability is given by (NGF, 1982a) as:

$$k = \frac{q}{Ai} \tag{3-5}$$

Where, q(m^3/s) is the amount of water traveling through a cross section A(m^2) at a certain time. A is the gross area normal to the current, $i = \delta h/\delta l$ is given as the gradient in the direction of the current.

3.2.2 Ions and water content

For soil, the electrical current will be electrolytic, which means that the current will travel as ions in the pore water. This means that with high salinity and sufficient water the current will travel faster (Samouëlian et al., 2005). The relation between pore-water and salinity and how this affect the electrical current is verified by laboratory testing and can be plotted as seen in Figure 3-2(Samouëlian et al., 2005). Figure 3-2 shows how the resistivity is decreasing as the volumetric water content is increasing.

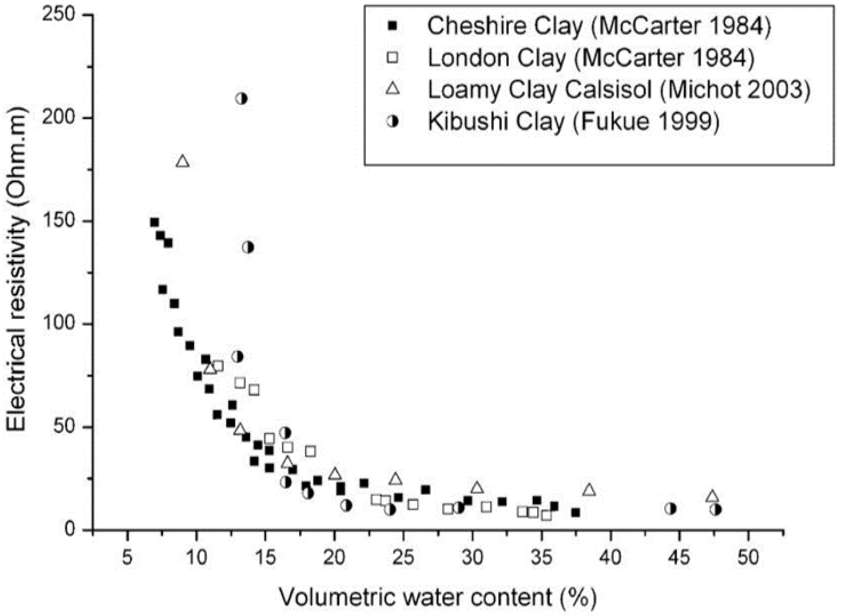


Figure 3-2 Relation between the electrical resistivity and volumetric water content. The figure is from (Samouëlian et al., 2005) and the values are gathered from (Fukue et al., 1999), (Michot et al., 2003) and (McCarter, 1984).

An empirical relations between resistivity and water content for saturated fine textured material was found by (Rhoades et al., 1976) transformed by (Samouëlian et al., 2005) to be the following equation:

$$\frac{1}{\rho} = \frac{1}{\rho_w}(a\theta^2 + b\theta) + \frac{1}{\rho_s} \tag{3-6}$$

Where, ρ is the resistivity, ρ_w is the pore-water resistivity, θ is the volumetric water content, ρ_S is the resistivity for the solid matrix and a and b are coefficients based on characteristics of the solid phase.

The results by (Kalinski and Kelly, 1993) when studying equation (3-6) was that the electrical resistivity decreases with increasing water content. Further explanation concerning laboratory measurements of soil resistivity can be found by (Kalinski and Kelly, 1993).

The ions that are referred to when it comes to quick clay is normally salt in seawater, which mostly consist of sodium chloride, NaCl. Other ions that are dissolved in seawater may be Potassium (K^+), Calcium (Ca^{2+}) Magnesium(Mg^{2+}), sulfates $SO_2{}^{4-}$ or carbonates $CO_2{}^{3-}$ (Montafia, 2014). The normal content of salt in seawater is known to be around 35 g/L (Solberg, 2010). When the salt content in the pore-water is reduced and equal or less than 5 g/L the clay is said to be quick (Rosenqvist, 1953).

It could however be ions presents due to pollution from agricultural industry or other type of industry and natural deposits that could affect the material as well (Samouëlian et al., 2005). Variations in dissolved ions, may affect the conductivity due to different ion mobility. The concentration of ions in the soil solution may be the same in several solutions with different ion compositions, which could result in different conductivities. This property can be used to identify the different ions (Samouëlian et al., 2005).

It is however often that pollution will enter after the structure already is formed, which doesn't necessarily add the same structural strength to the soil structure. The salt would not be distributed properly, and the strength of the soil becomes inhomogeneous. This is why it is difficult to add salt to strengthen the structure of quick clay deposits; because it is hard to distribute it properly to get the wanted uniformed strength. Since marine clay is known to be fertile and good soil for agricultural purpose, this form of pollution could be common. To get a proper picture of this inhomogeneity, resistivity measurements can be done to show the diversity of conductance.

3.2.3 Ions and resistivity

There has been previous studies, which indicates a strong relation between ions and resistivity, when the salt content is below 5 g/L (Bjerrum, 1954, Rosenqvist, 1953). Today's (2014) requirement for a clay to be considered as quick, is that the salt content in the pore water is less than 2 g/L (NIFS, 2014). A study from different areas shows the relation between resistivity and salt as shown in Figure 3-3. The graph indicates that as the salt content increases the resistivity decreases, and reaches a stagnation of the curve when the resistivity is approximately below 5 Ωm and salt content above 8 g/L (Long et al., 2012).

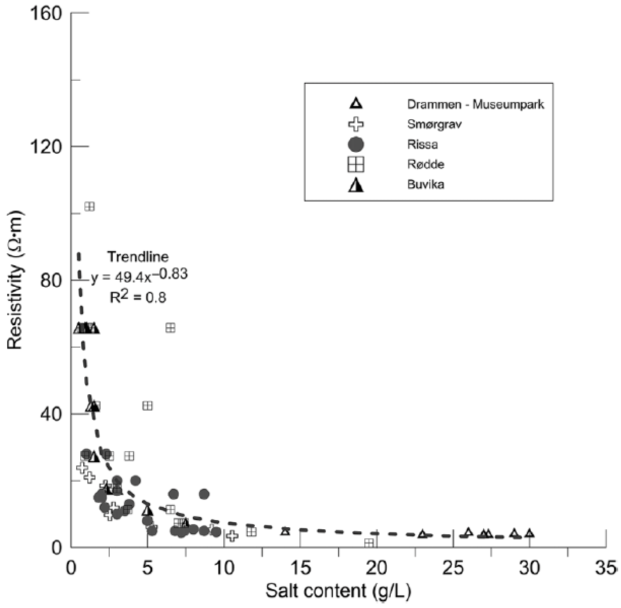


Figure 3-3 Resistivity and salt content of pore fluid (Long et al., 2012).

3.3 FICK'S FIRST AND SECOND LAW

Diffusion is defined by (Cussler, 2009) as "the process by which molecules, ions, or other small particles mix, moving from regions of relatively high concentrations into regions of lower concentration.". The rate of diffusion differ from the state of the materials. A liquid has a diffusion of around 0.05 cm/min, where as a solid may have a diffusion rate as low as $1 \cdot 10^{-5}$ cm/min (Cussler, 2009).

3.3.1 Fick's 1.law

Fick's first law for diffusion at steady state is defined by (Cussler, 2009) as:

$$J_1 = Aj_1 = -AD\frac{\partial c_1}{\partial z}$$

(3-7)

Where, J is the diffusion flux (transport rate) of the material, A is the cross-section area, j_1 the flux per unit area, D is the diffusion coefficient [m^2/second] and $\partial c_1/\partial z$ is the change in concentration across the distance of which the material is diffused. The negative sign in equation (3-7) means that the material is moving from a place of higher concentration to a place of lower concentration.

3.3.2 Self-diffusion and effective diffusion constant

The value of the self-diffusion coefficient, D, at other temperatures could be expressed by the following equation (Appelo and Postma, 2004):

$$D_{f,T} = D_{f,298} \cdot T \cdot \eta_{298} \,/(298 \cdot \eta_T)$$

(3-8)

Where, $D_{f,T}$ is the self-diffusion coefficient [m^2/s] at a chosen temperature T, $D_{f,298}$ is the self-diffusion coefficient at 25 degrees Celsius, η_{298} is the viscosity of water at 25 degrees Celsius and η is the viscosity of water at the temperature T. All temperatures are given in Kelvin.

To adjust for the pathway in a matter such as clay, one would have to adjust the diffusion coefficient with respect to the pores in the matter. When combining Archie's law and the formation factors the effective diffusion coefficient can be expressed as follows (Appelo and Postma, 2004):

$$D_e = D_{f,T} \cdot e_w$$

(3-9)

Where e_w is the water filled porosity (Appelo and Postma, 2004).

If the pores in a clay are fully saturated e_w is equal to the porosity of the clay, n. When knowing the specific density and water content of the clay, the pore number ($e = w \cdot \frac{\gamma_s}{\gamma_w}$) and porosity ($n = \frac{e}{(1+e)}$) can be calculated assuming fully saturated conditions, where γ_s is the density of the clay and γ_w (10kN/m^3) the density of the water.

3.3.3 Fick's 2.Law

Fick's second law or also known as the diffusion equation is defined by (Cussler, 2009) as:

$$\frac{\partial c_1}{\partial t} = D\frac{\partial^2 c_1}{\partial z^2}$$

(3-10)

This form of Fick's second law is a one-dimensional equation that is based on the assumption that the ions are moving in only one direction (z).

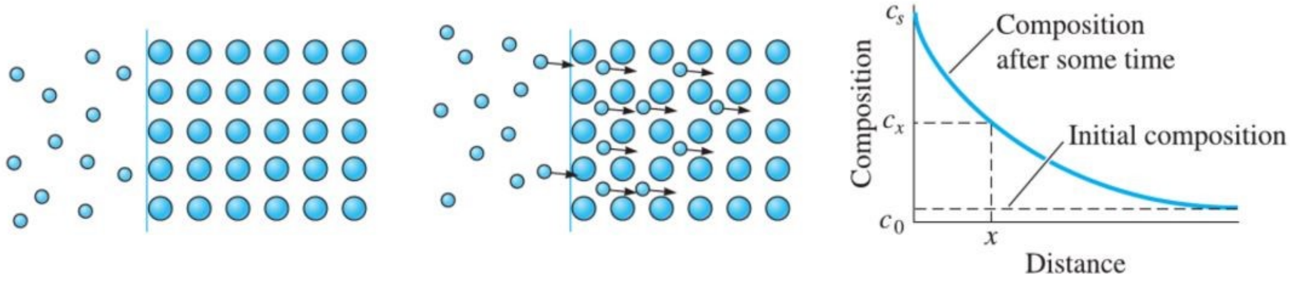


Figure 3-4 Diffusion of atoms into the surface of a material from (Cengage Learning 2014) sited by (Askeland and Wright, 2013)

Figure 3-4 illustrated Fick's 2 law, and shows how the composition is changing with time over a given distance. If one think of the small particles as ions and the large particles as clay particles in Figure 3-4, one can visualize how the particles are entering the clay. The start-out position at the left hand side, shows the initial condition before the clay is exposed to the brine, and the second picture is showing how the ions are diffusion into the pores in the clay. The third picture illustrates how the composition changes with time and distance.

The following conditions are set with respect to Equation (3-10):

$$t = 0 \;\; for \;\; all \;\; z, \qquad c_1 = c_{1\,\infty}$$

$$t > 0 \;\; for \, z = 0, \qquad c_1 = c_{10}$$

$$z = \infty, \qquad c_1 = c_{1\infty}$$

Both $c_{1\infty}$ and c_{10} are considered as constant, since $c_{1\infty}$ is infinitely far from the interface and c_{10} is the constant brine in the reservoir for the experiment. The calculations are simplified so that $c_{1\infty}$

will be considered infinitely far from the interface even though it is not in a practical sense. It is considered far enough away from the start out concentration to use this simplification.

The concentration profile given as the error function in equation (3-17) was found by Boltzmann when solving the differential equation (3-10) when introducing a new variable (Cussler, 2009) :

$$\xi = \frac{z}{\sqrt{4Dt}} = \frac{1}{\sqrt{D}}\frac{z}{2\sqrt{t}}$$

(3-11)

When multiply and dividing the differential of ξ to both sides of equation (3-10)

$$\frac{\partial c_1}{\partial t}\left(\frac{\partial \xi}{\partial t}\right) = D\frac{\partial^2 c_1}{\partial \xi^2}\left(\frac{\partial \xi}{\partial z}\right)^2$$

(3-12)

The partial derivatives of ξ with respect to z and t could be expressed as:

$$\frac{\partial \xi}{\partial t} = -\frac{1}{\sqrt{D}} \cdot \frac{z}{4 \cdot t^{\frac{3}{2}}} = -\frac{\xi}{2t}$$

(3-13)

$$\frac{\delta \xi}{dz} = \frac{1}{\sqrt{D}}\frac{1}{2\sqrt{t}}$$

(3-14)

When inserting equation (3-13) and (3-14) in equation (3-12) the equation becomes a partial differential equation.

$$\frac{\partial^2 c_1}{\partial \xi^2} + 2\frac{\partial c_1}{\partial \xi} = 0$$

(3-15)

When equation (3-15) is solved with the boundary conditions as for equation (3-10) (where the same boundary conditions for z applies for ξ)

$$\frac{\partial c_1}{\partial \xi} = ae^{-\xi^2}$$

(3-16)

$$erf\xi = \frac{2}{\sqrt{\pi}}\int_0^{\xi} e^{-s^2} ds$$

(3-17)

When the solutions for the differential equation is solved with the following boundary conditions:

$c(z,t) = c_i \ \ for\ z > 0, t = 0\ and\ for\ z = \infty, t > 0;$

$c(z,t) = c_0, \ \ for\ \ z = 0, t < 0$

The solution could be expressed by (Appelo and Postma, 2004) as:

$$c(z,t) = \ c_i + (c_0 - c_i)erfc\left(\frac{z}{\sqrt{4D_e t}}\right)$$

Where the error function complement is given as $erfc(\xi) = 1 - \mathrm{erf}(\xi)$.

$c(z,t) = \text{concentration at a distance z, and time t in g/L}$

$c_0 = \text{initial reservoir concentration in g/L}$ at t=0

$c_i \ = \text{background concentration in g/L}$

The error function and ξ is either tabulated or graphically illustrated in many text books, which can help identify the different parameters, when knowing(having decided) c(z,t), c_0 and ci. Such a graph is illustrated in chapter 5.5.2

3.4 TEMPERATURE

When the temperature in a matter increases the viscosity of the fluid will decrease, and it will be easier for the ions to travel through the matter. Due to this coherence, it will be essential to measure the electrical resistivity at a standardized temperature when comparing different resistivity results (Samouëlian et al., 2005) A study performed by (Campbell et al., 1949) shows that the relation of conductivity and temperature is increasing with approximately 2% in an interval from 15 °C to 35 °C. The experiment was performed on in total 30 samples, which consisted of both saline and alkaline soils. The relation between temperature and conductivity can be presented as follows:

$$\sigma_t = \sigma_{25°C}[1 + \alpha(T - 25°C]$$

(3-18)

Where, σt is the conductivity at when doing the experiment, T is the temperature (°C), $\sigma_{25°C}$ is the conductivity at 25 °C, α is the correction factor of 2 %. According to (Samouëlian et al., 2005) there has been attempts to verify this equation, by amongst (Colman and Hendrix, 1949) where the results support the results by (Campbell et al., 1949)

From (Allred et al., 2008) the resistivity is then given by:

$$\rho_t = \frac{\rho_{25°C}}{[1 + \alpha(T - 25°C)]}$$

(3-19)

Where , ρ_t is the resistivity when doing the experiment, T is the temperature (°C), $\rho_{25°C}$ is the resistivity at 25 °C, α is the correction factor of approximately 0,02 (Allred et al., 2008, McNeill, 1980).

The effects of temperature on the resistivity when doing field measurements is less than for other factors, such as salinity. The temperature in the ground will be more or less constant all year providing that the depth is more than 5 meters (Montafia, 2014). The variation in temperature will however be of great interests when performing laboratory resistivity measurements.

CHAPTER 4

4 FIELD MEASURING METHODS OF RESISTIVITY

4.1 HISTORY

Resistivity measurements dates back over a hundred years (Dahlin, 2001). At that point, it was in interest to use the method to find resources and not necessarily the stratification of the soil for construction purposes. Later on, the purpose of many investigations has been to determine how the material respond to electrical current and how that information could be used to get a grasp of the inhomogeneities of the soil (Reynolds, 2011). The research consisted of transmitting electrical current through fixed electrodes, while moving around on the potential electrodes. When doing so, the resistivity values could be obtained, and an image of the ground conditions could be presented.

Today resistivity measurements are used for different purposes such as determining the quality of the soil or materials in the ground, locating mineral deposits or altered zones in the ground (Solberg, 2010). It is also possible to say something about the contamination of the soil, which in many cases is relevant, especially when it comes to using ground water as a water source for drinking water. It can also be used to locate permafrost and buried foundations (Reynolds, 2011). For this thesis however, the most important purpose is the resistivity measurements ability to detect sensitive clay.

There are many different ways to measure resistivity such as by electromagnetic induction or by soundings (Reynolds, 2011). Since all the different methods all determine the resistivity, it is possible to verify the results by crosschecking against the other methods. This could be useful when in doubt of the results, and makes it easier to get the best possible outcome of the resistivity distribution (Solberg, 2010). The invention of the computer made the investigation method less time consuming, hence cheaper and could be used in a larger extent (Reynolds, 2011).

4.2 TWO DIMENSIONAL RESISTIVITY SURVEY

The invention and evolution of computers has made it more efficient to use resistivity measurements, and due to a reduction in costs and time it has resulted in a broader range of use (Reynolds, 2011). To get a 2D-image of the ground, one can use a 2D multi-electrode array (Samouëlian et al., 2005). This means that to perform a 2D resistivity survey there is need for cables with many electrodes added to them to be able to measure the current and voltage. When performing such measurements there are normally four cables and the number of electrodes varies from 20 to 80 (Solberg, 2010). The electrodes are coupled with a multi-core cable, which is connected to a resistivity meter and a computer (Loke et al., 2013). This is illustrated in Figure 4-1, where each vertical line drawn up for the horizontal axis represent a physical electrode placed in the ground. Because the 2D resistivity survey has a lot of output data, a computer controlled system is needed to be able to handle the amount of information in a controlled and efficient way.

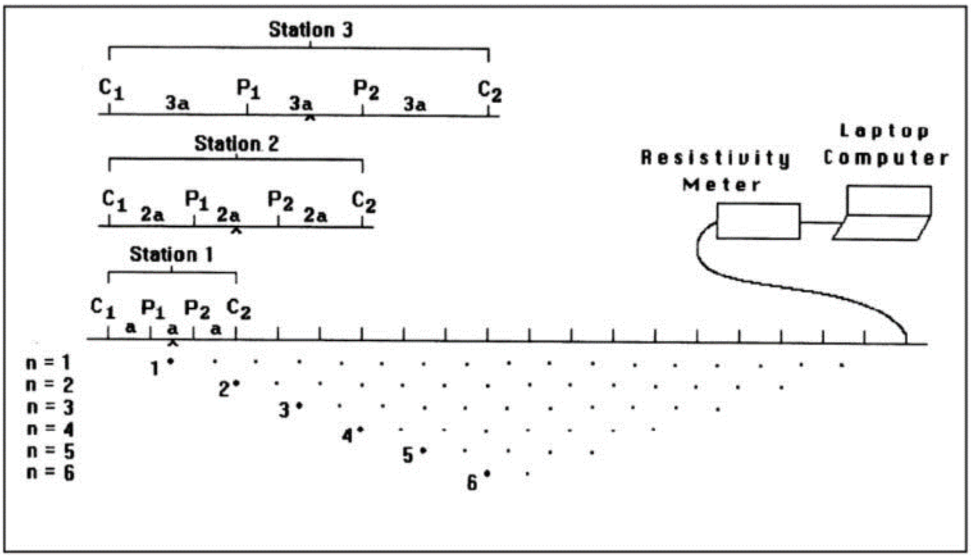


Figure 4-1 The current electrodes are C1 and C2, and the potential electrodes are P1 and P2. n is the number multiplied with the length between the electrodes, a. (Loke and Barker, 1995).

An electrical current is injected between the points C_1 and C_2, and the difference in potential is measured in P_1 and P_2. Since the electrodes has to come in pairs to be able to measure the current and the potential difference, the computer allows the different electrode pairs to change between adding current and measuring the voltage along the cable. The choice of sequence for this measurement is done in a predefined program (Reynolds, 2011). This program could appear as an microcomputer as part of the resistivity meter, which chooses the suitable four electrodes.

When a constant direct current is added, it will scatter in the subsoil as a half sphere, and the computer register how the current is flowing through the soil. The process is started in Station 1 with the smallest distance *a* between the installed electrodes, and moves horizontally with a step of distance *a* to the next four electrodes available. Therefore electrodes used for measuring potential and inducing current are interchanged depending on the position of the station. As soon as the whole array is scanned, the computer will change the distance between the electrodes to the next electrode increment (Reynolds, 2011). From Figure 4-1 this means that n=1 changes to n=2, and the positions for current and potential electrode used in the measurement are positioned with a distance *2a* from each other, as shown in station 2. The measurements are still done for every electrode available, by moving the measuring points given by station 2, by a horizontal distance *a.* The same procedure is then repeated for an increasing *n*, until Station *n* is covering as much the array as possible, while still maintaining a distance *na* between C_1,P_1,P_2 and C_2. This will give measuring data as shown by the dots under the horizontal axis in Figure 4-1. The dots will be placed either between or under the electrode, depending on n being an odd or even number, respectively. This is illustrated as ^ between P_1 and P_2 for every station drawing. By incrementing *n* by 1, the available data points between the first and last physical electrode will decrease by 3, but it will also increase the depth at which the resistivity is measured. This is due to the half sphere created by the electrical current between C_1 and C_2, which will reach deeper if the distance between C_1 and C_2 is increased.

However it is not east to calculate how deep the current will flow, for Station *n* due to the measurements being done in inhomogenous soil. Therefore, the apparent resistivity measurements are plotted between the potential electrodes at a chosen and not correct depth, to give an impression of the difference in resistivity at different depths. The chosen depth has to be adjusted to indicate the real depth and thickness of the layers (Solberg, 2010). Figure 4-1 shows one way to plot the apparent resistivity with a chosen depth, represented by the dots. Here, the apparent resistivity is plotted between the potential electrodes at a depth equal to the multiplier *n* of a given distance *a*.

The ”true” resistivity is found when inverting the apparent resistivity values (Reynolds, 2011). One way to do this is by dividing the profile into smaller parts with their respective apparent resistivity (Loke and Barker, 1995). The model is adjusted to correspond to the theoretical data, which is done in multiple iterations (Dahlin, 2001). Starting out with a thickness of the upper layer equal to half the electrode distance, and increase the thickness with ten percent with the following layers. It's important that an accurate topography is included, since it will affect the inverting (Solberg, 2010).

If there is too dry conditions to be able to get good enough data, it is possible to moist the ground around the electrodes with saline water, or add more electrode pairs to the cable to get a better resolution (Solberg, 2010).

4.2.1 ERT: Electrical resistivity tomography

The ERT-method is a method combining the pseudo sectional 2D plots to construct a 3D electrical picture (Edwards, 1977). Figure 4-2 is illustrating how variations in earth resistivity affects the subsurface measurement of the electric flow through the earth. An electrical current is injected between the points A and B, and the difference in potential is measured in M and N. As Figure 4-2 illustrates, the soil consist of different layers and this heterogeneity will give different resistance parameters in the soil. The orange material illustrates a material with more resistance than the blue material, which illustrates a conductive behavior.

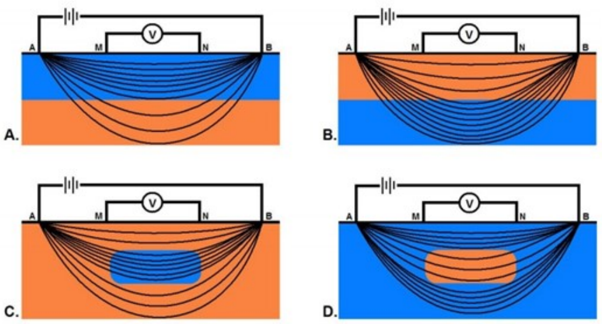


Figure 4-2 The figure shows how electrical current flow through the soil dependent on resistivity. It illustrates a 2D section with Wenner arrays (Pierce, 2012).

Figure 4-2 shows a 2D-section with only two different resistivities, to easy visualize how the current lines will develop dependent on the soil conductivity. If there are many different materials in the soil, as it normally is in nature, there will be more diversity in the resistivities.

A field section could look something like Figure 4-3. The soundings and samplings are illustrated along the cross section, and the resistivities are logged with depth. All the soundings indicated some quick clay deposits, and the resistivities is within the interval of where to expect quick clay. The sampling from borehole two (M2) verifies the assumption of quick clay (Solberg, 2012).

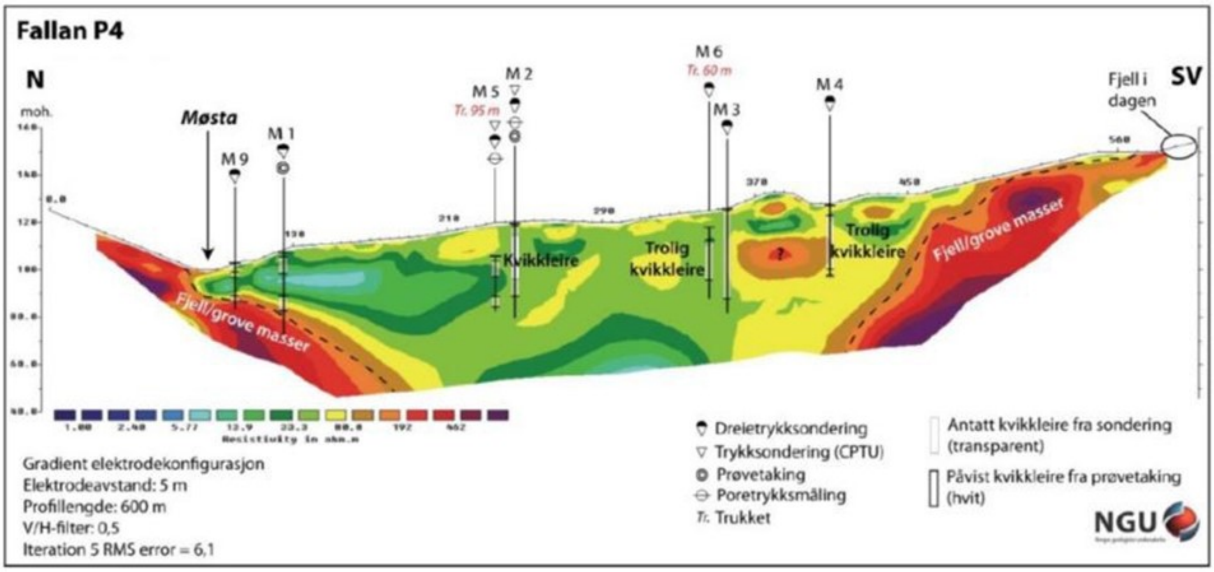


Figure 4-3 Interpreted geotechnical data from Fallan (Solberg, 2012).

When combining 2D sections in cross sections, one gets a picture of how well the sections are combined. As seen in Figure 4-4 the sections do more or less coincide with each other for part A. For part B however, the cross-sections are somewhat different. This can be due to the fact that the resistivity values are dependent on the direction on which the values are gathered, hence when combining resistivities from two directions, some geological information may be lost (Solberg et al., 2008).

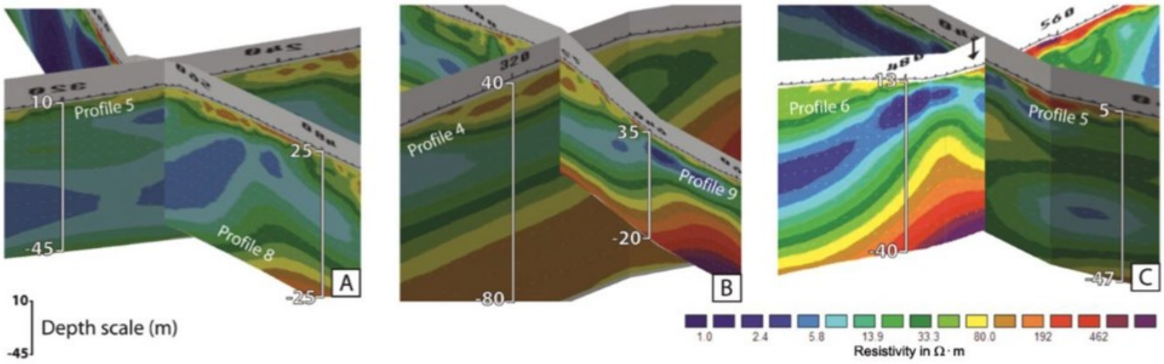


Figure 4-4 Crossing resistivity profiles where the cross sections in A coincide well; Geological homogeneous conditions horizontally, B coincide poorly; different potential electrode distances hence different depth, C coincide poorly; geological inhomogeneous conditions.(Solberg et al., 2008)

4.3 FIELD MEASUREMENT

4.3.1 CPTU

Cone Penetration Test Undrained is a field method used to measured the resistance at the tip of a pole when it's pushed through the soil. The cone located at the tip registers the pore pressure and the stresses at a given predefined step throughout the survey (NGF, 1982b). This can be illustrated graphically, and tells something about the soils ability to resist enforced stresses. This indicates the strength of the soil, and how the pore pressure is changing with depth. Both these parameters can tell something about what type of material is located underneath the surface. A brittle clay will in many cases have a more or less constant and low tip resistance. Combining field surveys with laboratory testing, one may be able to detect the quick clay.

4.3.2 R-CPTU

R-CPTU is a measurement method that includes resistivity measurement when performing a normal CPTU. The electrodes are pushed down in the borehole together with the CPTU (Montafia, 2014) which allows a vertical resistivity measurement. It is a measuring method where the bore-hole is used as a center and the electrodes are separated along the center point with a certain distance to the center.

One advantage with the R-CPTU is that the gathered resistivity doesn't need to be inverted (Long et al., 2012). This means that the results from the R-CPTU can be used to get a good basis, when inverting the resistivities from the ERT (Long et al., 2012) shows that the resistivity values from R-CPTU and ERT are comparable. The interpretation of the profile may be more reliable when using both ERT and R-CPTU (Montafia, 2014). For more information concerning equipment and procedure see relevant paper (Montafia, 2014).

4.4 INTERPRETATION OF RESISTIVITY

4.4.1 Interpretation

Since the natural soil is an inhomogeneous material, the resistivity that is contained from the survey is an apparent resistivity, and not the true resistivity as for a homogeneous matter. This means that the data from the field is the apparent resistivity, and it's the interpretation of these apparent resistivities that gives the ”true” resistivity (Reynolds, 2011). For further information concerning the inversion process see relevant paper (Øveraas, 2015).

When the resistivity measurements are done, there are a lot of data that has to be interpreted and classified. When the geotechnical samples are taken, and the properties are identified, this sets a basis for the resistivity interpretation. Without such a basis, it can be difficult to know exactly what the ground consists of, since laboratory testing of the geotechnical properties is the only way to be certain of the presence of quick clay (Solberg, 2010)

When the laboratory testing is finished the material in the ground can be classified. Multiple studies has classified materials by its resistivity, which can be illustrated graphically. As seen from Figure 4-5, many materials have the same resistivity. This makes it difficult to classify materials based on only a resistivity test, hence other measuring methods has to be executed. Figure 4-5 illustrates how the resistivity is classified for different types of materials.

As seen from Figure 4-5 the resistivity for clay varies from around 1-100 Ω m (Reynolds, 2011) which is a large interval. This includes what we earlier defined as clay, and not just the most interesting part, the quick clay. As we see from Figure 4-5 there are different types of materials that classifies inside this range. The type of material is easy to identify with supplemental on-site tests or by sampling.

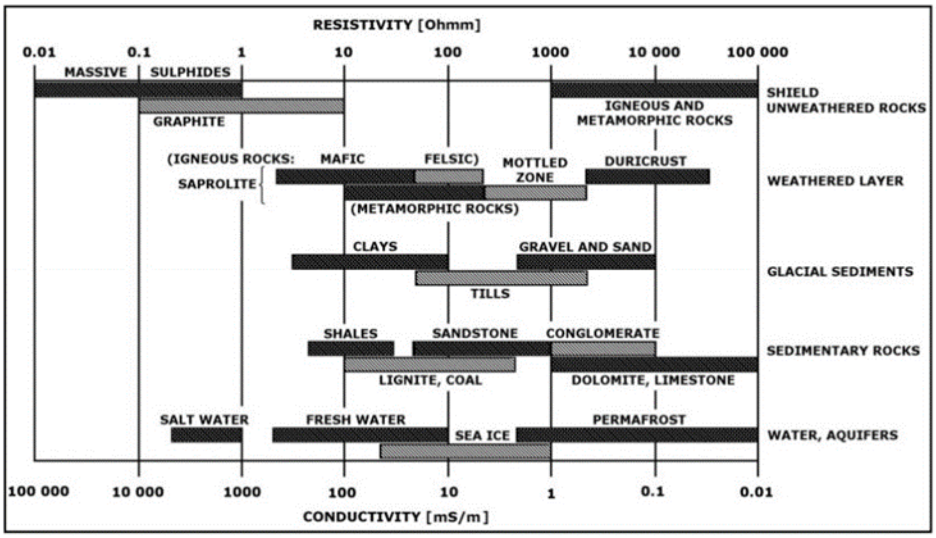


Figure 4-5 Values of resistivity in different geological materials. From (Solberg, 2010) cited (Palacky)

4.4.2 Classification dependent on resistivity

Table 4-1 shows classification of different types of soil dependent on resistivity. The classification is based on (Solberg, 2010), where data from studies in Norway, Sweden and Canada and comparison of laboratory testing and soundings is the basis of the evaluation.

Between low and high resistivity values there will be a gradual change in resistivity, which will give an impression of a gradually stratification, and not a distinct limit between the two layers. This makes it difficult to estimate the exact depth to bedrock by just doing resistivity measurement, and there will be need of other surveys to verify the stratification (Solberg, 2010).

Table 4-1 The table is from (Solberg, 2010). It shows different types of soil based on resistivity values. The classes are gradually flowing into each other. There may also be local variations, which will be depended on pore water chemistry, degree of saturation and mineral composition.

Classification of different types of soils dependent on resistivity			
Resistivity Ωm	**Characterization**	**Comment**	**Color code for NGU's projects with quick clay**
1-10	Not leached clay sediments	The clay has not jet been exposed to leaching. The ions still remain in the pore water, which stabilize the structure and results in high conductivity, hence low resistivity. Other reasons for low resistivity could be sediments with high content of ions or conductive minerals such as sulfides or graphite.	Blue: 🟦🟦🟦🟦🟦🟦
10-100	Leached clay sediments, potential quick clay	Leaching of the clay leads to less dissolved ions, and with salt content less than 5g/L quick clay can be formed. The resistivity is still low, but less than for the clay that had not jet been leached. The clay that is leached but not quick, clayey moraine and silty sediments may also be located in this interval	Yellow-Green 🟩🟩🟩🟩🟨(🟫)
More than 100	Clay crust/ Coarse Masses/Bedrock	Clay crust, masses of clay from avalanches, coarse moraine, and gravel will in many cases have larger resistivity values. The water content in the sediments will affect the resistivity. The bedrock may have resistivity as high as several thousand Ωm.	(Yellow)-Orange-Red-(purple) 🟫🟧🟥🟥🟥🟪

CHAPTER 5

5 THE LABORATORY EXPERIMENT

5.1 THE CLAY

There are several areas in Trondheim, which contains quick clay. Due to limitations in access of bore rig and labor, a minimum of samples were gathered. The samples were three cylinders from Dragvoll as part of the site from the ongoing PhD project of Tonje Helle Eide, all filled with presumable quick clay.

5.1.1 The choice of clay

The most interesting clay for this type of laboratory set up would be to study marine clay. Mainly because the clay is already leached and will give evident change in structural strength when adding salt. This will again give a decisive change in the resistivity, which is of most interest to measure. To be able to perform some of the index tests, such as the one for plastic limit, the clay should be as homogeneous as possible, with little to no element of silt or sand. The homogeneity aspect also applies for the use of the theoretical equations, which assumes a homogenous clay.

Trondheim is known for many and large deposits of quick clay, which makes it easier to collect the wanted cylinder samples. When ordering the samples, the following has to be taken into consideration such as site, type of clay and depth. The economical aspect is also a factor. Since the sampling is taking place in Norway during the end of winter/ beginning of spring, one has to consider temperature, snow and the fact that the ground might be frozen. One has to choose samples below the frost line and the dry crust, and at a place where the soil boring may be executed.

The best way to choose the place is based on former knowledge of the site, which can indicate to what extent the deposit consist of quick clay and information concerning the homogeneity of the clay. When having data such as national maps of soil and bedrock distribution, total soundings or CPTU, one can make profiles that indicates where one might find quick clay, and when comparing this to earlier samplings one may have located the best place to take up the cylinder samples. Resistivity measurements can also indicate the satisfaction, which can be useful when choosing depth. In this case however, knowledge of the NTNU staff that has worked with the relevant area has been the basis for the choice of site and depth.

5.1.2 The area

Dragvoll is part of the city/county Trondheim, which is located in the middle of Norway. The area is known for its quick clay deposits, and over the years, there has been damaging and destructive avalanches due to slope failure in these areas. NGU (Norwegian Geological Survey) has developed national maps, which indicates the highest level of which the sea has been located after the last ice age (NGU, 2015b). The map indicates the marine border and might indicate the locations of the quick clay. Such a map of Dragvoll is shown in Figure 5-1. The blue dotted line at the down right side of Figure 5-1 indicates the marine border at Dragvoll. Marine clay will in general not be located above the blue dotted line in the hatched area. Everything below this line might contain areas of quick clay. The site is located approximately 159 meters above sea level (Helle et al., 2015).

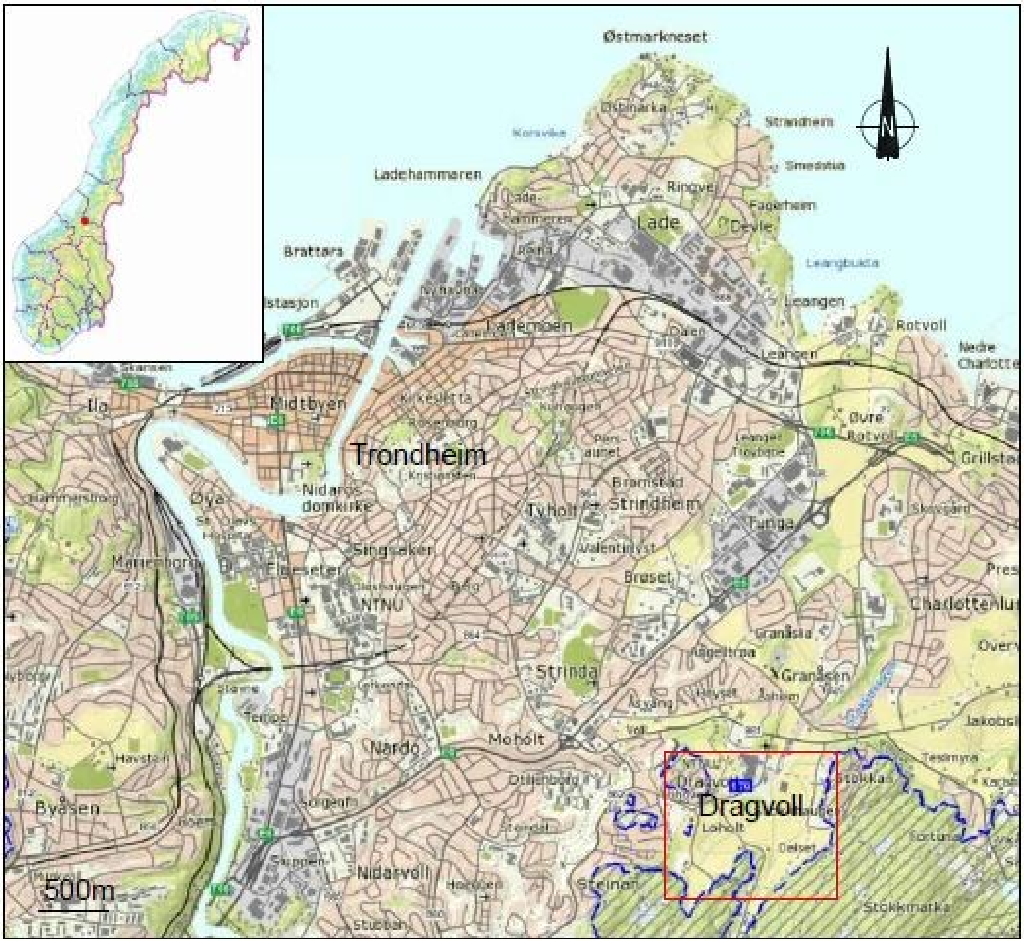


Figure 5-1 An overview of the marine border in Trondheim and the location Dragvoll where the samples has been taken (NGU, 2015a).

A closer view of the area reveals the presumed soil deposits, as shown in Figure 5-2. The site indicates thick marine deposits and thin moraine. The samples have been collected to left hand side in the thick marine deposit area, just before the road parts in two. The depth for all three samples are 9,0 to 9,8 meters. The area that is described as thick marine deposit in light blue in Figure 5-2 is all covered in fields, mainly used for agricultural purposes. It is a relativity plain field with a slightly inclination from southeast towards north-west at the site. In direction southeast from the sampling area, there is a slightly higher inclination towards some houses.

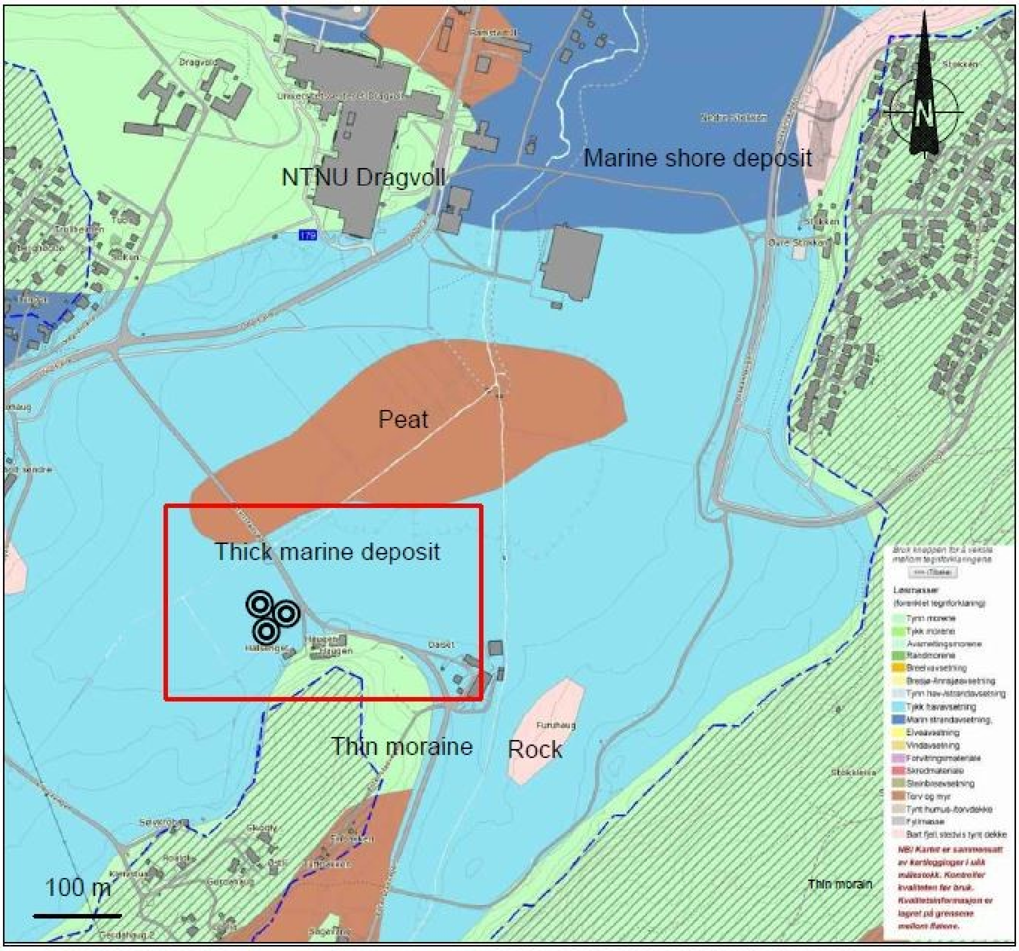


Figure 5-2 An closer overview of the specific site and marine border and deposits where the samples has been taken (NGU, 2015a).

5.1.3 Sampling ϕ54

The sampling was done according to Norwegian Standards with a piston corer (Vegvesen, 2014). One of the most common cylinder sizes has an inner diameter 54 mm, which gives samples with the same diameter. According to the Norwegian Standard, plastic tubes are commonly used (Vegvesen, 2014), but from work experience most of the cylinders used today are made of steel. The main reason might be that steel is more resistant towards changes in the soil strength of underlying soil when the cylinder is pushed through the ground, than for the plastic cylinder. On the other hand, steel is not resistant towards changes in temperature. Due to steel’s ability to lead electricity, it is in this case better to use plastic cylinders to prevent that type of disturbance. The piston corer is illustrated in Figure 5-3, and shows how the cylinder is pushed through the ground to get the samples.

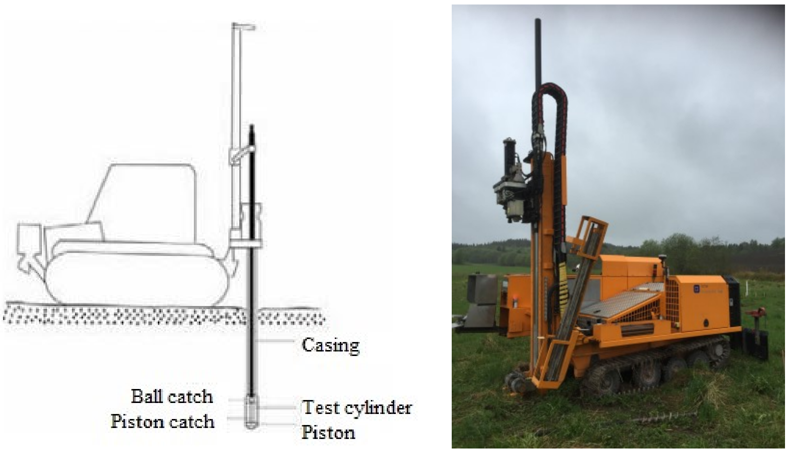


Figure 5-3 The piston corer from (Vegvesen, 2014) and the piston corer from NTNU(own picture).

The boring has been performed by NTNU staff as part of the PhD project to Tonje Eide Helle at NTNU. Each cylinder is taken from a depth from 9,0 to 9,8 meters, which might make it easier when comparing the results when all cylinders are taken from the same depth. Table 5-1 gives a summary of the data from the different cylinders.

Table 5-1 A summary of the 54 mm cylinder data

CLAY FROM DRAGVOLL				
DATA			**COORDINATES**	
Cylinder	**Date**	**Depth**	**North (Y)**	**East (X)**
A P7B	07.03.2016	9,0-9,8	7031331.585	573301.740
B P7C	07.03.2016	9,0-9,8	7031332.330	573301.142
C P7D	07.03.2016	9,0-9,8	7031331.649	573301.036

5.1.4 Earlier studies of the area

As mentioned, the cylinders are part of the same area as for PhD. Tonje Eide Helle's project. In relation to her PhD, there has been performed standard testing on the clay, which gives an indication of amongst others the remolded and undisturbed shear strength, the Attenberg limits and water content. According to the work performed by Tonje Eide Helle the clay content between 7-9 m depth is approximately 38% (Helle et al., 2015). The cylinders of this M.Sc. thesis have a depth of 9,0-9,8 as seen in Table 5-1, which leads to the assumption that the material is clay according to chapter 2.1.1.

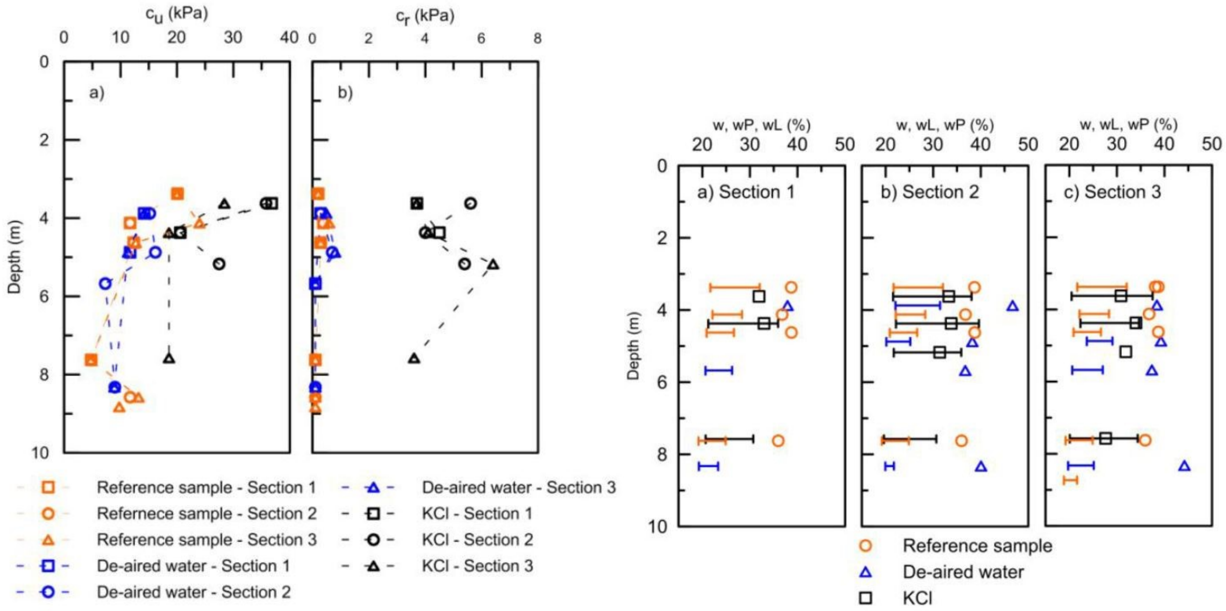


Figure 5-4 Fall cone test for undrained shear strength and remolded shear strength and the Attenberg limits (Helle et al., 2015)

Tonje Eide Helle has studied block samples, where different sections of the sample has been used to find reference values, the results from the clay in de-aired water and the clay with added KCl. The reference values gives an indication of the geotechnical properties of the clay prior to KCl exposure, which is of great interest comparing to the setup in this M.Sc. Thesis.

As seen in Figure 5-4 the reference sample indicates an undrained shear strength (c_u) of approximately 8-10 kPa at depth between 8,45-8,95 meters, and a remolded shear strength (c_r) of around 0,1-0,2 kPa at the same depth. Here c_r is the same as c_{ur} defined in chapter 2.1.2. This gives a sensitivity greater than 30 kPa, which indicates quick clay as described in chapter 2.1.2.

The water contents and Attenberg limits from Tonje Eide Helle's studies are also illustrated in Figure 5-4. The reference sample at the lowest depths indicates a water content (w) approximately 35. A value of 35% water content will be used for further calculations of the effective diffusion constant for the experiment described in this thesis. Therefore, the reference water content is defined as:

$$w = 35\%$$

(5-1)

The reference values from the deepest sections have a liquid limit (w_L) of approximately 22-25% and a plasticity limit of ca. 15-20% as seen in Figure 5-4. When comparing the reference values to the salt treated clay, the values indicates that w_P dose not change much before and after the introduction of KCL, but that w_L increases. For further information concerning pH and ionic composition of the clay see (Helle et al., 2015). The total salt content in the reference clay at the lowest depth is approximately 1 g/l as seen in Figure 5-5.

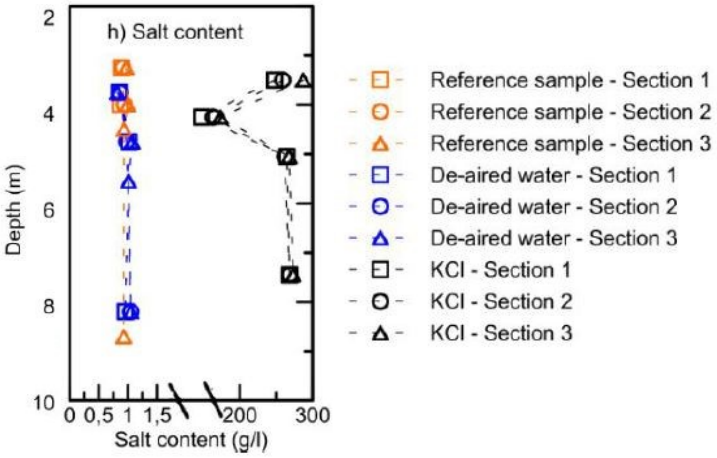


Figure 5-5 Total salt content of the clay (Helle et al., 2015)

As part of Alberto Montafia's M.Sc. thesis from 2013 there has been performed ERT-profiling and R-CPTU-testing in the area, where the area is known to have quite homogeneous resistivity values of around 40-50 Ωm (Montafia, 2013). The site where the ERT-profiling and R-CPTU have taken place are illustrated in Figure 5-6 where the R-CPTU is done in boreholes D1,D3 and D4.

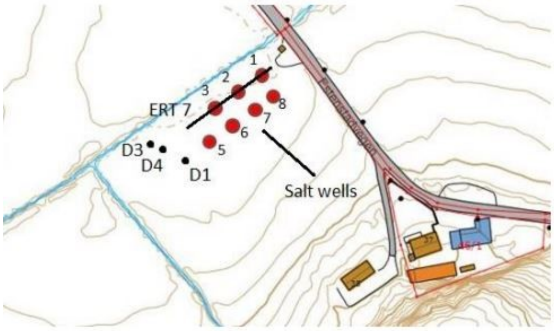


Figure 5-6 The field site (Montafia, 2013)

The results for tip resistance, pore pressure, side friction and resistivity in bore holes D1,D3 and D4 from Montafia as shown in Figure 5-7. It indicates a resistivity that changes with a presumably top layer at a depth of 3 meter, where as the lower part below 4 meter is quite constant. The results are from 2013, and when comparing resistivity measurements, one has to consider local and seasonal variations in temperature and precipitation. Local variations in ground water level, due to heavy rainfalls or melting of snow, may give different results than on a sunny dry day due to the change in water content. If the soil gets to dry, it will affect the ability of conductance and reduce the quality of the data. The temperature varies during day and season.

To avoid misinterpretation when doing field measurements, it is important to know the seasonal resistivity variation when comparing the resistivity results (Samouëlian et al., 2005). This will of course affect the resistivity values, and one cannot make a conclusive comparison.

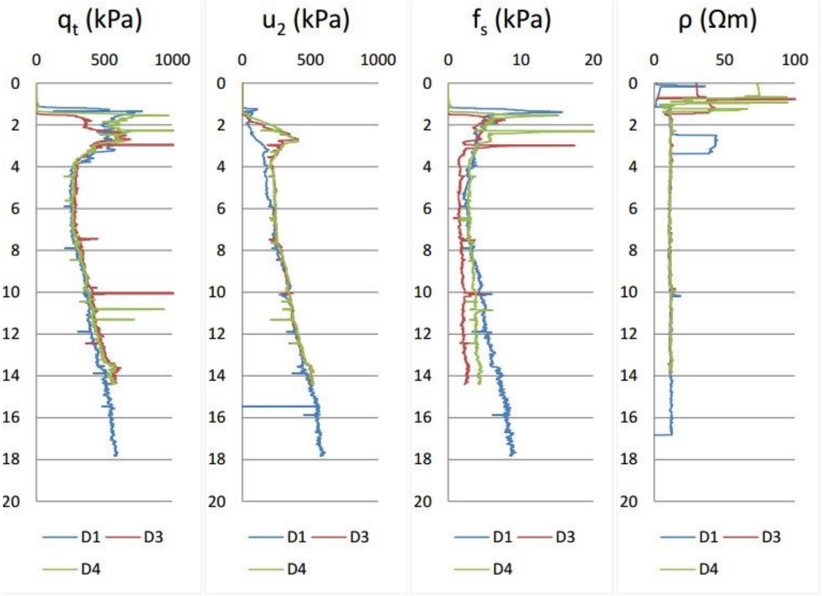


Figure 5-7 Tip resistance(q_t), pore pressure(u_2), side friction(f_s) and resistivity(ρ) from bore holes D1, D3,D4 as shown in Figure 5-6 (Montafia, 2013)

Figure 5-7 indicates that the results corresponds to the perception that the values are homogeneous, with exception of the top layer. As seen in Figure 5-7 the resistivity values are approximately 15 Ωm for the lower parts of the clay.

5.2 THE LABORATORY SET-UP

5.2.1 Preparation

The 54 mm cylinders were taken from Dragvoll as part of the PhD project to Tonje Helle Eide. The cylinders that are common to use is made of steel, but earlier both steel and plastic cylinder were common. Plastic cylinders in the right dimensions were therefore available. Since the objective was to measure change in electric potential, steel cylinders were not suitable due to the ability to conduct electricity. The three samples were therefore moved from the steel to the plastic cylinders a day after the samples were taken (08.03.2016). It was aimed for to change cylinders as soon as possible to prevent any sort of adhesion between the inner steel wall and the clay. After the clay was moved, the plastic tubes were closed (to prevent contact with air and moisture) and stored in a fridge at ca. 5,7°C until the set-up was decided and the experiment could be proceeded.

5.2.2 Electrical apparatus

To measure the resistivity one need to induce a current and measure the change in potential between two given points. The theory behind this procedure is explained in chapter 3. To do so one need an ampere meter, a voltmeter, a power source and a certain amount of electrodes (either four or more). A manual reading of resistivity is shown in Figure 5-8, where ampere meter and power source are combined. When manually conducting resistivity readings, it might be difficult to place the electrodes precisely. Also the thickness of the electrodes may vary. Because of this, it is important that the electrodes are placed far enough apart to reduce these effects.

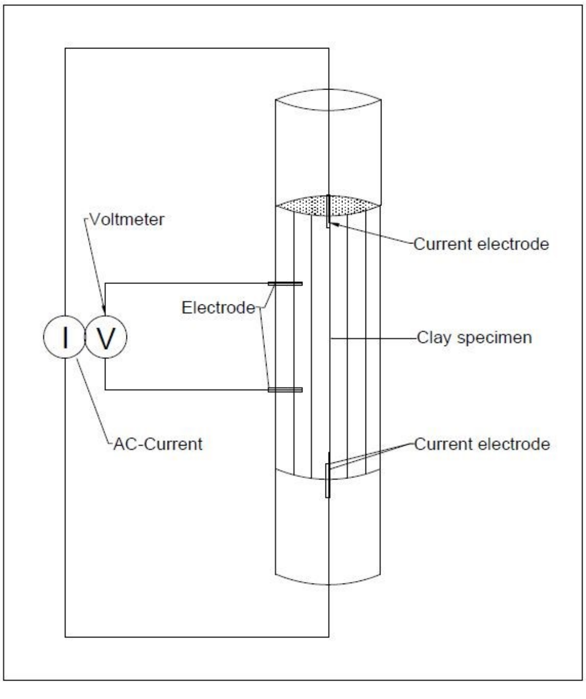


Figure 5-8 A sketch of how the electrical set-up might look like

To reduce the influence of human error and make the readings easier, a more favorable way to do the set-up is to couple it up to a computer which again could log all the data in a .tex-file. This way, it is easier to use more than four electrodes, which could give not only average change in resistivity but also the change between the chosen amounts of electrodes. This way, one will get a broader picture of the change in resistivity over the specimen, and be able to follow the front of the salt ions.

NTNU's head of engineer of the geotechnical division Per Østensen made a program by using LabView, where the input data could be illustrated with colors between the electrodes and gathered data could be plotted in a .lvm-file. This file is easy to transform to a .tex-file only by changing the name of the file from .lvm to .tex. The apparatus chosen for the experiment, worked as an ampere meter, a voltmeter and a voltage source, which then both added a chosen voltage to the sample and also read the information of the changes in volt at the measuring electrodes. The current was measured over the entire sample. There were in total three of these electrical apparatuses, one for each of the cylinder, which were coupled up to a computer that logged everything in the program in LabView.

5.2.3 The choice of salt

Different type of salt will have different type of effect on the clay, due to its variety of compounds. When introducing salt to a clay, one have a variety of salts to choose between. Former research as mentioned in chapter 2.2.7 has indicated that potassium chloride (KCl) would give fast and distinctive results with respect to geotechnical properties. Since time is of the essence, KCl is a natural choice. It is suitable to use the amount of dissolve K^+ in grams per liter as an indication of the amount of ions presence, since these former studies indicates that it is the cation that has the most impact. The salt (KCl) would dissolve in the water as showed in equation (5-2).

$$KCl + H_2O \rightarrow K^+ + Cl^- + H_2O \tag{5-2}$$

Table 5-2

Salt and ions	Atom weight (u) g/mol	Part of molecule
K^+	39,098	0,524448
Cl^-	35,453	0,475552
KCl	74,551	1

5.2.4 Decision of salt concentration

The salt concentration, which is used, might affect how fast the current will be able to travel through the soil. Based on Fick's law (equation (3-7) from chapter 3) a solution with higher salt concentration will increase the concentration gradient, which will lead to a higher diffusion flux.

Previous experiment indicated that KCl might give a stronger effect on the geotechnical properties as mentioned in chapter 2.2.5. Since this is a prototype project, a given salt concentration is not to be found in the literature, and one has to choose a concentration that seems suitable.

The saturation state for KCl at 7 degrees Celsius is 302,8 g/L (158,8 g/L K^+), which presumably would not lead to any precipitation of the salt since the temperature at the laboratory was just around 20 degrees. To be absolutely certain that no precipitation would take place after adding the salt the concentration of the liquid was set to 125 g/L K^+ based on Ingelin Gjengedal's project (Gjengedal, 2012). The concentration of KCl is shown in Table 5-3. The most important part with respect to salt concentration is that it is a sufficient amount of salt in the solution to give a readable resistivity change.

A second salt concentration was chosen to be half of the concentration of that used by Ingelin Gjengedal, and set to 62,5 g/L K^+. As seen in Table 5-3 this makes a KCl concentration of 1,6 mol/L, which is a concentration that might be comparable to other research where 1,5 mol/L was used (McKelvey and Milne, 1960).

Table 5-3 Summary of the amount of K^+, KCl and mol/L

K^+ (g/L)	KCl (g/L)	KCl (mol/L)
62,50	119,17	1,60
125,00	238,35	3,20

When making the solutions, the right amount of KCl was measured with respect to the right amount of K^+ wanted, and then water was filled until 1L of solution was reached. This was repeated until 3 L of each solutions was made.

5.2.5 Decision of water

In many cases when dealing with ions and polluted water, one uses distilled water to minimize any effect from other ions. Since this experiment first of all aims to measure the electricity and not any form for ionic composition in the clay nor water, the water used could be tap water. The quality of the water from the local water source Jonsvatnet in Trondheim is soft (with only an alkalinity of 1,154 mmol/L), which indicates a low ionic presence. The conductivity is measured to 13,5 mS/m (milli/Ωm) in 2015, which in this context is negligible since the resistivity vales are given in Ωm (Kommune, 2016).

It will however effect some of the estimates when it comes to effective diffusion length, but the main results depend on the drop in voltage along the clay. If studies such as this one aims to carry out chemical analysis of ionic composition, the water should be deaired and distilled.

5.3 DIFFUSION CELL

This particular laboratory set-up aims to measure the diffusion of salt-ions, when travelling from a high concentrated brine to the inner parts of a clay specimen with lower concentration of ions. This is a pilot project, which means that the process of finding the right set-up has been time consuming, and as much a part of the thesis as the results from the set-up itself.

5.3.1 Ways of conduct the experiment

There have been many thoughts of how to perform the set-up. The following chapters include ideas of how to perform the experiment to get the best possible outcome. The initial set-up was found to have some flaws, which would not have given the wanted outcome. Therefore, a more refined set-up had to be engineered. Both solutions are presented, to get a broader understanding of all the concerns in the pre-phase, where the final experimental procedure was decided. The first and flawed set-up has cylinders named ***a***, ***b***, ***c***, depending on what salt concentration the clays are exposed to. It is then discussed why this set-up was not suitable. Finally the final set-up will be presented with each cylinder named **A**, **B** and **C**, with its respective changes.

5.3.1.1 Preliminary set-up: Initial though of how to perform the experiment

The preliminary work of deciding what the diffusion cell might look like, was based on a diffusion cell made by Ingelin Gjengedal (Helle; et al., 2013, Gjengedal, 2012). However, the model have to also include current and potential electrodes to be able to measure the resistivity over a given time. A modified set-up based on the diffusion cell made by Ingelin Gjengedal is shown in Figure 5-9. She experienced that due to the lack of support under the clay in the diffusion cells; the clay sank into the salt slurry, and concluded that the results were not reliable. This would have to be taken under consideration when making a diffusion cell based on this model. As seen in the Figure 5-9 this could be solved with a membrane, for instance a piece of felt. Figure 5-9 also shows how the voltage can be introduced using the current electrodes, and the voltage read using the voltmeter and potential electrodes. Salt water is to be induced in the bottom of the clay specimen, while fresh water was put on the top to make sure the clay dose not dry out and is fully submerged in water.

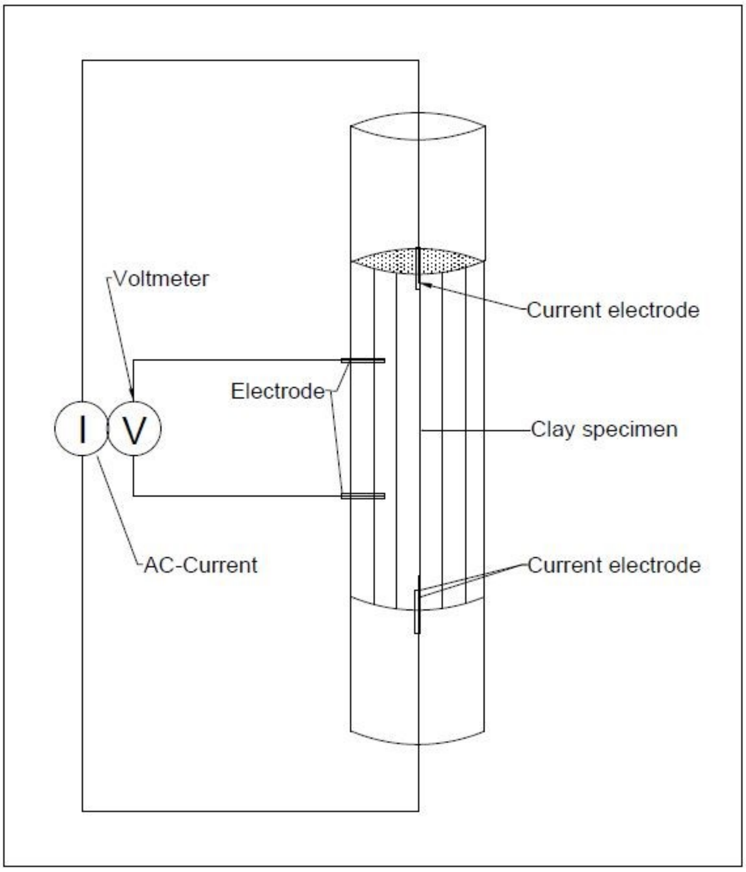


Figure 5-9 Sketch of one way to do the laboratory set up

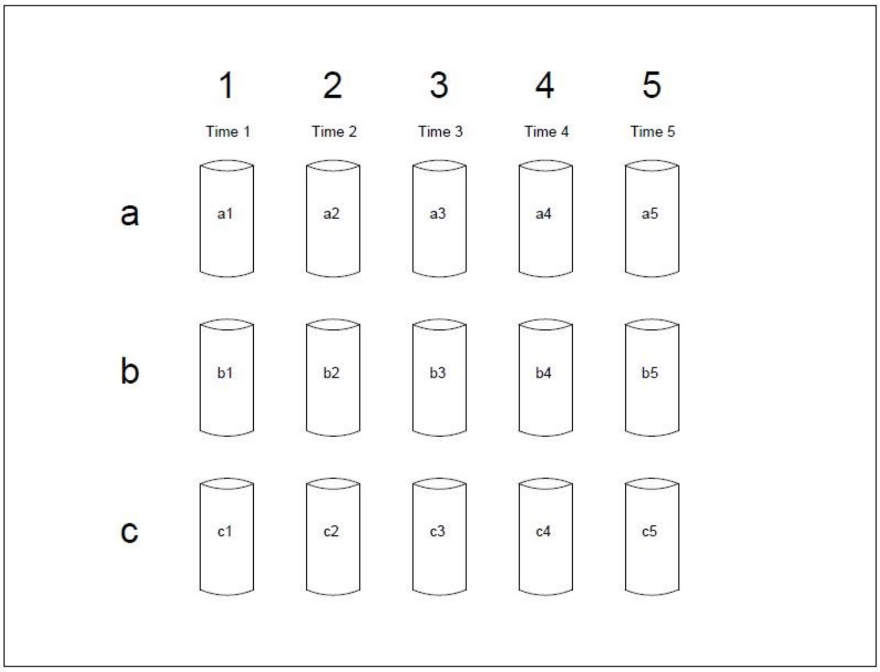


Figure 5-10 Sketch of the set up with the cylinders A, B, C and their respective parts 1-5.

However, the proposed way of setting up the diffusion cell in Figure 5-9 used only two potential electrodes, which would only give one resistivity value. It was proposed to divide each cylinder into five parts for resistivity testing, to get five data points for each cylinder.

The cylinders would be given a letter ***a***, ***b*** or ***c*** to be able to be able to distinguish which cylinder the clay in each diffusion chamber came from, and each part from the respective cylinder would be given a number from 1 to 5 as seen in Figure 5-10. This would give 15 diffusion cells in total. The thought behind this, was that each diffusion cell would be measured at a given time, but only once, out of fear that repeated manual measuring of resistivity data would tamper with the results. The diffusion chamber with the same number would then be measured at the same time, as shown in Figure 5-10. At this time when planning the experiment it was thought that the resistivity measurements would have to be done manually, and not with the electrical apparatuses and method purposed in chapter 5.2.2.

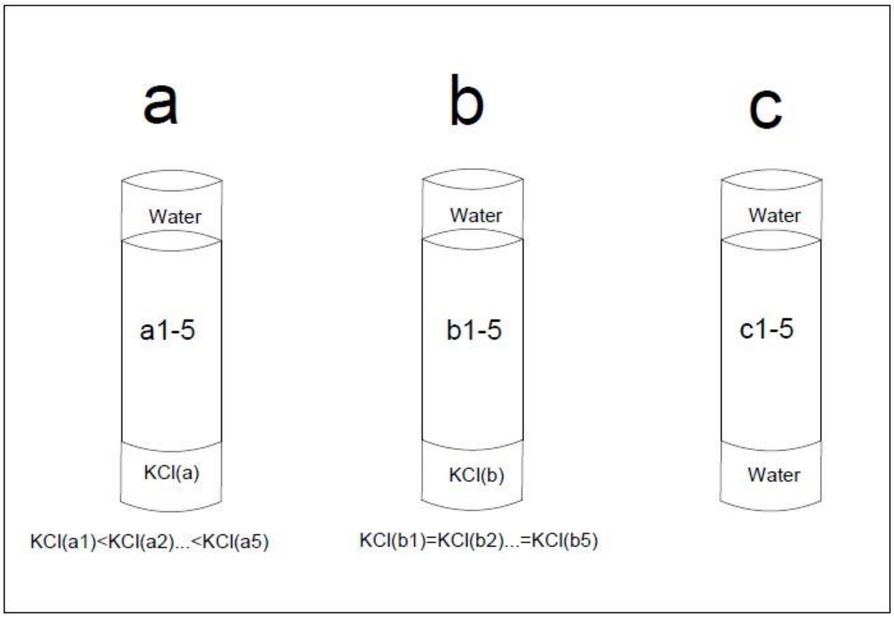


Figure 5-11 Differences salt concentration in the basins for the preliminary set-up

There would be conducted different experiments on the diffusion cells, depending on which cylinder they originated from, as seen in Figure 5-11. Cylinder ***c*** would be tested as a basis, with only fresh water in the top and bottom basin. Cylinder ***b*** would be set up with water in the top basin and the same salt concentration in the bottom basin for all five samples. This would give the change in resistivity for the clay from cylinder ***b*** over time. The diffusion cells with clay originating from cylinder ***a*** would be set up with water in the top basin and different but increasing concentration of salt slurry at the bottom basin, as seen in Figure 5-11. This was thought to be a reasonable set-up, to show how the different concentration of salt would affect the clay.

However, there are a number of problems with the preliminary set up that now has been proposed. First and foremost, conducting manual measuring of the resistivity, which limited the measurements to only be conducted once, is greatly hindering the experiment. While diffusion cells in b_n and c_n are set up to account for the single-time measuring method, diffusion cells a_n

would not give the same meaningful results, as both time of measurements and salt consecration are different between the diffusion cells in a_n. For diffusion cells a_n, it would be more meaningful to have several measurements done for each diffusion cell at the same time intervals. Secondly, by increasing the number of electrodes it would be possible to follow the salt front as it rises through the clay. Lastly, the osmotic effect due to the concentration difference between the upper and lower basin containing water and salt respectively, could be a problem in diffusion cells a_n and b_n.

5.3.1.2 The final and actual set up

By using the electrical apparatus presented in chapter 5.2.2, a set-up with more electrodes could be created. This also made it unnecessary to divide the cylinders into smaller parts, as measurement could be done multiple times at any time interval, and the diffusions cells would therefore contain the complete cylinder of clay. The experiment would only be done on three diffusion cells, as shown in Figure 5-12 where the salt concentrations are given as of Table 5-3 , and there is still a control sample of only water. Also to account for the osmosis effect, diffusion cells ***A*** and ***B*** have the same salt concentration at the top and bottom of the cylinder.

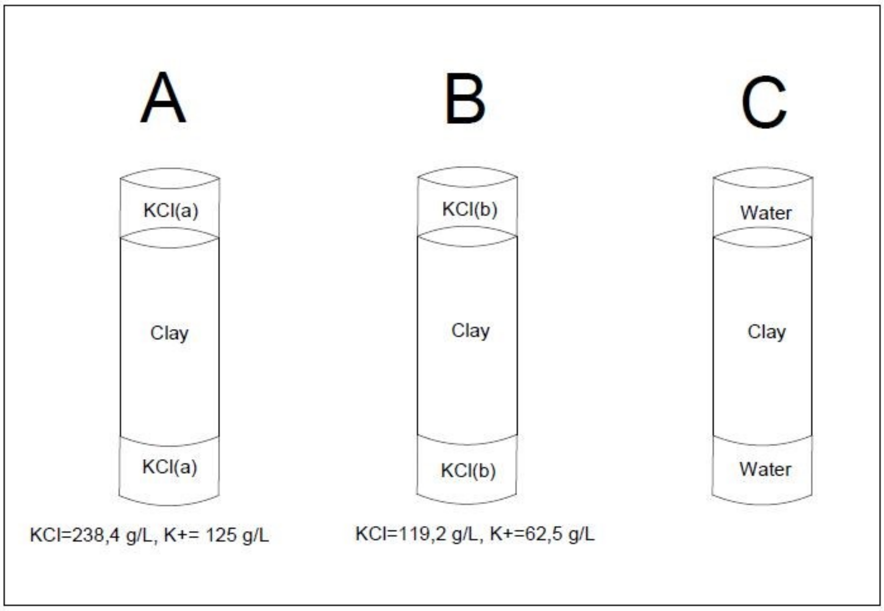


Figure 5-12 Differences salt concentration in the basins for the actual set-up

The electrodes would be placed at the bottom half of the cylinders as shown in Figure 5-13. Due to the same salt concentrations in both basins, the specimen would be axis symmetric along the horizontal mid-point. Since the clay is not a constructed homogeneous substance, one might get some sort of local variations. Hopefully, one will minimize the osmotic effect with a set-up like this, and will mainly have the effect of the salt diffusion. The salt is assumed, due to the difference in salt concentration inside the specimen and at the ends, to travel towards the center of the clay specimen.

The samples had to be moved from the steel to the plastic cylinders to avoid having a material that would disturbed the electrical current. A cylinder made of PVC has an electrical resistivity of 10^{16} Ω cm, which means that it can be considered an insulator (Abu-Hassanein et al., 1996). With help from Gustav Grimstad and Gudmund R. Eiksund, the samples were pushed into the plastic cylinders only a day after arriving at the laboratory, and placed in a fridge until further use.

The experiment is limited to the thickness and length of the cylinders, which are approximately 80 cm long and 5,4 cm in diameter. A part of the sample had to be taken out to preform index testing, so the total length available would be less than 80 cm. The exact length of the cylinder was measured to be 77 cm. To be able to get some clay for index testing a total length of 66 cm was chosen for the set-up. Since the specimen is axis symmetric, the electrodes would be placed at the bottom half of the sample, which is 33 cm. The top part of 11 cm was taken out of the cylinder for index testing.

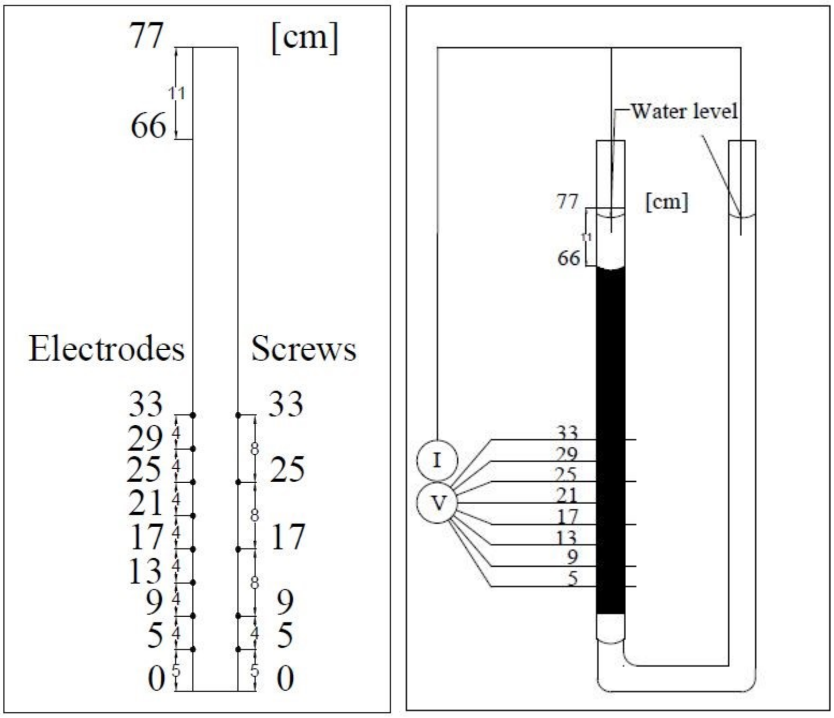


Figure 5-13 Description of the set-up and how the electrodes are placed in the cylinder

Eight electrodes were placed at the lower part of the cylinder, as illustrated at the left figure in Figure 5-13. The first electrode at 5 cm and the last at 33 cm with 4 cm between each electrode. As illustrated at the left figure in Figure 5-13 there were placed five stainless steel screws into the clay. These screws would also function as secondary electrodes, to be able to check if the readings were comparable to the volt that was measured at the electrodes at the same height. In reality, the electrodes and screws were inserted 90 degrees apart (and not 180 degrees as indicated by Figure 5-13), and the voltmeter and ampere-meter was one device.

Figure 5-14 Illustration of how the boring of the holes were done the 22. of March 2016.

To be able to get a connection between the electrodes and the clay, the cylinder had to be perforated with holes. The boring of the holes were done at one of the laboratories with a stationary boring machine as seen in Figure 5-14. The electrodes and screws were sealed with silicon, to prevent water from coming out and air to go in and dry out the sample. After the electrodes and screws were fixed to the cylinder, the cylinder was placed back into the fridge.

Cylinders, reducer fittings and pipe reducer socket were bought at a local sanitary store, with the intention to make a set-up that would be water-proof and able to supply the system with water at both ends. As seen in Figure 5-15 each end of the cylinders were coupled to rubber reducer fittings at each end with a bit of felt inside the fittings to prevent the clay from sinking into the water. At the top, the reducer fitting was connected to a cylinder with outer diameter 50 mm and height around 20 to 30 cm. At the bottom, the reducer fitting was connected to a pipe reducer socket, which again was connected to another tube with diameter 50 mm and height 100 mm.

To be able to connect the set-up to the wall, three boards were screwed into the existing studs behind the plasterboard to maintain a certain stability. The lower board were placed to function as a shelf, to prevent the cylinders from sinking, and to prevent the set-up to fall apart. The two upper boards had two clamps for each cylinder to create stability, which resulted in four clamps per cylinder.

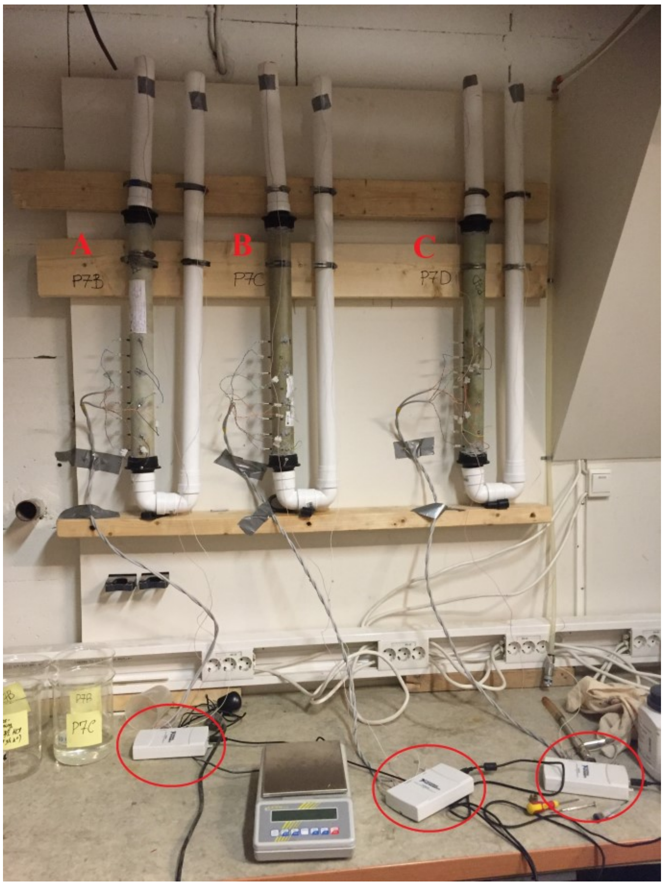


Figure 5-15 A picture of the laboratory set-up. The electrical apparatuses are illustrated with red circles.

When the system was in place, water from the sink was weighted and filled in each cylinder. This was done to get the system to get the same temperature as the room before starting the experiment but mainly to see if the system had any leakages. It also reassured that if the clay for some reason had dried out at the ends, the clay had time to get moist again. Preferably, the salt solution would be made first and then added to the cylinders to reassure that the concentration was right.

The electrical apparatus was coupled to two plastic covered wires with electrodes at each end. The electrodes were placed in the water at each end of the cylinders as showed in Figure 5-15, to supply the system with a current.

The water level of the brine was set to be the same level in the two cylinders, to get $\delta h \approx 0$ and reduce any affect from the water gradient i as described in chapter 4 and equation (3-5).

To be able to provide the clay continuously with salt during the experiment, each end was filled with a salt solution as described in Table 5-3.

5.3.2 Electrodes and apparatus

The electrodes were prepared and made by Head of Engineer Per Østensen at the Geotechnical institute at NTNU. The aim was to make electrodes with little to no resistivity, to be able to get the right potential drop in the clay without interference from the electrodes it self's. To ensure that this premise was met the potentials were measured to know the influence from the electrodes, which was minimal to non, and assumed neglectable. The surface of the electrodes should also be of stainless steel to prevent the ions to move towards and attach to the electrodes. To control the voltage drop across the level, stainless screws were inserted at the opposite side of the electrode to reassure that they gave the same results.

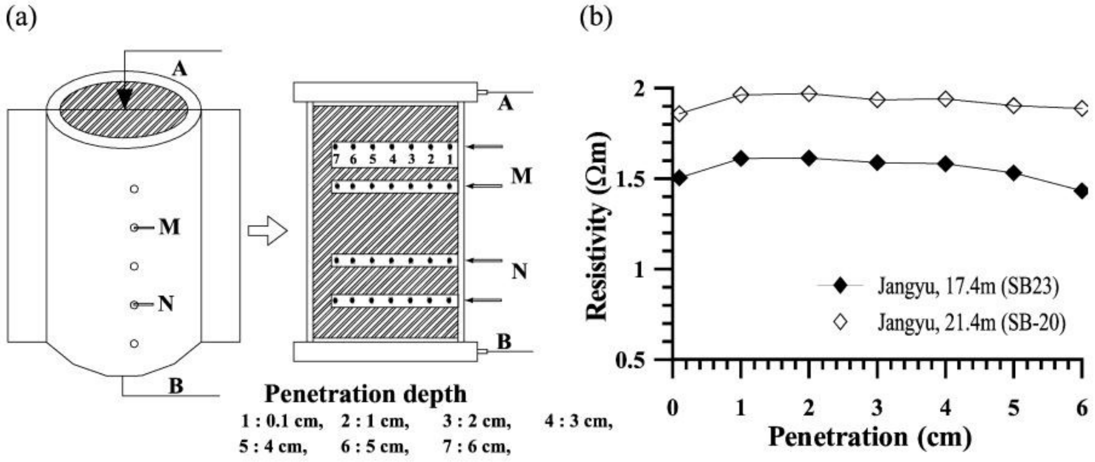


Figure 5-16 Resistivity results with respect to penetration depth (Giao et al., 2003)

Based on laboratory results from an experiment where penetration depth of the electrodes were compared to the resistivity results, it was found that different penetration depths gave more or less the same resistivity as seen in Figure 5-16 (Giao et al., 2003). This applied not only for a circular cross section, but also when tested on a half and a quarter of a cylinder. This indicates that the length of the electrodes are not a decisive element, which gives the opportunity to select a length of own choosing. Since the inner diameter of the cylinder sample is 5,4 cm, an electrode with a length from the outer part of the cylinder of 3 cm was chosen, as seen in Figure 5-17. Since the thickness of the cylinder is ca. 2 mm, this makes the electrode length inside the ca. cylinder 2,8 cm, which lets the electrode to reach approximately into the middle of the sample.

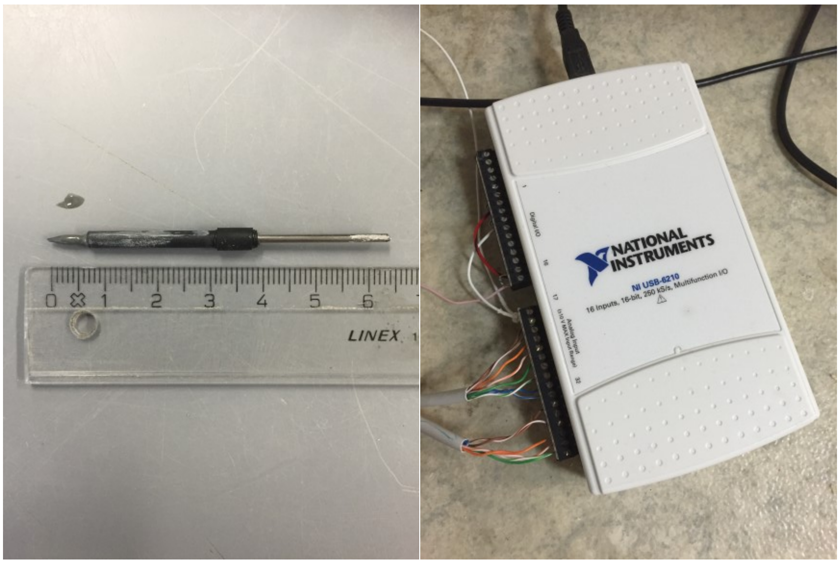


Figure 5-17 The length of the electrode and the electrical apparatus

The apparatus and program was design by Østensen to be able to connect all of the electrodes to it, and to change between different electrodes to be able to measure the voltage between them. Østensen prepared a program in LabVIEW that visually related each electrode to each pin, and illustrated the resistivity in colors so that it was easy to see how the resistivity changed. He sat the input voltage to be 5 V, and the program registered the changes throughout the soil, and measured the average current. The apparatus was connected to a computer where the data was plotted from LabVIEW into a .tex-file. This ensured a minimum human error due to the ability to send a fast electrical impulse trough the soil, and made the readings much more efficient. As seen in both Figure 5-15, as three white boxes illustrated with red circles around it, and Figure 5-17, the electrical apparatus works as both the voltmeter and ampere-meter and a power source.

5.3.2.1 Induced polarization

Electrode polarization is known as a voltage transmission from the equilibrium potential at an electrode. It is caused by electrochemical reactions at the boundary between the pore fluid and electrical charged mineral surfaces, and the accumulation of the ions near the surface of the minerals. These ions oppose the direction of the current, which is called a polarization of the interface (Sumner, 2012).

The choice between direct current and alternating current will have an effect on the results from the laboratory testing. Whilst the direct current only travels in one direction the alternating current changes direction periodically. When doing such an experiment as this, one will like to prevent a polarization effect than might occur when using direct current and the influence this might have on the structure of the clay minerals. Due to this unwanted and disturbing effect, an AC-current should be used (Montafia, 2014).

The current in the system is a DC-current. The current is added for just a few seconds when measuring with an apparatus coupled to a computer, which hopefully would make the induced polarization effect minimal. If everything had been done manually, the current should be an AC-current to ensure that the polarization effect was kept at a minimum. That being said, the polarization effect on this type of laboratory set-up may still be present and give some errors to the results.

5.4 TESTING AND ADJUSTMENTS

5.4.1 Testing of the system

To be sure that the system worked as intended, a lot of different testing had to be made before adding the right concentration of salt to the cylinders. First the cylinders were filled with water to reassure that the system was closed, and without any form of leakage. There was registered some leakage and the places were filled with silica, to prevent further leakage.

When checking cylinder A the voltage was not reduced along the clay, which indicated some sort of measuring problem or noise from the system itself, since an increasing voltage along a material is not physically possible. A measurement was done when not inducing any current at all, which showed an error expressed as a drop in voltage between the electrodes and screws in the clay cylinder. Different things could cause the error, such as abrasion at the oxidized screws, which could induced a current due to the migration of ions that would travel to the places of the screws that had non-oxidized iron. This would result in some current activity, which would disturb the diffusion of the salt. If this was the case, the screws should be oxidized again at some point, and this effect should cease to exist. Since the extent of this effect is unknown, one will have trouble to know when it would stabilize. Another error could have been the current electrodes, which were made of cupper, and not an oxidized material.

The solution to reduce this error was to register both the data from when there was no current added and from inducing the current, to be able to get the difference between the two. This way, one might be able to get the actual current caused by the diffusion of the salt. The error could cause an effect on the results even though it would be removed from the actual result. The error could affect how the salt travels, and give different results than if the error never was presence in the first place. This has to be taken into account when interpreting the results. When the program was calibrated for the error, the voltage between the electrodes and the screws at the same height gave more or less the same result, which was what was aimed for.

There was also a problem with cylinder B, which gave no measurements at all. Per Østensen had designed the program so that the resistivity would show as different scales of colors for the different cylinders as seen in Figure 5-18. The results should be given as a blue scale, and not red, which visually indicated that the there was no current.

To find the problem it was first added a small amount of salt to the fresh water to see if that would give an effect on the current (2 ml 239,3g/L KCl were added to the left side and 8,5 ml 239,3g/L KCl were added to the right side). When trying to measure the activity again, no current was registered. To reassure that the salt had been properly distributed the right hand side cylinder was emptied with the siphon method into a bulb, and filled back into the cylinder. There were still no current registered when trying to measure the current activity after having mixed the solution properly. Another reason for the lack of current could be the congestion of air in the lower socket that prevented a continuous current. When boring a little hole in the lower rubber reducer fitting it was registered air coming as small water bubbles. The air was let out and the connection between the lower part of the clay and the water was established. A screw was placed back in the hole to prevent any further leakage. When checking for results the program measured a current, which gave an indication that the system worked as desired. When having the program all set, all that was left was to add the salt solution. The siphon method was used to remove the water in the cylinders, and the salt solutions were filled back in the cylinders.

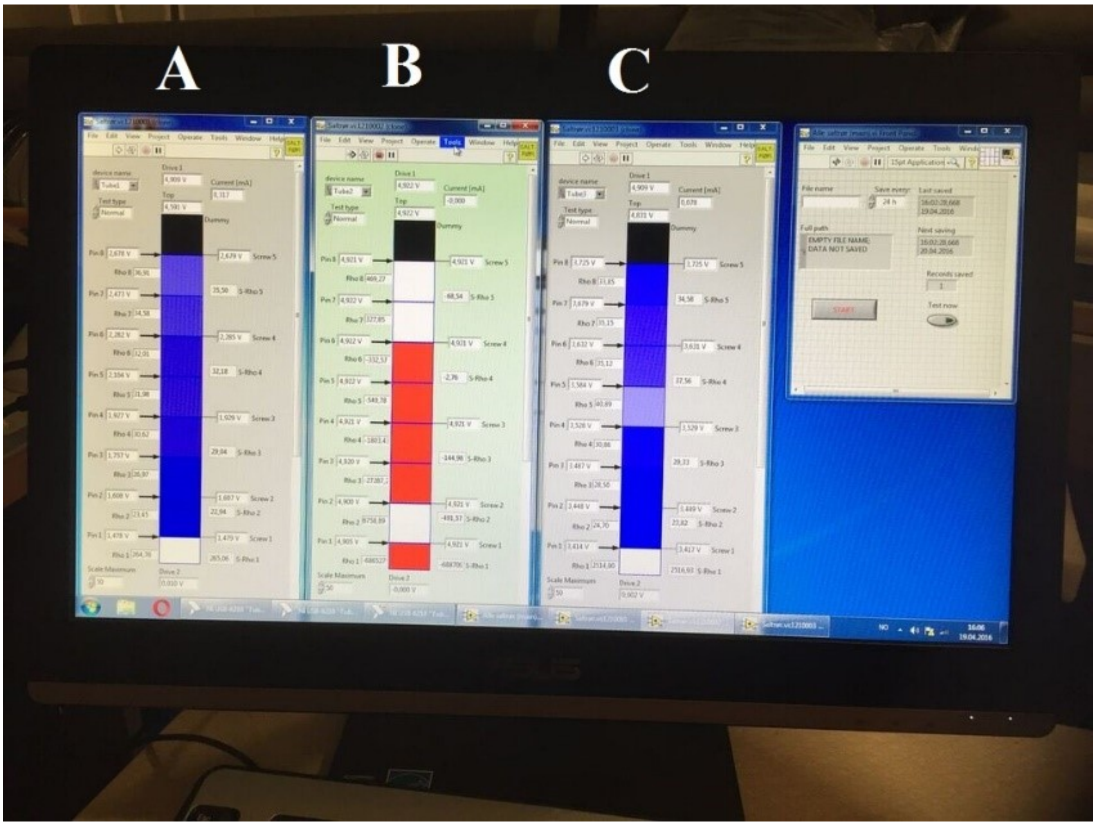
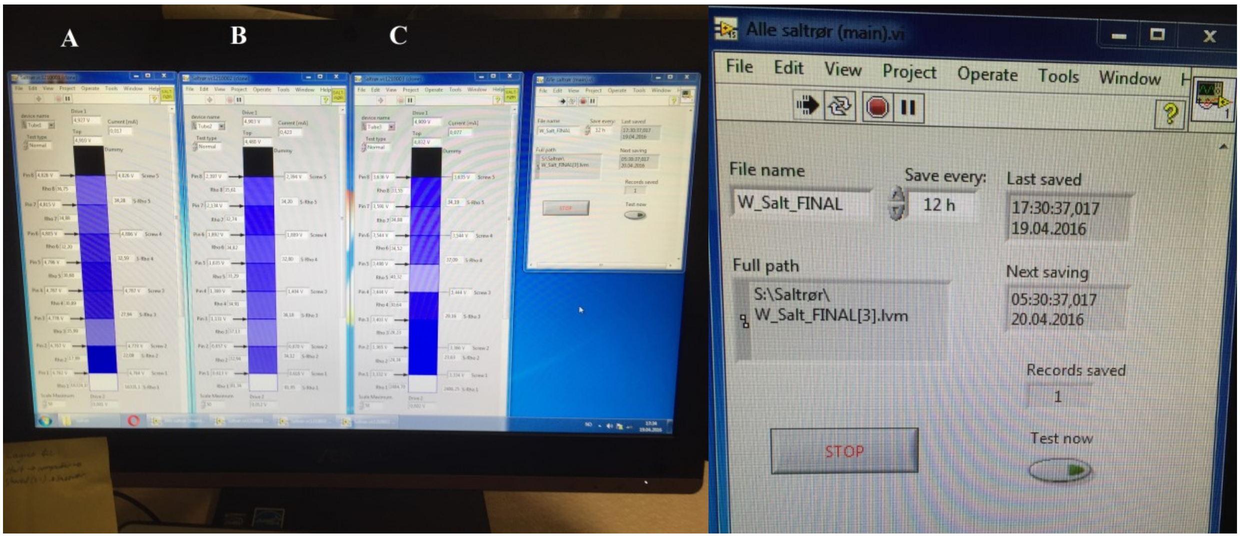


Figure 5-18 Test of set-up after one day

When the system was tested after the first day of measuring, there was still a small problem due to what was presumed air in cylinder B. When removing the screw in the lower socket to let the presumed air out of the cylinder, the scaling for cylinder B showed colors of blue indicating a current through the sample. The cylinders were checked the next days to see if the air was properly removed, which turned out to be the case. The data were then registered every 12 hours the next week to be able to retrieve information concerning the time interval if some problems should occur.



File name: W_Salt_FINAL

Save every: 12 h

Last saved: 17:30:37,017 19.04.2016

Full path: S:\Saltrør\W_Salt_FINAL[3].lvm

Next saving: 05:30:37,017 20.04.2016

Records saved: 1

Figure 5-19 Picture of the program showing how the results appear in LabVIEW.

When having added the salt, all the cylinders showed that the current went through the sample as shown in different shades of blue in Figure 5-19. The picture on the right hand side in Figure 5-19 shows the input data with the choice of deciding how often the program saves the data. This is convenient because it reduces the manual work, as well as the ability to save the data in different intervals during the testing time. When all the data were saved, the file was imported to excel where the resistivity calculations were done.

5.5 THEORETICAL CALCULATIONS

5.5.1 Diffusion coefficient

When inserting the values in equation (3-8) from chapter 3.3.2 with respect to a temperature of 20 degrees Celsius the self-diffusion coefficient for K$^+$ will be:

$$D_{K^+,20} = \frac{(1{,}96 \cdot 10^{-9}) \cdot 293{,}15 \cdot (0{,}893 \cdot 10^{-3})}{298 \cdot 0{,}1} = 1{,}72 \cdot 10^{-9} \ \frac{m^2}{s}$$

(5-3)

When going forward with the calculations it is assumed that the diffusion coefficient is independent of the change in concentration of the solution. Even though there are exceptions, the diffusion coefficient varies little with respect to temperature, solute or solute concentration (Cussler, 2009), which in this case is the basis for assuming the diffusion coefficient as a constant.

A summary of the self-diffusion coefficient at relevant degrees Celsius are listed in Table 5-4. The self-diffusion coefficient is free diffusion in water, and has to be adjusted for the pores in the matter as described in chapter 3.3.2. To simplify the equation the pores are assumed fully saturated which gives: $e_w = n$, $w = 35\%$ Equation (5-1), $\gamma_s = 27 \frac{kN}{m^3}$ specific grain density (Helle; et al., 2013), $\gamma_w = 10 \frac{kN}{m^3}$ water density, $e = w \cdot \frac{\gamma_s}{\gamma_w} = 0{,}35 \cdot \frac{27}{10} = 0{,}945$, $n = \frac{e}{1+e} = \frac{0{,}945}{1+0{,}945} = 0{,}486$

The effective diffusion coefficient is then:

$$D_e = D_{K^+,20} * e_w = 1{,}72 \cdot 10^{-9} \ \frac{m^2}{s} * 0{,}486 = 8{,}36 \cdot 10^{-10} \ \frac{m^2}{s}$$

Table 5-4 Calculations of S\self-diffusion coefficient for K$^+$- ions at different temperatures. Numbers water viscosities are gathered from (Vanoni, 2006).

Self-diffusion coefficient for K$^+$-ions					
D$_{K+}$ (298K)	T in °C	T in Kelvin	η water (298K)	η water (T)	D$_{K+}$ (T)
1,96E-09	25,0	298,15	0,00893	0,00893	1,96E-09
1,96E-09	20,0	293,15	0,00893	0,01000	1,72E-09
1,96E-09	19,0	292,15	0,00893	0,01030	1,67E-09
1,96E-09	18,9	292,05	0,00893	0,01030	1,66E-09
1,96E-09	18,3	291,45	0,00893	0,01050	1,63E-09
1,96E-09	18,0	291,15	0,00893	0,01050	1,63E-09
1,96E-09	17,8	290,95	0,00893	0,01060	1,61E-09
1,96E-09	17,2	290,35	0,00893	0,01080	1,58E-09
1,96E-09	17,0	290,15	0,00893	0,01080	1,58E-09

5.5.2 Change in concentration

The change of concentration along the clay is calculated based on the solute concentration in the clay (which is assumed zero) and in the brine added in the tubes in connection with the clay. The salt concentration in cylinder A was made to be 125 K^+ g/l. The change in concentration would then be dependent on the diffusion coefficient, the length of the part tested, and time.

5.5.3 Effective diffusion length

As described in Chapter 3.3.2 the diffusion gives more sense explained as a concentration change dependent on time. Fick's 2.law allows us to explain the change of concentration dependent on the diffusion coefficient, the length of the specific part and time. The practical case will be a third dimensional case, but to simplify the calculations it is looked upon as a 1D problem.

The diffusion coefficient has been determined in chapter 5.5.1 as a constant, which allows us to find one of the remaining parameters when choosing the other. From chapter 3.3.3 Fick's 2.law has been solved by introducing a new parameter ξ. When ξ is solved it gives a solution expressed as an error function. The relation between ξ and the error function of ξ, erf(ξ), is given in tabular form, and when plotted gives a Gaussian distribution. This allows diffusion to be looked upon as a statistical process (Appelo and Postma, 2004). The relation between erf(ξ) and ξ is illustrated in Figure 5-20.

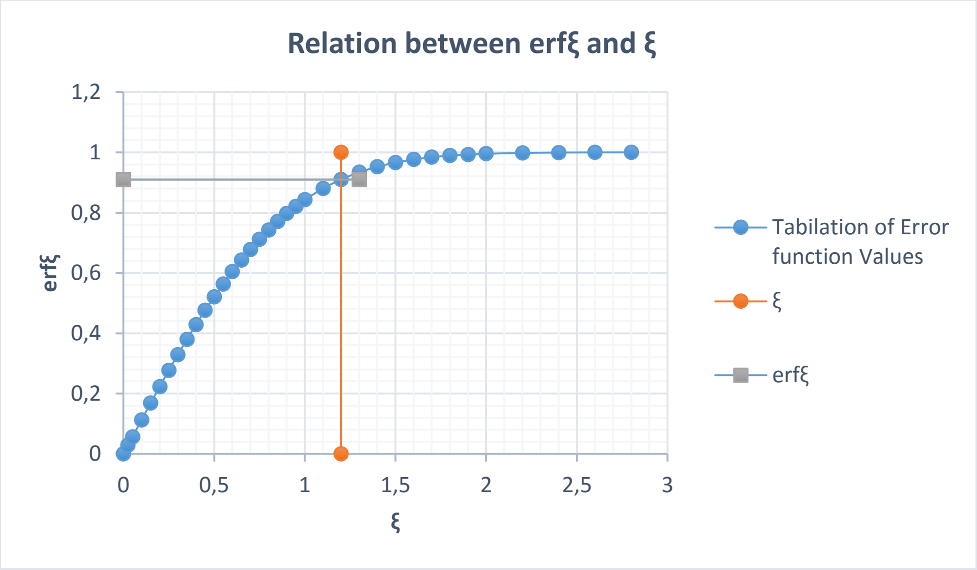


Figure 5-20 The relation between the error function erf(ξ) and ξ based on tabular values from (Appelo and Postma, 2004).

A concentration profile can be calculated in a chosen time interval, when the average diffusion distance is set with chosen intervals. This distribution allows us to see how the concentration changes and when the clay has a decided concentration front.

To find the effective diffusion length for potassium one has to decide the input parameters, and may present it graphically by comparing the distance from the start out point into the clay by time. There are many variables that vary, when studying Fick's 2 law. To be able to solve it, one has to choose the input parameters so that it gives a usable outcome. To simplify the problem it is assumed that the background concentration in the clay is equal to zero (c_i=0 K^+ g/L) (Moum et al., 1968, Helle, 2013, Gjengedal, 2012). The concentration presence in the water reservoir is measured and assumed to be equal to 125 g/L (c_o=125 K^+ g/L) for cylinder A. To find the error function complement $erfc(\xi)$ the concentration with respect to time and distance c(z,t) has to be set.

Since there has been too few studies, which could relate the c(z,t) to resistivity, one would have to choose it based on other aspects. A c(z,t)=0,5 K^+ g/L has been shown as the lowest concentration of which the geotechnical properties of the clay gives a noticeable change (Moum et al., 1968). Since the clay is going to be tested to find the change in geotechnical parameters after the resistivity measurements, it would make sense to use a concertation based on these assumptions. When having found the error function complement, the error function and its respectable ξ can be found. A number of suitable distances is chosen up to the total length of 33 cm, which is sat as the ending point. The curve for a concentration of 0,5 g/L with variations of the distance versus time shows that the salt diffuses faster in the beginning and reduces over time. The estimate of the time it would take for the diffusions length to be 33 cm, is based on a constant concentration input, which in practice would vary. The estimate may therefore vary a bit due to the change in concentration.

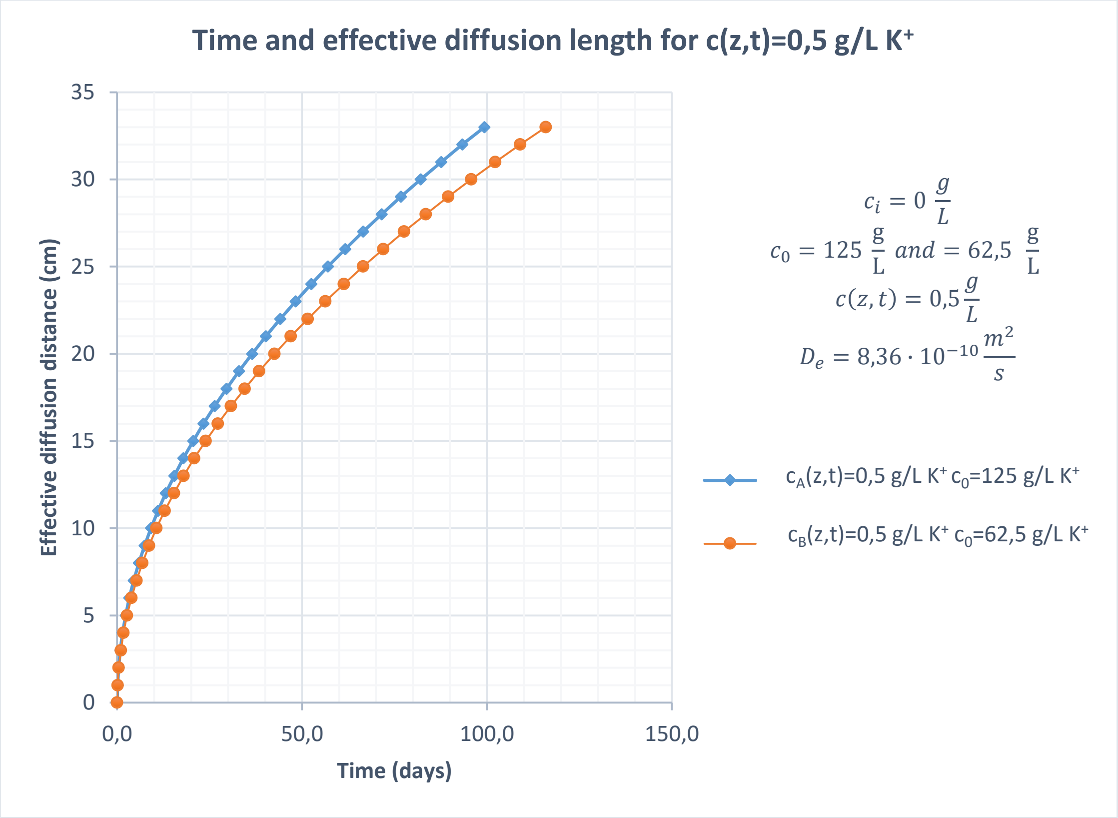


Figure 5-21 Time and effective diffusion length for potassium front c(z,t)=0,5 g/L for cylinder A and B

As indicated in Figure 5-21 the diffusion is rapidly increasing the first days and then the gradient for the diffusion front is decreasing as time passes. The diffusion front of 0,5 g/L K$^+$ will have reached half the way after approximately 24 days for cylinder A(125 g/L K$^+$). After around 97 days the front has reached the top electrode at 33 cm. Since time is limited, the clay will be tested after 38 days, to see how the changes have affected the geotechnical properties, and cylinder B (62,5 g/L K$^+$) will be left for 110 days to gather the last resistivity information.

Since the electrode closes to the midpoint of 33 cm would be the one 17 cm from the bottom of the sample, one make the cylinder ready for geotechnical parameters after the front of c(z,t)=0,5 g/L K$^+$ has reached beyond this point. The raw data for Figure 5-21 could be found in attachment 3.

CHAPTER 6

6 RESULTS

The results are presented graphically to be able to see the change of the parameters with time. The resistivity values are first presented for all cylinders at the start out point and ending point. Each cylinder is further presented alone, with the resistivity values for different times during the measuring period. The resistivity is calculated as the average resistivity between each pin.

The index data are first presented for the entire clay with its respectable values. Then the index data are compared with the resistivity values for the lower part where the measurements have been done.

6.1 RESISTIVITY

When retrieving the data after 38 days (27.05.2016) of the resistivity measurements, the data were logged at the time of ending the measurements. For cylinder A it was clearly that there had been some leakage, resulting in the salt migrating to the outside of the rubber socket at the lower part of cylinder ***A***, as seen in Figure 6-1. When retrieving info on the 21.05.2016, there was not visually registered salt at the outside of the rubber socket for cylinder A, so it has likely happened the last days between the readings. This will likely affect the readings the last week, due to the salt going out of the clay, rather that up in the clay.

6.1.1 Salt migration due to leakage

If taking a closer look at Figure 6-1 one could see a color change from the white salt to a brownish color around the lowest screw. This could indicate rust at the screw due to the contact with the salt and the surrounding air, which had allowed access to oxygen. Since it was reassured that both the screw and the electrode was stainless steel, this effect was suppressing. After the last resistivity reading was done, the set-up was prepared to be taken down. After the screws were unscrewed, and it was clearly that it was neither the screw, electrode nor the coupling between them that was the reason for the corrosion. If taking a closer look at the system as seen in Figure 6-2 the bolt nut between the screw and the coupling could presumably be the reason for the corrosion.

Figure 6-1 Salt migration due to leakage at the lower rubber socket for cylinder A (27.05.2016).

The bolt nut was not in the original plan of the set-up, but a necessity when realizing that the screw did not want to stay in contact with the coupling. As with many project, one solve the problem as you go, but do not necessarily think of every outcome. Every iron part was chosen to be of stainless steel to prevent the salt from sticking to the electrode, rather than traveling through the clay. Unfortunately, the bolt nut was clearly not. This could have caused the salt to seek its way to the bolt nut, when having a small leakage there in the first place.

One reason why this happed to the lower screw and not any of the other screws could be that it was easier for the salt to travel at the outer part of the clay. One can imagine that the clay at the very bottom of the sample had either shrunken a little due to drying out while preparing the set up or sunken a bit as an effect of gravity, causing a small pathway at the sides of the clay between the plastic cylinder.

Figure 6-2 Corrosion from the bolt nut, the unaffected screws and coupling.

6.1.2 Retrieving of the data

The values from the setup is loaded in a .lvm file from LabView, which is easily transformed to a .text file and imported to Excel to interpret the data and calculate the resistivity. The data are logged for the specific date and time, giving an output of voltage for each electrode and screw for each cylinder and a current. The drop in voltage between the electrodes are then calculated, the cross section area ($A = \pi r^2 = \pi * \left(\frac{0,054}{2}\right)^2 = 2,29 \cdot 10^{-3} m^2$) and length between the electrodes (4 cm for all, except for the bottom part that are 5 cm) are given, which with the output current is enough information to calculate the resistivity based on equation (3-3) from chapter 3.1.1.2. The raw data file is found in attachment 1.

6.1.3 Relation factor due to temperature change

The resistivity then has to be adjusted for the temperature difference between the laboratories were the set-up has been executed (20°C), and where the index testing is performed(25°C). As elaborated in chapter 3.4 the relation between the two, might be expressed as equation (3-19), which gives a relation factor of 0,9 (if having a α=0,02). This means that a resistivity at 25°C is 0,9 times less than a resistivity at 20°C. This makes sense since the increase in temperature increases the conductivity, which decreases the resistivity.

6.1.4 Resistivity represented graphically

When the resistivity between the pins are calculated a graphical illustration as the one in Figure 6-3 shows the change in resistivity two days after the start of the measuring time. As expected the cylinders have some variation in the start-out resistivity values. When compare the resistivity measurements when the brine has had time to diffuse into the clay after 38 days as seen in Figure 6-4 the resistivity is clearly reduced for both cylinder A and B. The reduction for cylinder A is larger than for cylinder B, as expected, due to the different concentrations in the brines. What might be surprising is that there also has happened some change in cylinder C, which is further explained when presenting the resistivity for the water at different dates in Figure 6-7.

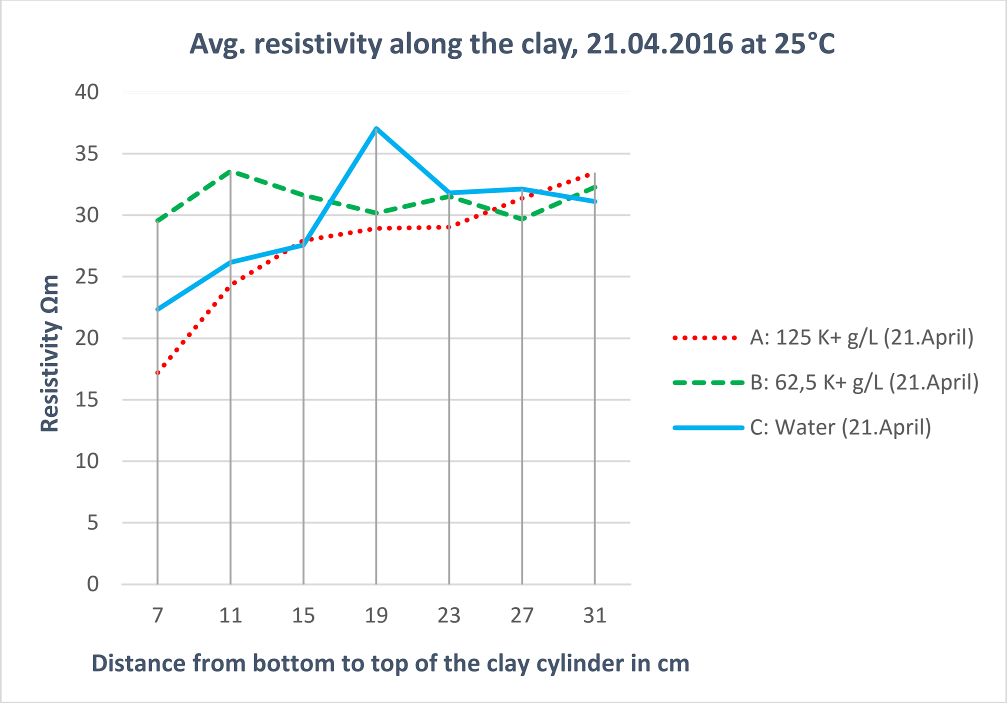


Figure 6-3 Average resistivity along the clay 21.04.2016 for all cylinders.

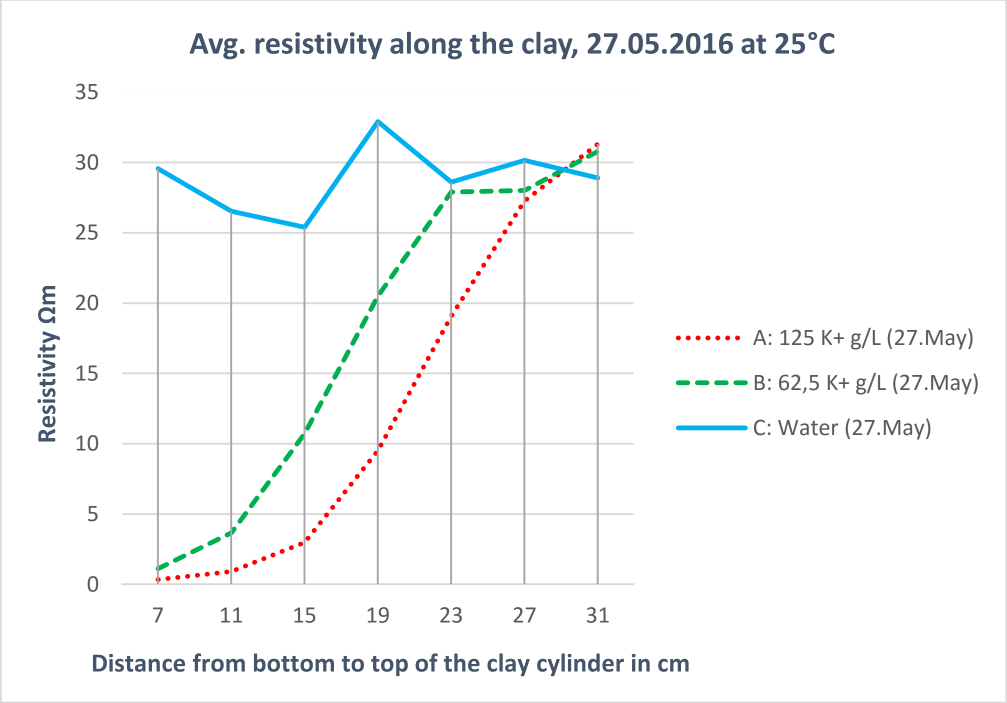


Figure 6-4 Average resistivity along the clay 27.05.2016 for all cylinders.

If one take a closer look at what happens to the resistivity at chosen dates, a picture of the changes over a shorter time interval can reveal how the curves are changing. As seen in Figure 6-5 the resistivities for 19.April, 21.April, 28.April, 5, May, 12.May and 27.May are plotted.

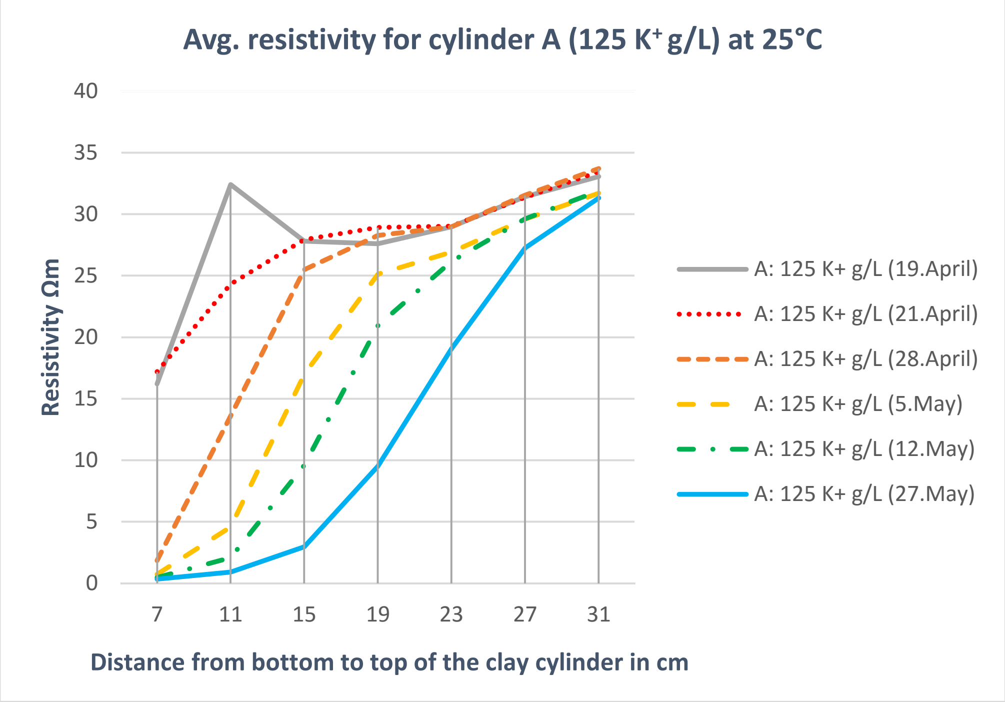


Figure 6-5 The average resistivity along the clay for cylinder A (125 K^+ g/L) for given dates.

As expected, the trend for Figure 6-5 is that the resistivity is reducing with the time that the clay is exposed to the brine. The first dates (19.April and 21.April) shows a fast stabilization of the resistivity and after 9 days the curve has adjusted to reached a very low resistivity as the bottom of the clay. This indicates that the salt has been able to diffuse well into the lower part of the clay.

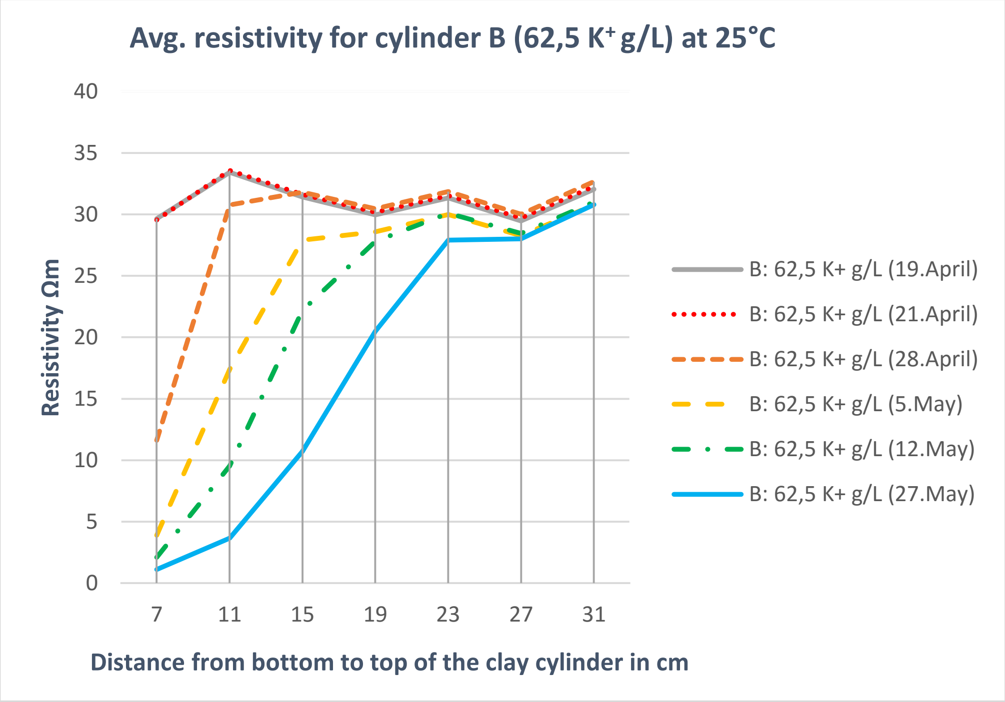


Figure 6-6 The average resistivity along the clay for cylinder B (62,5 K^+ g/L) for given dates.

The reason why the curves for cylinder B in Figure 6-6 is quite equal for both 19.April and 21.April can be explained by the issue with getting a proper connection between the clay and water. It was fixed on the 20.April, which would let the clay to absorb the brine again. On the 28.April one see a reduction in the resistivity, but not as fast a reduction as for Figure 6-5. This could be explained by the input concentration that is twice as high for cylinder ***A*** as for ***B***. For Figure 6-6 the resistivity never reaches zero, as it appears to do for cylinder ***A*** in Figure 6-5.

The resistivity for the cylinder filled with water changes a bit over the 38 days of measurements, as seen in Figure 6-7. It could be that some of the already existing ions in the clay had been moving downwards, due to a gradient as a result from a height difference in the two water cylinder reservoirs, or due to forces from the self-weight of the overlying clay and water. The most likely reason is thought to be to the concentration difference between the inner clay and the water, which could cause the ions to travel towards the water reservoir rather than stay inside the clay. As seen in Figure 6-7 the resistivity is lower for inner part on the 27.may than for the 19.April, and higher for the outer part on the 27.May than on 19.April. This means that the inner resistivity has been reduced, whilst the outer has been increased, which supports the assumption that the ions has travelled out of the clay towards the reservoir. Over an infinite time, one might suspect the graph to even out, with a constant resistivity.

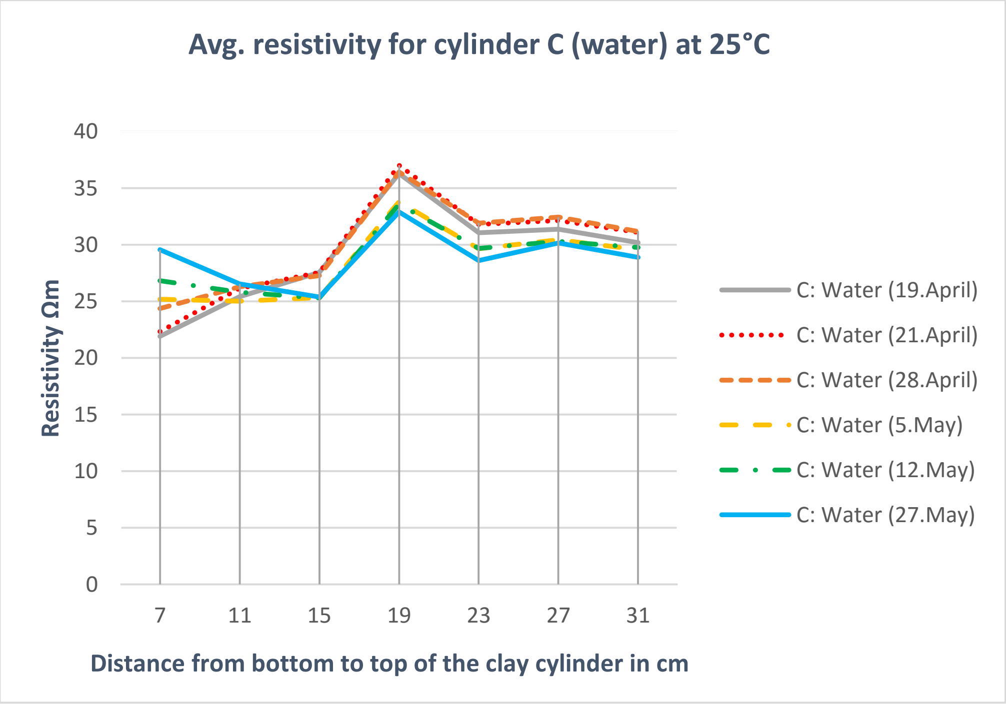


Figure 6-7 The average resistivity along the clay for cylinder C (water) for given dates.

6.2 INDEX TESTING ON SALT TREATED CLAY

As explained, the top layer of each cylinder was put aside for index testing. At this point it was done to reassure that one could retrieve a reference point for the geotechnical parameters. The reliability of the index testing for the top part of the clay would be low. This is due to the errors caused by disturbances, such as vibrations, temperature changes, evaporations and so on. Since there only was three cylinders available, the upper part of each cylinder was removed for the index testing. It might have been remolded, which will mainly affect the undisturbed shear strength, but could give an effect the water content too. This will give an error to the Attenberg limits and remolded shear as well. Since most of the cylinders needed to be intact, there was no possibility to use the mid parts of the cylinder sample, as most common used when doing index testing. One could have gathered more samples for index testing, but limitations due to cost and time made it not possible to get more cylinders. The raw data from the index testing can be found in attachment 2.

The clay was pushed over in plastic cylinders as early as 8.03.2016, which could have disturbed the clay at the top part. The clay was then stored for some weeks to get a proper adhesion between the clay and inner part of the plastic cylinder. The clay was prepared the 22.03.2016 with perforating the cylinder with holes and adding electrodes and screws, and the top part of the cylinder was sawed off for index testing. The part was covered in plastic film, and put in separate plastic boxes and stored in the fridge until 22.05.2016.

All these errors related to the samples intended for index tests makes the results from Tonje Eide Helle more suitable to use as a reference, since these results are more reliable.

A Grain size distribution and hydrometric analysis has not been performed to find the clay percentage of the sample, since Helle already has done this test. The clay content was found to be approximately 38% as mentioned earlier from the earlier studies.

The index testing of water content, plasticity index, and a fall cone test have been performed according to Norwegian Standards (Vegvesen, 2016). The sensitivity, water content, plasticity index and have been calculated as explained in chapter, 2.1.2, 2.1.3, and 2.1.4 respectively. Salt content is normally not included when performing an index test, but in this case, it is of relevance. To find the salt content the clay is put into a centrifuge, that pressure the pore water up at the top of the clay. To reassure that there were enough saltwater after the centrifuging, the liquidity index has not been tested after the fall cone test due to lack of clay.

After 38 days the resistivity-measurements have been carried out on cylinder A, to see how the salt has affected the geotechnical parameters. The last cylinder has been allowed to stand with the effect of the brine until the diffusion front with concentration 0,5 g/L K^+ has reached for a distance of ca. 33 cm.

Due to time limitations index testing were only performed for cylinder A. Before the cylinder was taken down for standard testing, the order of each step had to be planned, so that the sample is tested as fast as possible after ending the resistivity measurements. A proposed solution to such a plan is summarized in Table 6-1. This plan was started on the 27.th of May.

Table 6-1 Summary of the procedure for taking down the set-up and the laboratory testing

Summary of the procedure for taking down the set up and the laboratory testing on cylinder A	
1	Do a resistivity reading
2	Remove all the water from the water reservoir
3	Unscrew the set-up and take the clay sample down carefully
4	Bring the cylinder into the laboratory for index testing
5	Remove all the electrodes and screws connected to the sample
6	Remove the sockets
7	Push out the clay
8	Divide the clay in parts of 4 cm (except for the bottom/upper part of 5 cm)
9	Take a 1 cm from the upper part for each piece and remember to do numbering for all pieces, and weigh each part before putting it in the oven.
10	Wrap all the remaining parts in plastic and number them
11	Perform cone testing
12	Save the remolded clay, and put it in small tubes for centrifuging. Number the tubes.
13	Centrifuge the samples, and find the salt content
14	Stir the saltwater back into the clay and find the plasticity limit
15	Repeat step.11-14 until all samples are tested.

The first step was to do a reading of the resistivity before taking down the set-up. After the resistivity measurements were loaded and the data were retrieved, the water could be removed from the reservoirs at each side of the cylinder. This was done using the siphon method. The wires coupled to the electrodes were then carefully removed and the electrical apparatus were uncoupled from the system. The electrical system should preferably be taken down before the removal of the water for safety reasons. The pressure from the water could affect the index data, by causeing a flow of water when having opened the perforated hole. Therefore, the water had to be removed before the screws. The screws were then removed for the entire system, and the clay cylinder was taken down. The cylinder was then brought to the laboratory for standard testing.

A very interesting aspect which had caused some worrying, was if the filter had been able to withhold the clay inside the cylinder, and preventing any clay from sinking into the water. When uncoupling the bottom socket from the clay cylinder, the filter had some clay at the side of filter that was in contact with the water. This amount of clay was less than expected, and it looked as if the clay had been prevented from leaking into the water reservoir as seen in Figure 6-8 . There was also registered surprisingly little sediments in the bending point of the reducer socket. This support the assumption that one could solve the clay from sinking, by using a filter.

Figure 6-8 The filter of the lower and upper part of the clay in cylinder A after testing, respectively.

The cylinder was brought to the laboratory and the electrodes and screws that were connected to the sample were to be removed. When these were removed and the sockets were taken of each end, the clay was ready to be pushed out for index testing.

The lower part of the clay had been compressed a bit due to self-weight of the clay and the weight of the overlying brine. As a result the lower part of the clay has moved to the end of the plastic cylinder, whilst the upper part has sunken by approximately 0,5 cm as seen in Figure 6-9. This also results in the upper part being more wet, that the lower part, since the upper part has had more space between the clay and the filter.

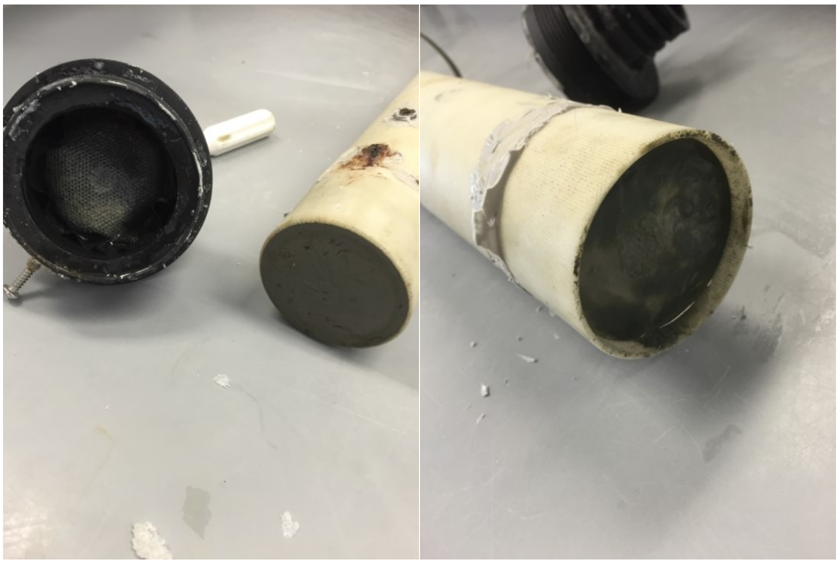


Figure 6-9 The lower and upper part of the clay in cylinder A after removing the sockets, respectively.

The distance between each electrode is 4 cm, which makes it logical to divide the clay cylinder into parts with this length, to find the parameters between the electrodes. Since these parts are quite small compared to the normal testing parts of 10 cm, the order of the laboratory procedure is crucial.

6.2.1 The dividing of the clay sample

An ideal way of dividing the sample would be to divide it vertically in half and do the test on parts with heights of 4 cm symmetrically on the center. This way the parameters would be the average between each electrode, except for the undisturbed shear strength. This is not possible to do in practice due to the size of the sample, which is too small.

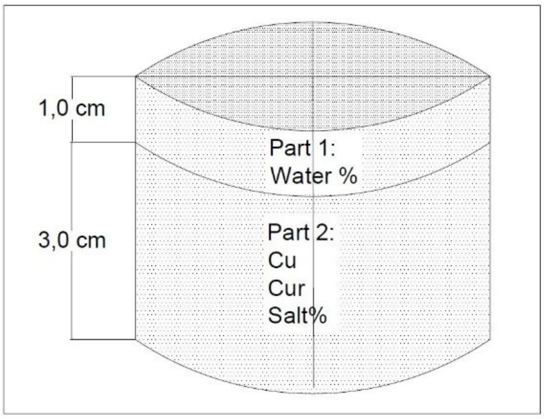


Figure 6-10 Dividing of the sample for index testing for cylinder A.

A purposed solution for how the samples could be divided is showed in Figure 6-10. Each sample is divided into two parts with heights of 1 cm and 3 cm. Part 1 is cut of from the side of the clay sample closest to the center of the complete clay cylinder. Part 1 of the sample is taken to find the percentage of water in the clay. Part 2 is prepared for cone testing and testing for salt content. After the salt content is found, the water is then put back into the clay, and stirred, so that it is possible to find the plasticity index.

Before doing the index testing the cylinder is weighted. The cylinder was put down at the machine that pushes the clay out of the cylinder and stabilized, since the clay is shorter than a normal 54-mm sample. When trying to push out the clay, it was clearly that speed was to slow to prevent the clay from go out of the perforated holes as seen in the left picture in Figure 6-11. The machine was stopped, and the holes were clogged. The clay was then pushed out of the cylinder with success as seen in the right picture in Figure 6-11. As seen in the right picture in Figure 6-11, the clay looks wetter in the mid part, and stiffer at the ends. This coincides well with the idea that the salt has been able to diffuse into the ends, but not fully to the mid part of the clay, which should still be quick.

Figure 6-11 The clay moving out of the perforated holes in cylinder A and the end result, respectively.

After the clay was pushed out of the cylinder, the length was measured and divided into parts of 4 cm except for the end pieces, which is 5 cm. Part 1 of 1 cm of each piece closest to the center was removed, weighted and put in the oven to get the water percentage of the clay. This means that parts for water testing from part 1-8 was the upper part of the clay piece, and the water testing part from 9-16 was the lower part of the clay piece as seen in Figure 6-12. It was repeated for all the pieces, so that the time before water testing was minimized. When these parts were weighted and put into the oven for all parts, the rest of the samples was carefully wrapped into plastic, to prevent it from drying out. The procedure is illustrated in Figure 6-12. As seen from Figure 6-12 the dividing of the clay was done as good as possible with respect to the length decided, but there was some trouble when reaching the soft part. As a result, part number 16 ended up being a bit more than 6 cm instead of 5 cm. However, a simplification is made assuming that all pieces are 4 cm, except the end pieces, which are 5 cm. Some inaccuracy due to this is expected.

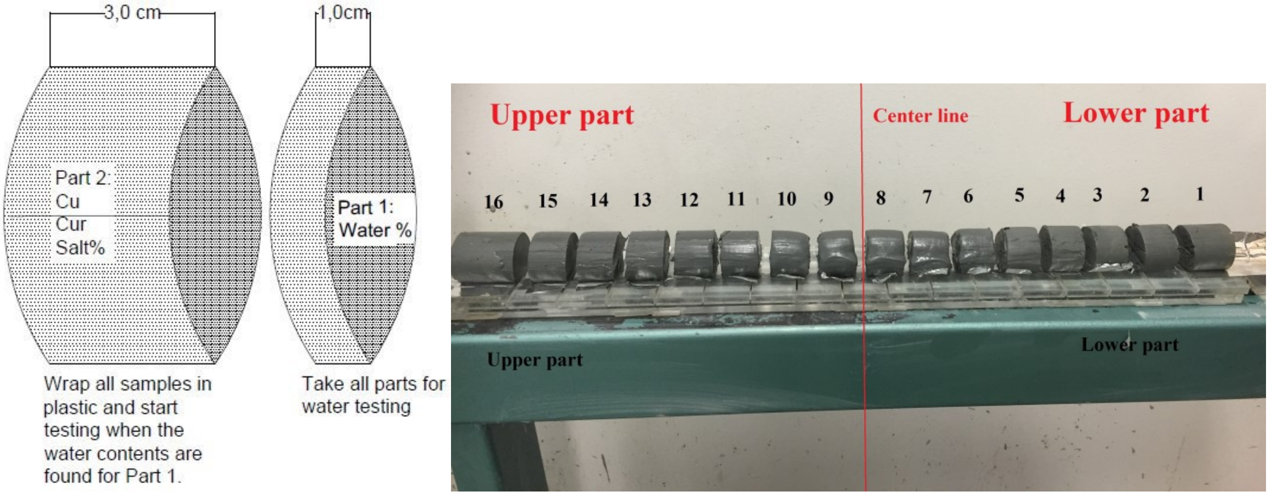


Figure 6-12 Procedure for index testing and the division of the clay from cylinder A, respectively.

6.2.2 Fall cone test

It could then be performed cone fall testing to find the undisturbed and remolded shear strength of the sample. These values were plotted into Table 6-2 using Equation (2-1). The fall cone test is illustrated in Figure 6-13, where first the undisturbed fall cone test was performed, then the clay was remolded and tested for the remolded shear strength. Three tests were performed for each sample, to get an average value of c_{ur} and c_u.

Figure 6-13 Cone test for sample 10 with 60g/60° cone for Cu and 10g/60° for Cur, respectively.

The samples in the mid part were the softest clay and the outer part were not soft, as observed in Figure 6-11. The fall cone test verified this when comparing the results of the sensitivity and remolded shear strength to the reference values that define quick clay (C_{ur}<=0,5 kPa,S_t>30). A summary of the results from the fall cone test is shown in Table 6-2.

Table 6-2 A summary of the sensitivities for the sample taken from cylinder A.

Falling cone					
Sample	**Part**	**C_u**	**C_{ur}**	**S_t**	**Sensitivity**
no.	***cm***	***kPa***	***kPa***	**-**	***($C_{ur} <= 0,5$, $S_t > 30$)***
1	0-5	60,2	18,3	3,3	Not quick
2	5-9	70,2	10,1	6,9	Not quick
3	9-13	42,3	19,8	2,1	Not quick
4	13-17	30,4	11,1	2,7	Not quick
5	17-21	9,9	3,0	3,3	Not quick
6	21-25	7,3	0,5	16,1	Quick
7	25-29	3,7	0,1	37,3	Quick
8	29-33	6,6	0,1	66,0	Quick
9	33-37	7,8	0,1	77,7	Quick
10	37-41	9,0	0,1	90,0	Quick
11	41-45	4,6	0,3	15,9	Quick
12	45-49	6,6	2,0	3,4	Not quick
13	49-53	16,3	7,9	2,1	Not quick
14	53-57	28,3	11,1	2,6	Not quick
15	57-61	33,0	14,5	2,3	Not quick
16	61-66	24,0	11,6	2,1	Not quick

From Table 6-2 the values from sample 6 and 11 are considered quick, because of the higher reliability of remolded shear strength than the sensitivity for the sample. Clays with sensitivities between 16-32 could be defined as medium quick clays (Rosenqvist, 1953). One would expect a decrease in C_u and C_{ur} from sample 1 into the middle part to sample 8, and an increasing in C_u and C_{ur} from part 8 to part 16. It is assumed that the undisturbed shear strength (C_u) would be disturbed from cutting and moving it to the fall cone test, which will reflect on the sensitivity. For this data there will be a certain uncertainty, which makes is logical to classify the clay with a higher weight from the values of C_{ur} when evaluating the results, especially for the parts that are quick. The parts at the end, which were in contact with the salt brine, is assumed to behave a bit differently than the inner parts, due to the contact with saltwater. If taking a look at sample 16 (the very top part of the clay) the C_u and C_{ur} is lower than for sample 15. This may be explained by the fact that the clay had sunken in the upper part (as seen in Figure 6-9) and allowing the clay to be more moist than it's lower part number 15. One could imagine the water to go through the filter and allowing the clay particles to move a bit between the upper part of the clay and the filter, which results in a lower C_u for part 16 than for part 15. For the lower part from 15 to 8 the C_{ur} and C_u decreases, with exception of part 11. As seen in Table 6-2, this is in the quick area, and the C_u might therefore be more easily disturbed.

For the lower part, the overlying weight of the salt brine and the clay might be the reason for a higher C_u than for the upper parts. The clay at the very bottom, sample number one, has been in contact with the filter, which as for sample 16, allows it to be a bit more moist than sample number 2. This may explain the lower C_u for sample one, than sample 2. The C_u is then decreasing from sample 2-7, and is a bit higher for sample 8. As for part 11, this part might be disturbed.

Table 6-2 corresponds well to the assumption that when the diffusion coefficient has a front of 0,5 g/L one can see changes in the geotechnical parameters. After 38 days the diffusion coefficient should theoretically have reached 20,4 cm into the clay as seen from $c_A(z,t)$ in Figure 5-21. Sample number 5 is the sample between the electrodes of 17,0 cm- 21,0 cm, which by looking at the parameters has been able to change from quick into not quick. It has a lot less remolded shear strength than the one for sample 4, which indicate that the salt front is higher for part 4 than part 5. This reflects on the remolded shear strength, being less than for sample 4 than 5. For sample 6, which is the sample between the electrodes 21,0-25,0 it is clearly that the clay still is quick, but has had some effect of the diffusion since C_{ur} has increased a bit comparing it to part 7. The front has not yet reached a high enough concentration to give a significantly higher $C_{ur.}$

Figure 6-14 shows the plotting of the remolded shear strength against the resistivity values from the latest data points 27.05.2016, for the lower part of clay cylinder A. It is clearly that there is a relation between the two. The resistivity is higher for the average values of 23, 27 and 31 cm in the inner part of the sample were the clay is quick, and reduces closer to the bottom part of the clay. At the average length of 11 cm into the clay, which is the data from sample 3, it has clearly a higher C_{ur} than for the rest of the samples. This could be explained by the much lower water content for this sample compared to the rest as is illustrated in Figure 6-34. One might expect a higher C_{ur} for sample 2 at an average distance of 7 cm, but as explained earlier the ends may have some errors, hence might give curious results.

The reference values from Helle indicated an approximately c_u=8-10 kPa, and a c_{ur}=0,1-0,2 kPa, which fits the inner sample from 6-11 very well for the remolded shear strength with values from 0,1-0,5 kPa. The undisturbed shear strength for sample 6-11 does not fit as good with variations from 3,7-9 kPa, but have likely been disturbed. These results are comparable since the inner parts from 6-11 are still quick.

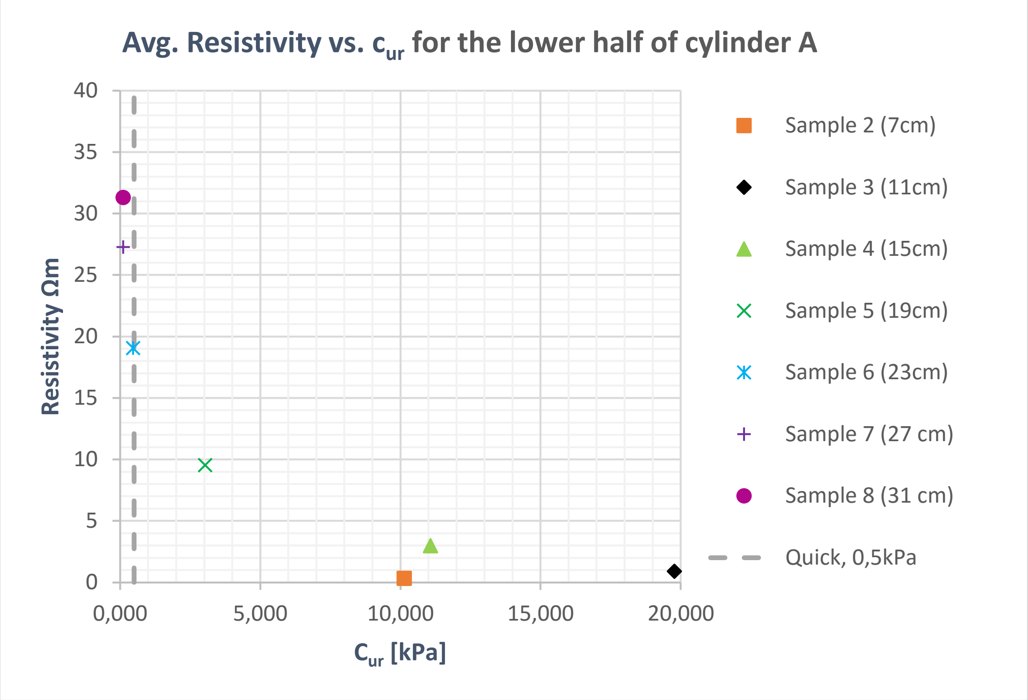


Figure 6-14 Average resistivity vs. remolded shear strength, with latest data points from 27.05.2016

Figure 6-15 shows the undisturbed shear strength with respect to the resistivity. The undisturbed shear strength is decreasing with increasing resistivity, which is expected. As mentioned the inner part of the cylinder is quick, and some parts of these samples may be disturbed, which explains why the C_u is larger for part 8 with average distance 31 cm than for part 7 with average distance of 27 cm.

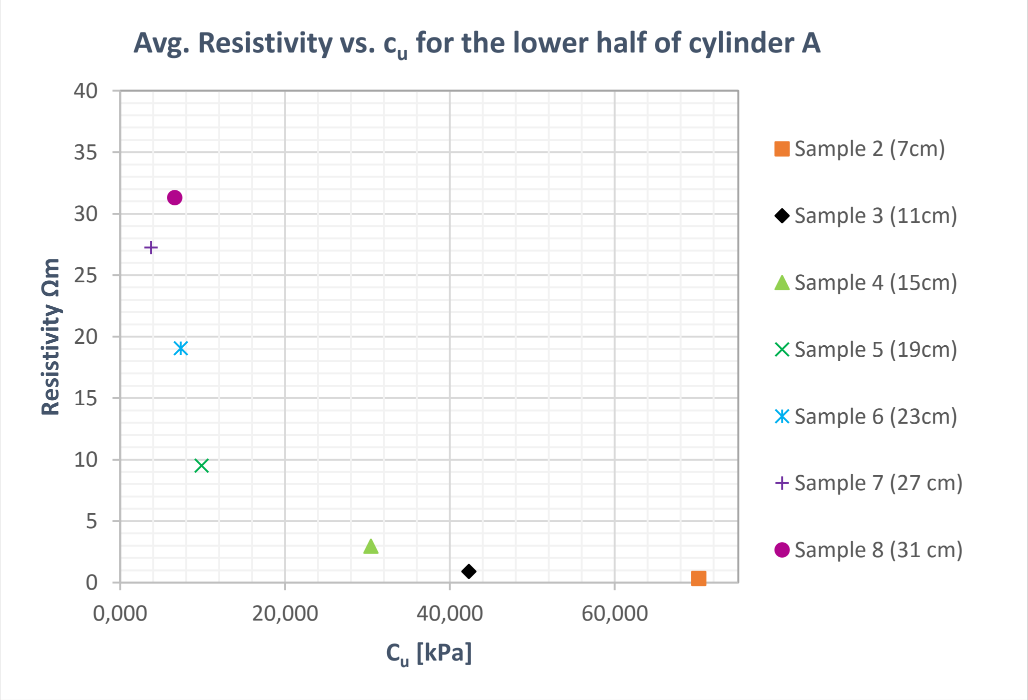


Figure 6-15 Average resistivity vs. undisturbed shear strength, with latest data point from 27.05.2016.

The average resistivity versus sensitivity is plotted in Figure 6-16. An increase in resistivity shows an increase in sensitivity, except for part 2 at an average distance at 7 cm. The salt content in sample 2 is too high, which makes it curious to relate these values to sensitivity, since the sample is clearly not sensitive at all, and for this reason give a deviation in the graph.

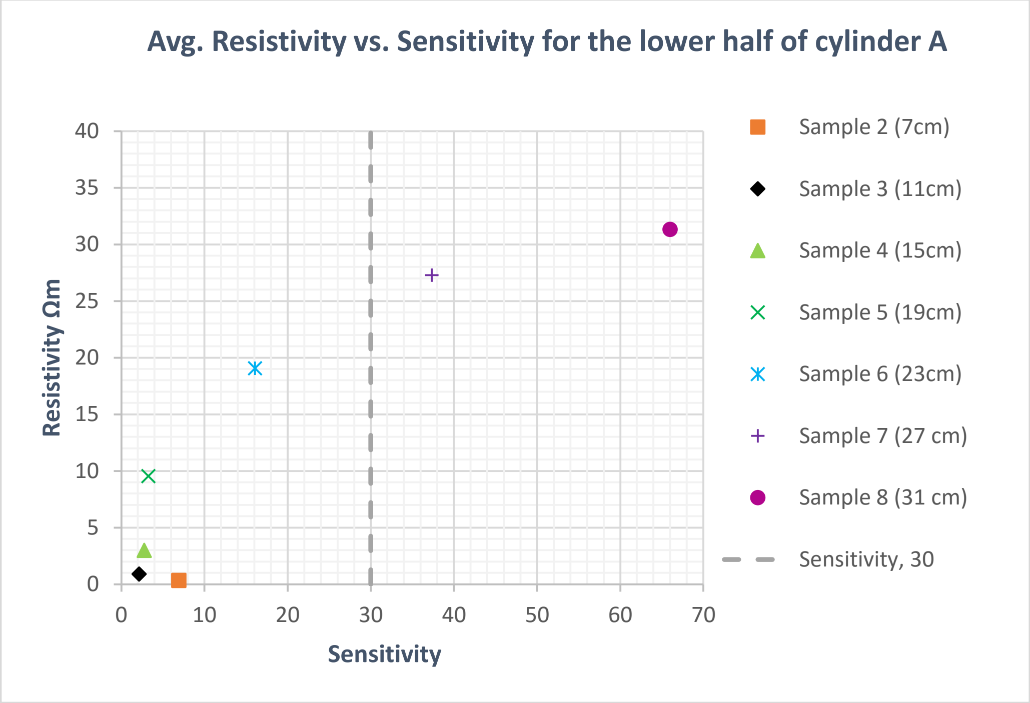


Figure 6-16 Average resistivity vs. sensitivity, with latest data point from 27.05.2016.

6.2.3 Salt content

After the clay was disturbed, it was placed into a tube so that it could be put in the centrifuge. There was too little clay for liquidity limit testing (to do w% of the disturbed clay after cone fall testing), since the clay needed to be put into the tubes for salt-testing to get enough salt water. The centrifuge has room for four tubes, and was set to 4,4 turns per. sec for 30 minutes (recommended by Helle). The machine used for centrifuging the salt water out of the clay is a Eppendorf centrifuge 5702 as seen in Figure 6-17. The machine was filled with 4 samples at approximately the same size to get an even weight distribution.

Figure 6-17 Centrifuge 5702 from Eppendorf, with speed 4,4 rps

The salt in the pore water had to be tested after centrifuging the clay. A conductivity meter was used to find the salt content to comparing the conductivity to the salt content in g/L by a graph at the laboratory as seen in Figure 6-18.

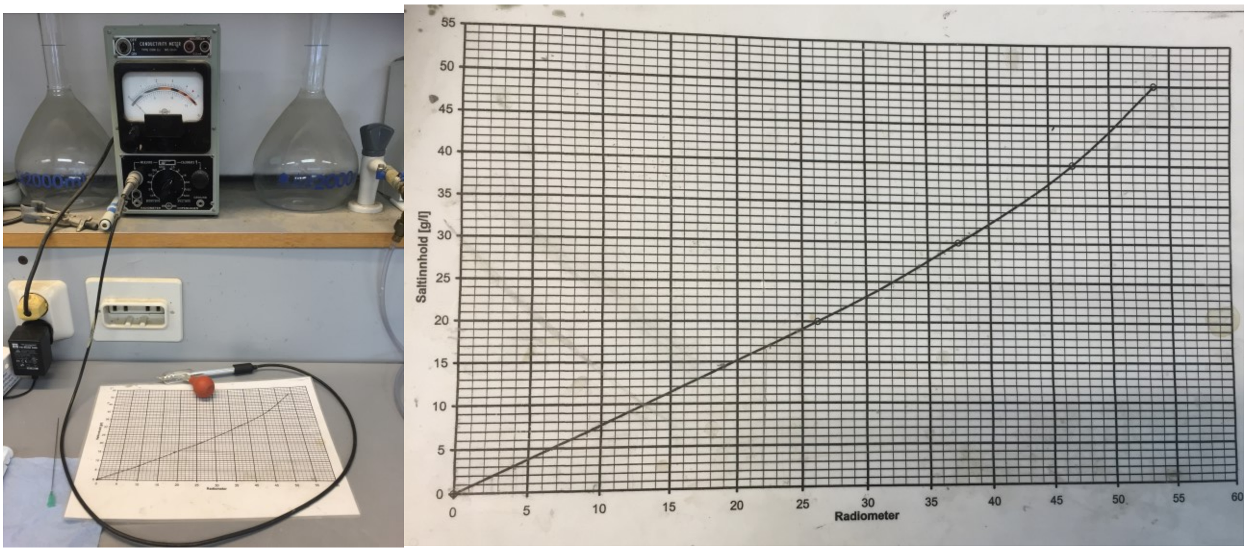


Figure 6-18 The conductivity meter (radiometer) and the graph with salt content / conductivity relation.

The radiometer curve at the laboratory only reaches to a conductivity of just above 50 mS/cm (milli Siemens /cm), which only gives a salt content up to 50 g/L. For the outer parts in the clay, the salt content will be at least the input value of 238,4 g/L KCl. It is expected to be a bit higher than this due to the increasing of the concentration in the brine due to evaporation or the water entering the clay. The relation as shown in the radiometer graph is not linear, which makes it difficult to estimate the salt content in the outer parts. To be certain that the readings were correct; the data was compared to a conductivity converter online (Lenntech, 2009). The converter multiplied the electrical conductivity (EC) with a value of 0,64 (or 640 from mΩ to ppm), to get a TDS (Total Dissolved Solids) value which then could be multiplied with the weight of the solution to get the salt content. These results corresponded quite good with the readings, as seen in Figure 6-19. For Figure 6-18, this part of the graph looks linear for the values up to 30 g/L. Note that this graph is also experimental, which could make the actual graph with more values a non-linear one.

For the upper part of the graph however, the results have great inaccuracy. This is due to the changing of the curve, and the curvature that appear due to the salt slowly beginning to reach its upper limit to conduct. To be able to analyze the conductivity results from the lab, data from former tests giving the conductance data for potassium chloride might be used. At a weight percent of 25, the conductivity is approximately 375 mS/cm for potassium chloride as seen in Figure 6-19. This will be the weight of 250 g/L KCl in a solution.

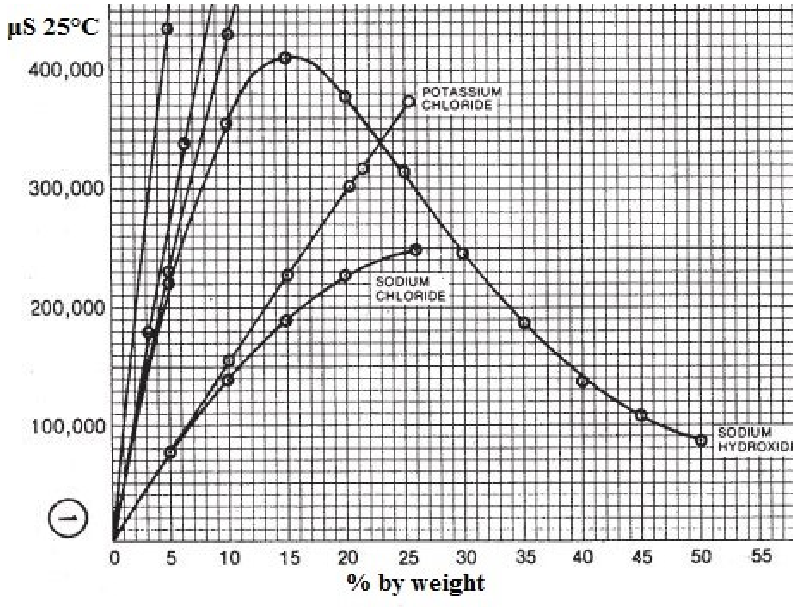


Figure 6-19Micromhos (µS/cm) at 25°C vs. % by weight (Analytical, 2010).

When plotting the values for potassium chloride from Figure 6-19 together with the empirical graph given in Figure 6-18 from the laboratory the graphs does not fit very well, as seen in Figure 6-20. The values at lower salt content are larger for the earlier data than for the empirical graph from the laboratory. From results from UiO as part of Helle's Ph.D. project a conductivity of 150 mS/cm gave a TDS of 269 000 mg/kg (*mg/kg=ppm*). With a solution of approximately 1,2 kg/L this gives a salt content of 322,8 g/L. When using this as an upper limit an attempt of a curve can be made to fit the lower part as well as the upper point, without getting a straight line between the last reading form the radiometer curve and to the value given by Helle. One would assume an inverse curve of the one in Figure 3-3 from chapter 3, which would grow exponentially. To get an exponentially growing curve it was assumed a three-degree curve with different constants. Different type of values was tried out until the curve fitted well with the values from the radiometer at the lab and the value from Helle. The values from the radiometer from the lab and the one from Helle corresponded very well after trying and failing a couple of times, which could indicate something about the salt-values above 50 g/L.

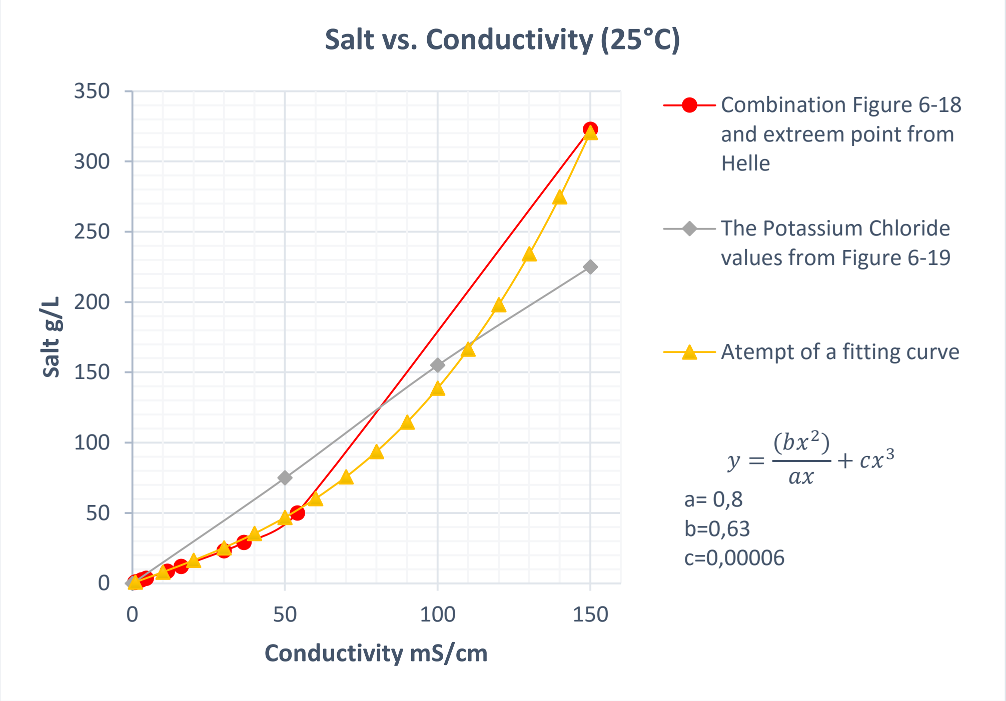


Figure 6-20 Attempt to find the upper salt values corresponding to the conductivity test 1

The salt content in each part are presented in Table 6-3, where the values for part 1,2,15 and 16 are estimated with the attempted fitting curve in yellow from Figure 6-20. These values are illustrated in blue, to emphasize that the values are estimated, and holds a greater error than the other values.

Table 6-3 Salt values of the different parts of the clay. The values in blue are estimated.

Salt test (25°C)						
cm	**Avg.cm**	**Part no**	**Input**	**Reading**	**Radiometer mS/cm**	**Salt (g/L)**
0-5	2,5	1	150	13,75	137,50	264,26
5-9	7	2	150	9,50	95,00	126,26
9-13	11	3	50	3,65	36,50	29,00
13-17	15	4	50	1,60	16,00	12,00
17-21	19	5	50	0,45	4,50	3,50
21-25	23	6	15	1,75	1,75	1,25
25-29	27	7	5	1,30	1,30	1,00
29-33	31	8	1,5	0,75	0,75	0,50
33-37	35	9	1,5	0,95	0,95	0,90
37-41	39	10	1,5	0,88	0,88	0,80
41-45	43	11	5	1,30	1,30	1,00
45-49	47	12	50	0,30	3,00	2,30
49-53	51	13	50	1,15	11,50	8,50
53-57	55	14	50	3,00	30,00	23,00
57-61	59	15	150	7,00	70,00	75,71
61-66	63,5	16	150	11,75	117,50	189,87

When plotting the average salt content with the distance from the bottom of the clay, it is clearly that the outer parts contain a lot more salt than the inner part of the clay. The content is higher for the two lower parts than the two upper parts. This supports the values from the fall cone test, where the undisturbed and remolded shear strength were higher at the bottom part than for the upper part, which could be explained by the higher salt content. Sample 1 has an estimated salt content of approximately 265 g/L KCl, which is higher than the input data of 238,3 g/L. Sample 16 has a salt content of approximately 190 g/L KCl, which is far less that the input value of 238,3 g/L.

If the cylinder set-up was entirely symmetrical, these values should have been the same. There could be many reasons for this deviation. The immediate though is that the estimated graph either does not have an upper point as given, or behaves as illustrated by the attempt of the fitting curve in Figure 6-20. If these values are incorrect, these reference values are not comparable to the input values. If however this assumption is correct, an error could be in the measurements of the KCl, but should not give deviation like this. Another reason could be that the system did not work as a symmetrical system at all.

Another way of retrieving the highest salt values would be to assume that part 1 would have a value of 238,3 g/L, when testing the sample at the final date. This would not be entirely correct, as the value is assumed to be a bit higher due to the evaporation in the reservoir. Using this assumption, the salt levels would be lower for sample 1,2,15 and 16. When repeating the procedure of finding a fitting curve, as for Figure 6-20, with the maximum value of 238,3 g/L for 137,5 mS/cm, this gives a new curve ($y = \frac{(bx^2)}{ax} + cx^3$, a=0,87 b=0,685 and c=0,00005). The new salt values could then be calculated for sample 1,2,15 and 16. These values give: sample 1=238,24 g/L, sample 2=117,67 g/L, sample 15=72,26 g/L and sample 16=173,63 g/L. The lower values would still be the same. Note that these values (for sample 1,2,15 and 16) are relatively high in the first place, so the changes does not make a considerably great difference when interpreting the results. These results are not presented in graphs, but are mentioned to illustrate that the highest salt concentrations have a high uncertainty. The values from the fitting curve with the extreme point from Helle, are used in the following graphs.

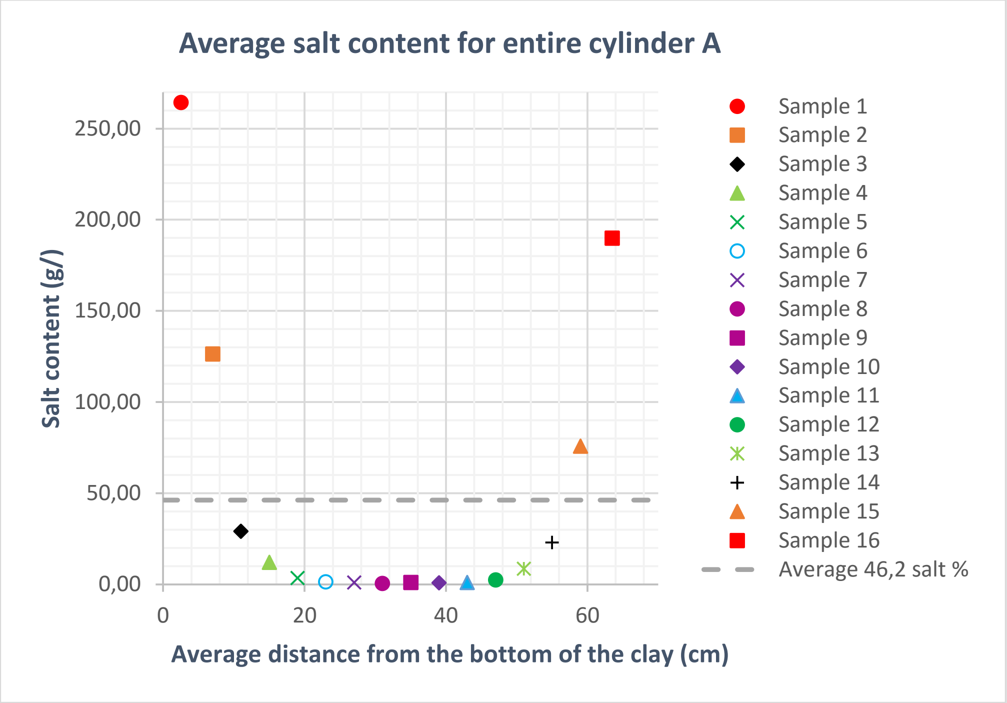


Figure 6-21 Average salt content for the different parts of cylinder A with latest data point from 27.05.2016.

Even though the concentration in each reservoir should be the same at the start out point, the amount of salt in total was not the same. The overlying brine in the upper basin was approximately a quarter of the amount of brine in the lower basin. A thought could be that the overlying reservoir was drained for ions, which were traveling into the clay, leaving the end concentration at 190 g/L KCl in the upper reservoir. Even though the brine should have a theoretically homogeneous concentration in the reservoir for the lower part, one could assume that gravitational forces (H^+,O^{2-} are not as heavy as K^+ and Cl^-) could work together with the diffusion force and force the ions to the bottom of the reservoir. This could lead to a slightly inhomogeneous brine, which could be the reason for the higher concentration in sample 1, than for the input value. Diffusion in a liquid is however quite fast, and is thought to prevent this gravitational affect. The salt migration to the lowest screw could also have caused an extra driving force for the salt, which increased the salt content in sample 1 beyond the input concentration. This value, as explained, is based on a fitting curve with high inaccuracy and the value might therefore not be correct.

When taking a closer look at the samples with a salt content below 5 g/L, which could be quick according to (Rosenqvist, 1953), sample 5 to 12 satisfies this requirement. Part 6-11 has been defined as quick from the fall cone test, having a salt-content below 2 g/L as seen in Figure 6-22. Today’s (2014) requirement for a clay to be considered as quick, is that the salt content in the pore water is
less than 2 g/L (NIFS, 2014).

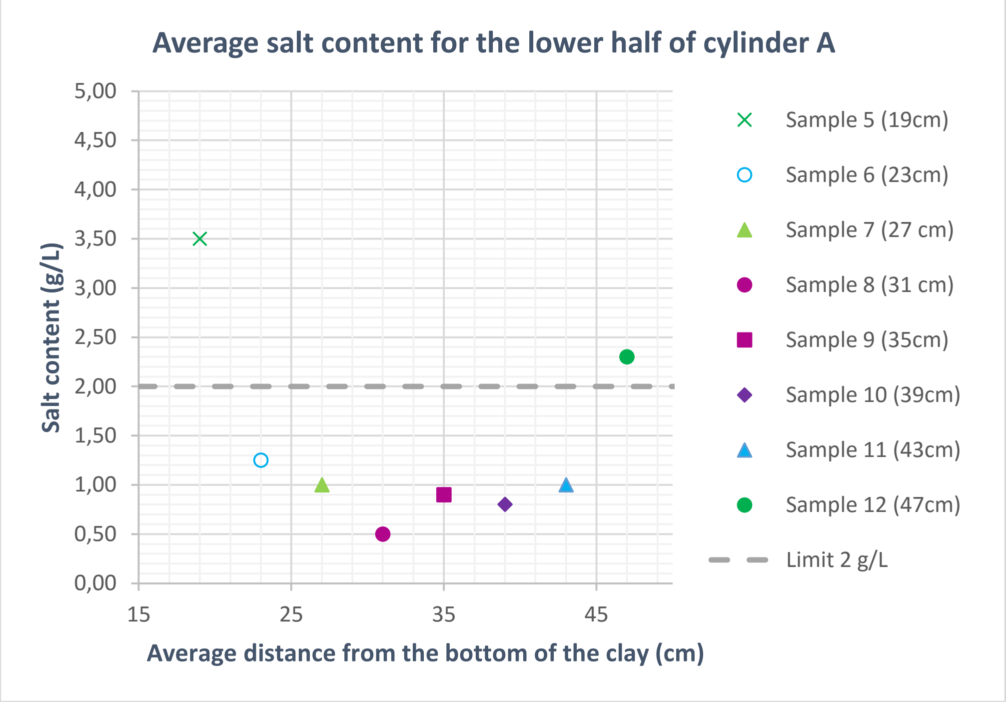


Figure 6-22Average salt content for the lower values under 5 g/L for cylinder A with latest data point from 27.05.2016.

The average resistivity versus the salt content is shown in Figure 6-23. The resistivity decreases as the salt content increases. The drop in resistivity between sample 8 and 4, which is the average resistivities between 31 cm and 13 cm, is quite large from ca. 31 to 3 Ωm. The resistivity is starting to stagnate below 13 cm with a salt content higher than 12 g/L. There is a little change in the resistivity at a salt content between 30 g/L and 125 g/L. As previous discussed the salt content for sample 2 has a great uncertainty, but will still be relativity large and cause a stagnating of the curve regardless of using the highest or lowest value, as earlier purposed.

For the quick clay (sample 6-8), the resistivity range between 19-31 Ωm. This coincide well with the classification of quick clay from chapter 4.4.2, which indicates leached clay in a range between 10-100 Ωm. Sample 5 is just below this value at 9,5 Ωm, and were found not to be quick.

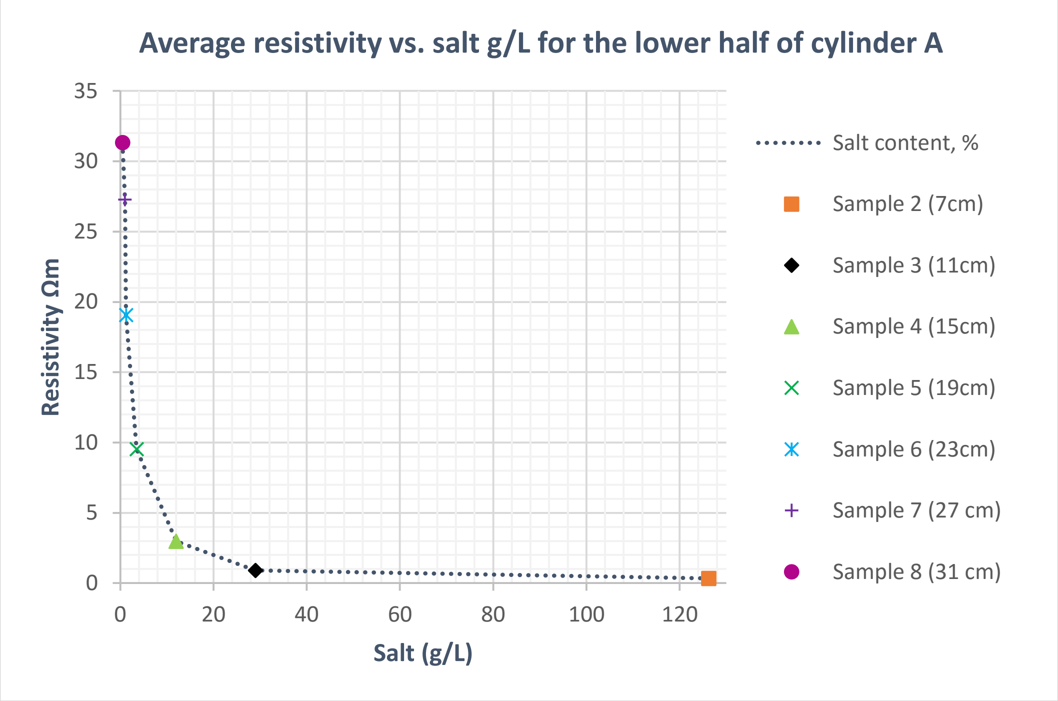


Figure 6-23 Average resistivity vs. salt content with latest data point from 27.05.2016.

The comparison between the measured values from this experiment with the trendline $y = 49{,}4x^{-0{,}83}$ from (Long et al., 2012) from chapter 3, Figure 3-3, are shown in Figure 6-24. The comparison to the trendline does not fit entirely, but the shape of the two curves are very similar. The trendline has a regression of 0,8, which means that the values does not coincide fully.

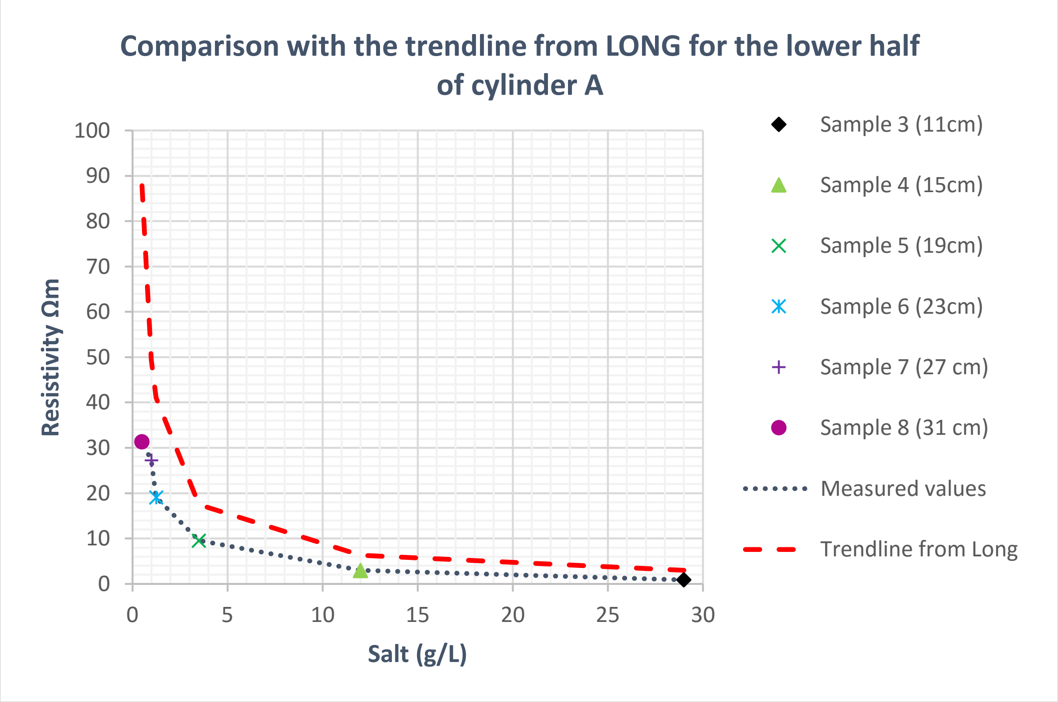


Figure 6-24 Comparison of resistivity and salt with the trendline from (Long et al., 2012) with latest data point from 27.05.2016.

As seen earlier in from Figure 3-3 there are many plots below the line in the left downside corner, which coincide well with the measured values. The grainsizes, water content, temperature etc. are all factors which makes the resistivity values varies, which means that a comparison to these clays can not only be done by looking at the resistivity and salt content alone.

6.2.3.1 The change in diffusion front

After retrieving the salt values from each sample at the testing day (27.May), the salt contents could be compared to their average sample distance, which is assumed to be the effective diffusion lengths of the samples. For the higher concentrations the clay will be saturated after a relatively short time, and therefore only the effective diffusion length of the lower salt concentrations are presented for the bottom half of cylinder A. Note that all salt concentrations now are given in KCl, as the measured salt content in the clay is the total salt content. This is also a simplified way of looking at it, since there are other ions present in the clay than just KCl.

If repeating the procedure from chapter 5.5.3 for the effective diffusion length, with different diffusion fronts set to be the measured salt content from Table 6-3, one might get a grasp of the actual effective diffusion length. The salt values measured are total salt content, which means that the input value has to be given in 238,4 KCl. Some troubles does occur concerning the boundary conditions and simplification that the initial concentration in the clay was 0 g/L. This is clearly not the case, since the salt content in sample 8 is measured to be 0,5 g/L, and it is earlier calculated that a front with this magnitude only has reached into sample 5. The inner parts will therefore have a great inaccuracy do to the uncertainty of the original salt content. As given earlier in Figure 5-5, Helle measured a reference value of total salt content to be approximately 1g/L (the deepest value).

It is now further simplified that both sample 7 and 8 have an initial concentration of 1 g/L, the initial concentration in the clay is set to this value (c_i=1 KCl g/L). The input concentration has to be the total input concentration of 238,4 KCl, (c_o=238,4 KCl g/L). The c(z,t) is then changing dependent on the measured salt concentration in the samples, as given in Table 6-3. When setting c(z,t) equal to the different values for sample 3 (29g/L), 4 (12g/L), 5 (3,5g/L), 6 (1,25g/L) and 7(1(g/L). the effective diffusion lengths are given in Figure 6-25. Note that for calculation purposes the value from sample 7 has to be set to a bit more than 1 g/L to avoid erfcξ to become zero. The value chosen is 1,03g/L, because it corresponds well with the assumed effective diffusion length in this sample. The measured and calculated effective diffusion length for the bottom half of the sample, with exception of sample 1,2 and 8, are shown graphically in Figure 6-26 and as a table in Table 6-4.

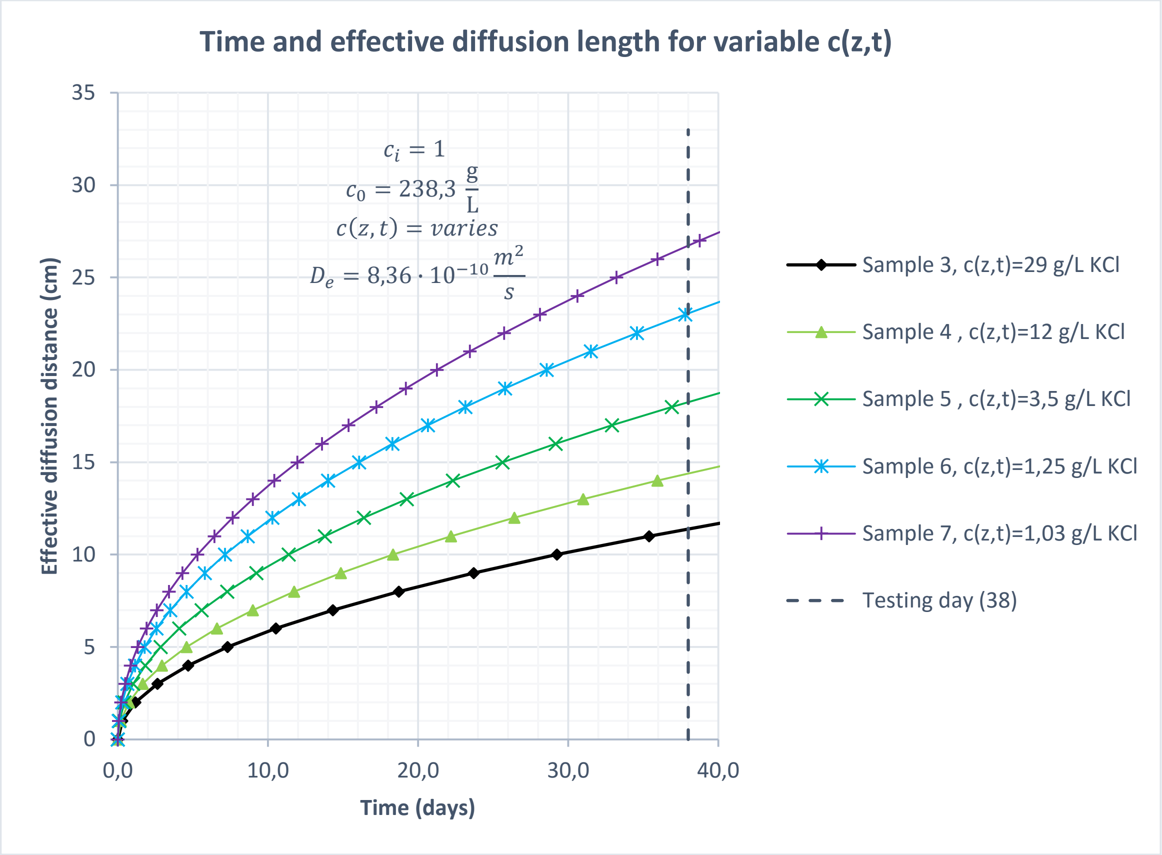


Figure 6-25 Calculated diffusion front based on measured average salt content in KCl, with latest data point from 27.05.2016.

As seen from Figure 6-25 the effective diffusion length after 38 days are dependent on the measured concentration front. The distance is increasing as the front c(z,t) is decreasing throughout the sample.

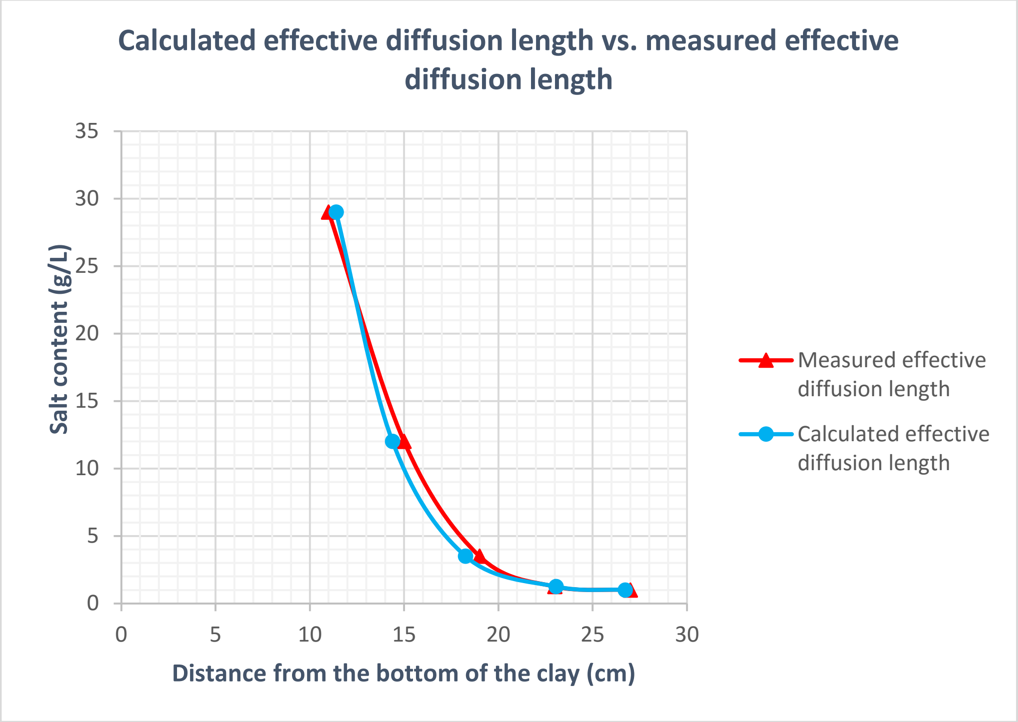


Figure 6-26 Calculated effective diffusion length vs. measured effective diffusion length with latest data point from 27.05.2016.

Figure 6-26 shows that the calculated vs. measured effective diffusion length corresponds well. The values are shown in Table 6-4.

As seen in Table 6-4 the measured and calculated effective diffusion length corresponds very good for sample 6, and the largest deviation is to be found for sample 5 with a difference of about 0,7 cm. There are some deviations between the measured and calculated effective diffusion lengths, but this is though to be due to errors in the chosen input data, readings, and lack of accuracy in the comparing of the data. The average salt content is compared to the average distance of the sample, which could lead to some deviations in the results comparing it to the calculated values. This means that the salt content from sample 3 is measured for the entire sample of 4 cm (9cm-13cm), and not only at 11 cm. This applies to all the other samples as well. However, the measured and calculated effective diffusion lengths corresponds relatively well, despite the errors.

Table 6-4 Measured vs. calculated effective diffusion length.

Measured vs. Calculated effective diffusion length			
Part no	**Salt (g/L)**	**Measured effective diffusion length (cm)**	**Calculated effective diffusion length (cm)**
3	**29,00**	11	11,40
4	**12,00**	15	14,39
5	**3,50**	19	18,26
6	**1,25**	23	23,06
7	**1,00**	27	26,73

6.2.4 Plasticity limit

After the salt test was performed, the tubes were stored overnight in the fridge, and on the 28.05.2016 the plasticity index test was performed on sample 5-12. The samples 1-4 and 6-12 were tested for plasticity index on the 29.05.2016.

When having stirred the saltwater back into the clay it could be performed plasticity limit test on the clay. The difference in remolded shear strength was very clear, when stirring the clay as seen in Figure 6-27. One can clearly see the quick clay from sample 8, as it can not be stirred into a firm lump as for sample 5 and 1. The reason why it was not performed any liquidity limit test for some part of this clay, is due to the time it took stirring the water back into the clay. Stirring the water back into the quick clay was time consuming. It had time to dry out, and it would not give an accurate picture of the liquidity limit. Even though the saltwater was carefully put back into the tubes after testing, some water may have gotten lost, which could give an error to the results.

Figure 6-27 The difference of the remolded clay after stirring the saltwater back into the clay for sample 8, 5 and 1, respectively.

Figure 6-28 Finding the plasticity index of the clay

The plasticity limit was found by rolling the clay until it became brittle and began to crumble at a thickness of 3,2 mm (Vegvesen, 2014). It is recommended by the standard to use cups with a lid, so that the clay dose not dry out between the rolling of the parts of the clay. There were however not enough cups available at the laboratory. To prevent the rolled out clay to dry after it was put in the cup, the procedure had to be made more efficient with respect to time. The clay was dried out, and divided in parts, which were dried out on turn, so that the last time the clay was rolled out, it took very little time for all the clay to be rolled out. Every cup was then weighted at once, after putting the last part of clay in the cup.

There were found some inhomogeneities in the clay during the plasticity test, which are shown as grains in Figure 6-29. This part of the clay was the stiffer one, but it is surprising that the grains were not found when remolding the clay and moving it into the tubes. These grains may have caused an error for undisturbed and remolded shear strength for part 2 and 3. This may have caused some disturbances to the resistivity measurements and to the diffusion of salt when the clay still was intact in the laboratory set-up.

Figure 6-29 Grains found in part 2 and 3 respectively.

There is expected a slightly difference in the plasticity limit due to the in situ depth difference between the samples (1-16). From earlier data from Helle, as presented in chapter 5.1.4, the plasticity index was not found to increase when introducing the clay to KCl. The limit varied for the different stations, and with different depth. The deepest values gave a plasticity limit between approximately 15-20% for the three stations from Figure 5-4.

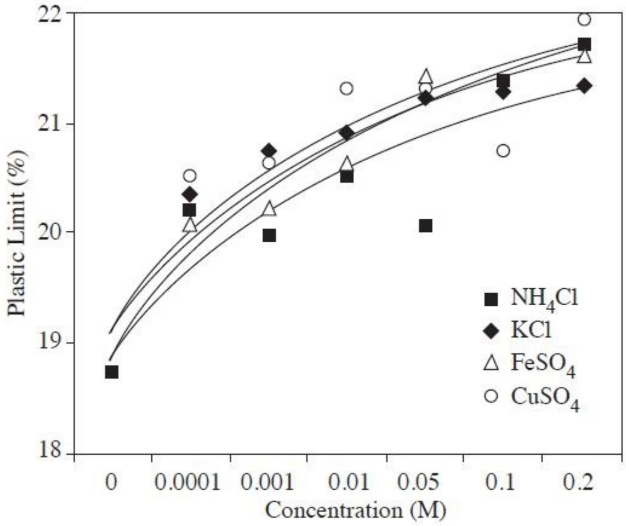


Figure 6-30 Effect of salt concentration on the plastic limit of a low plastic clay (Arasan, 2008)

Figure 6-30 is from an earlier study, which shows the change in the plasticity limit (which is the same as what the figure call plastic limit) for different salt and concentrations for a low plasticity clay. Quick clays are known *not* to behave as a plastic material. As seen in Figure 6-30 the experiments shows an increasing for w_P from very low values to about 0,08 M, and then a stagnation at about 21,2% for the higher concentrations. The total span in plasticity limit is however very low for KCl of under 1 % from ca 20,4 % to 21,2 %

The experiment from Arasan concludes however that only values below 0,2 M can be used, because a higher concentration changes the clay fabric, and effects the plastic behavior into a non-plastic material. This means that according to this study only values below 0,2 M can be used, which equals to about 15 g/L KCl. This means that only sample 4-13 are valid, which varies from 18%-29% as seen in Figure 6-31. Meaning that sample 1-3 and 14-16 are overexposed to the salt, and that these values do not give a meaningful result.

The trend in Figure 6-31 for sample 4-13 is that the plasticity limits increases as the salt content increases, with exception of sample 10, which has the lowest plasticity limit value even though the salt content is the second-lowest value. This is probably just an error in the conducting phase in the laboratory.

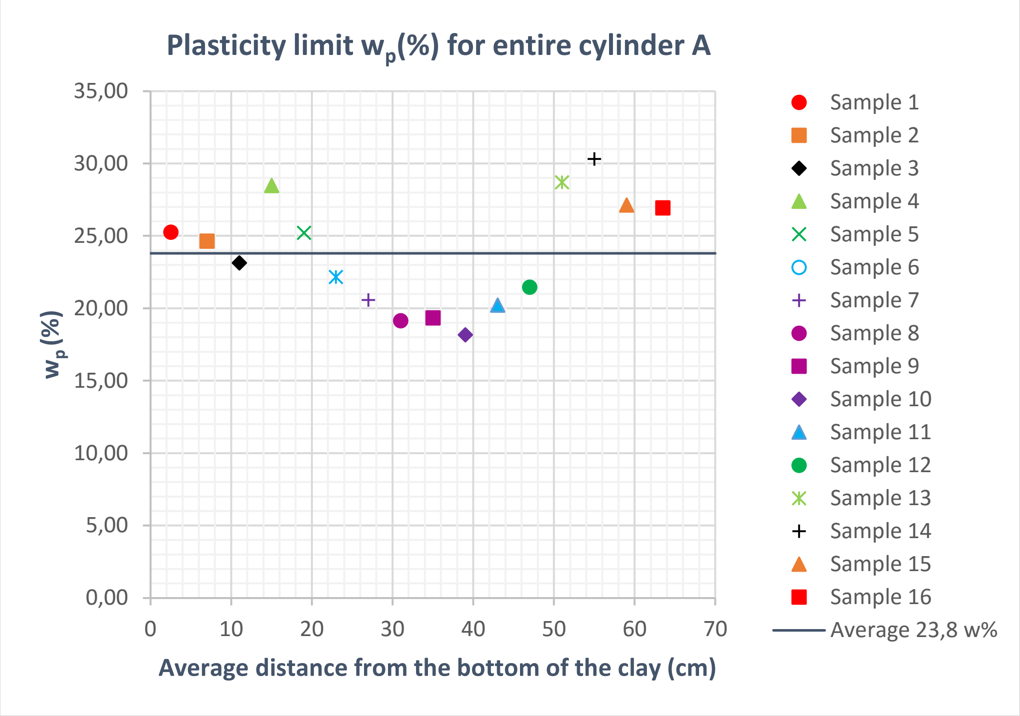


Figure 6-31 Average plasticity limit for the samples 1-16 with latest data point from 27.05.2016.

Figure 6-32 shows the resistivity vs. the plasticity limit for the lower half of cylinder A. Both sample 2 and 3 has a higher concentration of salt than 0,2M (15g/L) and will therefore be neglected in the description of the plastic behavior of the clay. The resistivity is higher for the inner parts of the clay with less salt content, and has a lower plasticity limit than for the outer parts.

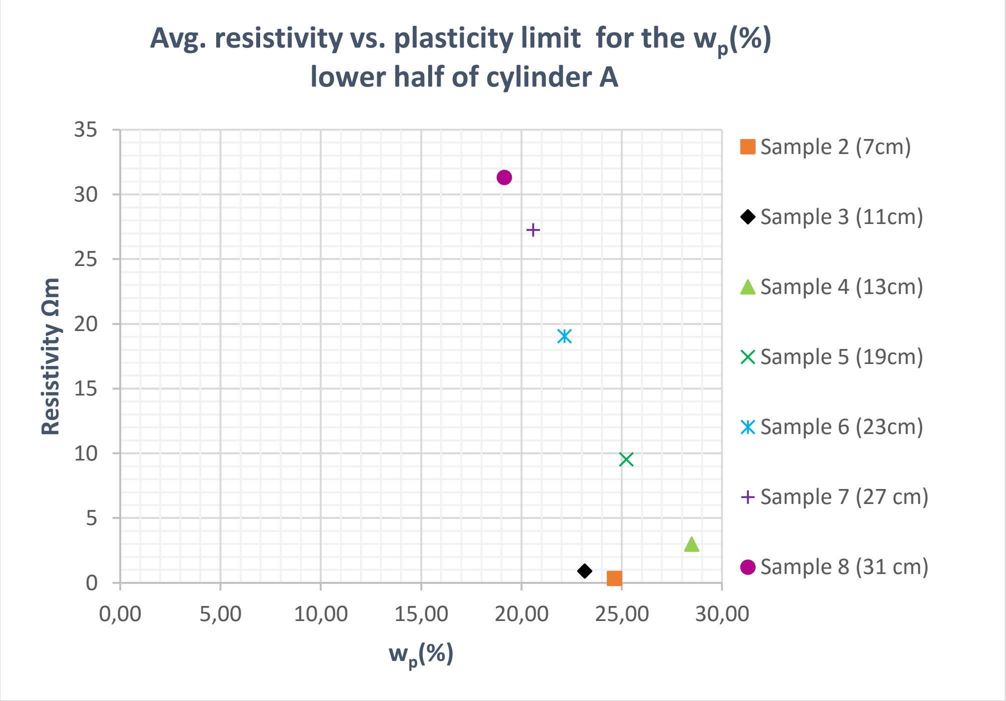


Figure 6-32 Average resistivity vs. plasticity limit for the samples 2-8 with latest data point from 27.05.2016.

These findings dose not correspond with the ones from Helle or Arasan, which indicates that the plasticity limit should not change much (less than 1%). Where as in this experiment the span is ranging from 18-29%.

The procedure could have been performed the wrong way, giving wrong results. However, since the results have such a clear trend, this could not be decisive for the results. Every of the 16 tests are performed the same way, so if an error occurred in the performing of the method, one should still have comparable results between these 16 samples as a sealed system. These findings might be explained by first separating the water from the clay, and stirring it back into the clay again. This might have changed the properties of the clay, which gives a deviation from the previous experiments.

6.2.5 Water content

The results from the water content for the different parts from 1-16 are illustrated in Figure 6-33. The average water content for the samples is 33,3 %, which is a bit less than the original water content that was assumed to be 35 %. This coincide with previous research from Helle, where the change in water content before and after treating the clay with KCl slurry is low (Helle, 2013). The water content has a span from 25-38,5 %, which is quite large, and indicate that the porosity is not homogeneous throughout the cylinder.

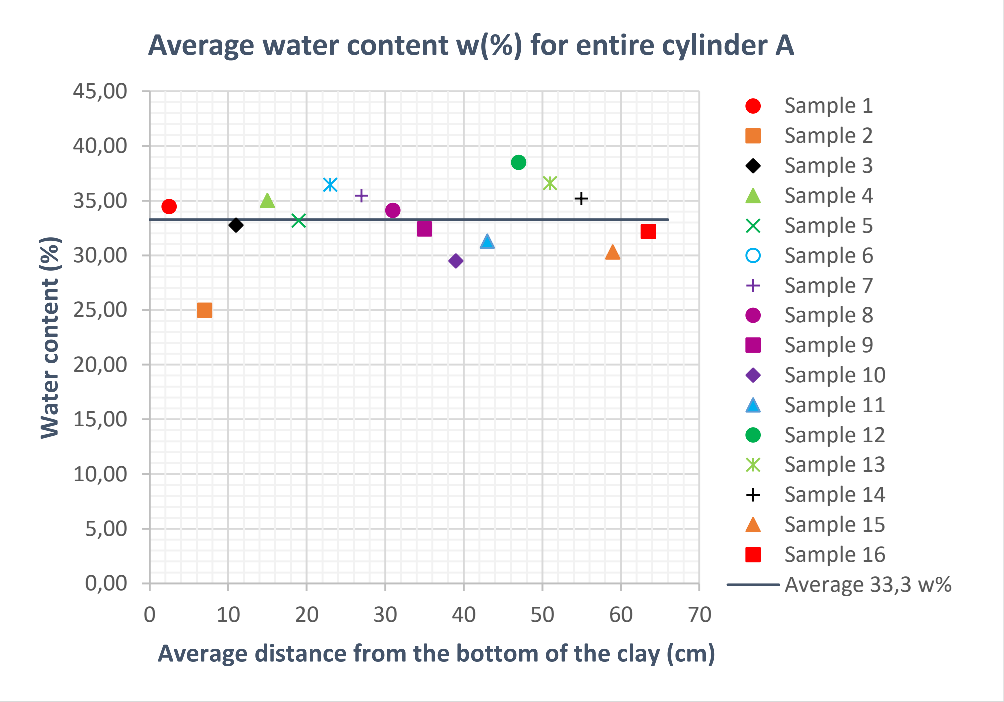


Figure 6-33 Average water content of the samples 1-16 with latest data point from 27.05.2016.

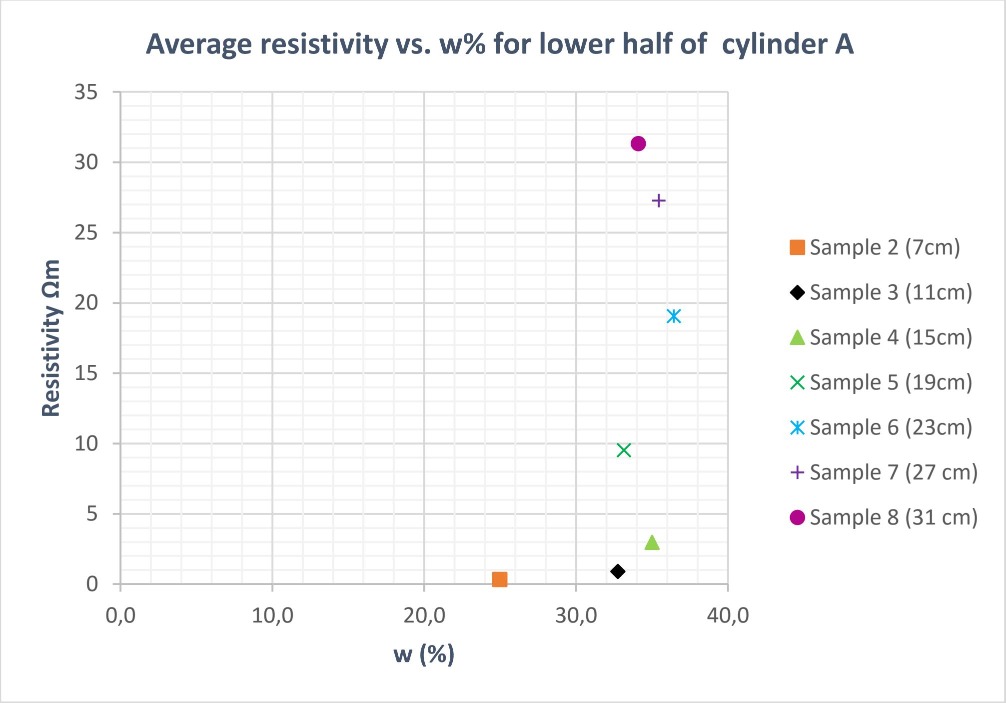


Figure 6-34 Average resistivity vs. w% with latest data point from 27.05.2016.

The average resistivity and the water content for the lower parts it plotted for the data from 27.05.2016 in Figure 6-34. It shows a higher resistivity in the inner parts than the outer parts, and a water content that varies from 25-36%. The change in resistivity is of course due to the change in salt content, but needs certain amount of fluid to be able to conduct. The water content is quite stable through the clay, with exception of part 2 at 7 cm. This deviation may be explained either by the clay being quite compacted at the lower part, giving a lower volume of pores, which reflects on the water content. The lower end part (part 1), might be more moist due to contact with the brine reservoir, giving a higher water contentment than part 2. Another reason could be that Part 2 had small grains that were not detected when weighing the clay. As seen in Figure 6-29 there was found grains in this part when finding the plasticity limit.

7 DISCUSSION

Local variations in the clay, which results in an inhomogeneous matter, could affect the diffusion and the ability of ions to diffuse in the clay. This will reflect on the ability of salt transportation, which might give results that are not consistent with the theoretical assumptions. The effective self-diffusion constant considers an average porosity in the clay. It is likely that the porosity changes along the clay, which in practice will reflect on the effective self-diffusion constant. The clay is generalized to be a homogeneous matter, so the theory does not consider a change in porosity or other inhomogeneities. The results from the falling cone test shows however, that the results coincide very well with the theory. An improvement in the geotechnical parameters did occur for a salt front of 0,5 g/L at the theoretical given length and time. One could see a strengthening in the material, due to the increase in salt diffusion both for the top and the bottom of the clay cylinder. The difference in the results for the top and bottom part, could be explained by the self-weight of the clay and the overlying brine, which would cause the lower part to set. The results are discussed for each subchapter after presenting the results in chapter 6.

7.1 SOURCES OF ERROR

7.1.1 Cylinders

Since the cylinders gather information at a depth with magnitude of 70- 80 cm, there might be local variations, and one may expect some diversity in the results based on this. These variations could be local layers of silt or sand, bigger grains or other elements that would disturb the homogeneity. These aspects would not only give errors when comparing the results from the index test to the variation of resistivity measurements, but also when comparing the resistivity measurements against each other. There might also be disturbances to the cylinders when moving them from the field to the laboratory and while being stored at the laboratory. This might give an effect on the results from the index tests that are hard to locate, because there are not stored one cylinder, which could compare its results to the reference values. If having the possibility to get more cylinders, this would be recommended. Disturbances is here meant as; vibration, variation in temperature and moisture, exposure to the sun, etc.

7.1.2 Laboratory set up

The set-up is a simple one, hence a numerous of sources of error may occur. Gravitational forces have affected the sample, in that way that the lower part of the clay was more compacted than the upper part. When pushing the sample into the plastic tube, one might have applied stresses that made the sample stick to the tube. The salt might not have dispersed properly, and could have travelled at the edge of the sample along the plastic tube and not though the soil. Constant external conditions may be hard to maintain, and some variation in temperature and humidity might have occurred in the laboratory.

The aspect of time, and errors caused by storing and preparing the cylinders and the set-up would lead to errors as well, because it causes a variation in the boundary conditions. Some former studies also indicate that chemical weathering of the clay could occur due to storage, which affects the geotechnical parameters, and the clay should therefore not be stored long before tested.

Measuring and making of the brine may not be entirely accurate due to human error. The salt used was industrial KCl, which could attain pollutions. When the water was filled into the cylinders, the height of the water level at the left and right side was adjusted to be the same. This adjustment was very difficult to do, because the cylinders were colored and not transparent. Some effect of the height difference between each side could cause a permeability gradient, which could lead to an error in the results.

7.1.3 The quality of the salt

The salt used for the testing of this experiment is an industrial potassium chloride. This is not as pure as a salt made for laboratory use, but is the one that would be used in field strengthening projects, where one would like to strengthen quick clay deposits. It is also an error in the measurements of the KCl solution because the water was not deaired, which will give a slightly stronger solution.

7.1.4 Electric apparatus and electrodes

This is a pilot project, which means that there are more room for error than regular in the electric apparatus and electrodes. The electrodes are not mass-produced and tested accordingly, but made for this project in particular. The same applies for the apparatus, where commercial off-the-shelf products are coupled together with wires, which makes the set-up. The electrodes are oxidized, but if they gets any scratches, they might attract ions that should be diffuse upwards in the clay. There might also occur errors due to polarization since a direct current is used.

7.1.5 Index testing

Human error is the main source of error when performing the index testing. When the cylinder was pushed out of the clay, some of the clay got out of the perforated holes before they were clogged. This could have caused some disturbance to the clay. Since the inner part of the clay was clearly quick, the dividing of the clay caused some troubles, which affected both the thickness of the parts and caused disturbances to the clay. Other errors that are worth mentioning is human errors due to the weighing of the clay, readings from the fall cone test, and the readings from the salt contents. Another error will be time, causing the clay to dry out between the tests. This will reflect on the water content, and other geotechnical parameters. The order of which the tests were performed, were done with respect to this, and the clay was wrapped in plastic to prevent evaporation. This reduces the error, but does not eliminate it. After the salt testing, the water were put back into the clay, and the clay was stirred to be prepared to find the plasticity limit. The clay would be dried out anyways, so the loss of freshwater should not affect the plasticity limit in a worth mentioning way. The loss of saltwater however, could affect the plasticity limit, since the salt is part of the structural components, which strengthens the clay, and could have an effect on the plasticity. The water drops were carefully put back into the clay to prevent this from happening.

8 CONCLUSION

The purpose of the laboratory experiment was to study the relation between resistivity and salt, when introducing a clay sample to a brine over a given period. It was also performed index testing to be able to indicate the change in geotechnical properties of the sensitive clay when introduced to salt.

After retrieving the results, most of the results came out as expected. For the geotechnical parameters, one observed an increase in remolded (c_{ur}) and undisturbed(c_u) shear strength when introducing the clay for more salt than in its natural state. This is in accordance with earlier findings, which indicates that salt increase the clays strength. An increase in plasticity is expected to be relatively constant, but it showed to increase as the salt content increased. This is thought to be due to the water being centrifuged out of the clay, and then stirred back into the clay, and might have changed some properties of the clay. Since there was not enough clay to retrieve the liquidity limit, the plasticity index was not found. The water content was found to be more or less the same as for the reference data, as expected based on the results from Gjengedal and Helle.

The results from the salt concentrations in the different samples gave a variation between the two bottom and upper parts of the clay. It was expected for the upper and bottom part to have the same concentration as the input concentration, if having access to unlimited amount of brine. The inner data was estimated based on a curve from the laboratory. The two upper and bottom parts were estimated based on earlier data, and an experimental curve, which hold a great error. The concentration difference could however be explained based not on input concentration but volume difference, and the access to about fourth times as many ions in the lower chamber than the upper. Evaporation of the brine and gravitational and diffusion forces could be some of the reasons why the brine did not stay homogeneous, and gave a higher concentration value than the input concentration. As well as to the bolt nut not being of stainless steel, which could pull the ions toward this point. For the upper clay this concentration was lower than the input value, which could be explained by the drainage of ions from the brine into the clay.

Another way of interpreting the salt values in the two bottom and upper part could be to set the salt concentration in the sample from the lowest part to be the input concentration of 238,4g/L, and evaluate the other samples depending on this assumption. Regardless of which of the two ways one chose to use to estimate the two upper and bottom parts, the values will be so much higher for these parts than the inner parts, which does not make a considerably difference when interpreting the results.

The change in resistivity will be affected by the input concentration in the brine reservoirs, where one would assume the resistivity to be lower at the same time for a tube containing a solution with high salt concentration, than for a lower concentration. The calculated diffusion front for the brines, indicated that the front would reach a concentration front of 0,5 g/L faster for the higher concentration reservoir than for the lower. This reflected well on the resistivity values that were gathered for the two tubes, were the resistivities for the tube with highest concentration was reduced faster than the one with a lower input concentration.

The average salt values for the parts at the bottom part of the clay cylinder are compared to the average length of the sample, which is considered to be the measured effective diffusion length. The measured and calculated diffusion length for the samples and its respectively salt content, shows that they correspond quite well, despite all simplifications made to be able to relate these values.

The trendline for the resistivity and salt based on different clays in the earlier study by Long, is a bit higher than for the resistivity values retrieved from this experiment (Long et al., 2012). Some of the values does however correspond quite well, and any deviation may be caused by local variations or errors such as temperature, water content, clay content, porosity etc.

Since cylinder A had the double amount of salt content than cylinder B, there might be some comparable relations in the results based on this. Having only two tubes makes such a relation difficult to find. One might be able to find a relation, if having many cylinders to test, to see if there are any trends. One can however conclude that the salt do decrease the resistivity, which with a high enough concentration front of approximately 0,5 g/L influence the clay in such a way that it is more suitable for construction purposes. The cost of such a procedure in the field is very high and also a very time-consuming proses (Helle, 2013). It will however be of interest to improve the ground conditions in many cases, such as in highly populated areas, mainly because the value of a secure and buildable ground may exceed the downside of the high costs related to the development.

9 IMPROVEMENTS AND FURTHER STUDIES

Cylinder B and C will remain over the summer, to collect data until the diffusion front has reached 33 cm into cylinder B. This makes it possible to do further studies regarding the changes in resistivity over a longer period. It is uncertain at this point, if there will be performed standard testing on the clay since this requires labor to do it, and this may be limited at the university. The data will however be attainable, and if there is any wish to pursue the work, one may get hold of the data-file and get the resistivity values. A broader understanding of the topic may then be presented in an article.

A pilot project like this includes a time-consuming preparation part, when it comes to how the set-up should be made and what type of results to expect. It includes a lot of study of the subject to get a grasp of the extent of former studies, but also the theoretical part to be able to understand how the set up could be made. As for all studies, there are limitations, which in this case also has limited how the procedure and set-up has been carried out. All these aspect has to be considered, when making a set-up like this, because the limitations also affects the wanted results. One has to try to provide the best possible results by reducing the effect of the limitations. This will of course be difficult, and sometimes not possible.

The different tubes and cylinders could be more effectively put together, which both will save time and errors due to leakage. The clay from the steel cylinder was pushed into a plastic cylinder with the same size. If the clay was pushed into a smaller tubes, with the same size as the water tubes (50mm), it could easily be connected it with the sockets. There would not be need of the rubber reducer sockets, which has caused some trouble due to leakage. On the other hand, the rubber reducer sockets have been shown useful in that sense that when the air was trapped between the clay and water, it was possible to make a hole in the rubber to get the air out. In a system more or less closed, as the one proposed, it would be more difficult to let the air out, if air gets trapped in the lower socket when filling the tubes with brine.

It is recommended to use stainless steel for the bolt nuts between the coupling and the screws to prevent any form of corrosion. All other steel parts were made of stainless steel, but due to the bolts not being a part of the original set up, the correct material was not used.

The set-up has been put together and been placed in the basement at the institute, which has had a relativity stabile temperature, but not entirely constant. It is recommended, that if possible, the set-up should be placed in a room with a more constant temperature, to avoid any errors due to temperature changes. As discussed in chapter 3.4, changes in temperature will have an effect on the resistivity, which will give results that are not entirely accurate, if allowed to be changed.

To reduce a height difference between the left and right water tubes, the cylinders should preferably be transparent. This way it would be possible to reassure that the permeability gradient would minimal, and therefore could be neglected. If one could get sockets in transparent plastic as well, it could be possible to see if the some clay in the bottom part got out in the water tubes during the experiment. With a set-up with nontransparent tubes, this would not be possible until the experiment is finished.
Since the tubes and sockets that was used in this project originally was intended for indoor plumbing, which intends to hide it's content, it was not possible to get transparent tubes.

For further studies, with more time and more resources available, it could be interesting to test the resistivity on numerous cylinders with different salt concentrations to get a clearer picture of how the relation between different concentrations effects the resistivity. In such studies, a chemical analysis of the ion composition could also be of interest to see if there are differences or deviations due to different ion compositions in the clay. This would of course only be possible after the cylinders have been applied with salt. This relies on the water being distilled when making the brine, to avoid any form of pollution. A recommendation is also to get some cylinders for index testing, so that one have reference values to compare the results too. In this study, there has already been performed geotechnical parameter testing, which is published by Tonje E. Helle (Helle et al., 2015). Even though it would be preferable to do index testing of the clay to get to know the clay before starting the resistivity measurements. This way one would get a clearer idea of the clay's homogeneity and extent of elements/layers of silt, which could present itself at the laboratory, or other sources of error that would interfere with the simplified assumptions.

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APPENDIX A

ACRONYMS

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
AC	Alternating Current
CPT	Cone Penetration Test
CPTU	Cone Penetration Test Undrained
DC	Direct Current
EC	Electrical concuctivity
ERT	Electrical Resistivity Tomography
R-CPTU	Resistivity Cone Penetration Test Undrained
Sampling	Usually performed as a 54 mm sampling, (NGF, 1997)
TDS	Total Dissolved Solids

APPENDIX B

SYMBOLS

A	areal [m^2]
c_0	initial reservoir concentration at t=0, [g/L]
c_i	background concentration [g/L]
c(z,t)	concentration at a distance z and time t [g/L]
c_u	undisturbed shear strength [kPa]
c_{ur}	remolded shear strength [kPa]
D	diffusion coefficient [m^2/second]
D_e	effective self-diffusion coefficient, with respect to the material pores [m^2/second]
$D_{f,T}$	self-diffusion coefficient, with respect to temperature [m^2/second]
erf(ξ)	the error function
erfc(ξ)	the error function complement, erfc(ξ)=1-erf(ξ)
γ	gravity density [kN/m^3]
γ_s	gravity density of the solid [kN/m^3]
γ_w	gravity density of the water [kN/m^3]
h	general term for potential height [m]
I	electrical current [Ampere]
I_L	liquidity index (Attenberg)
I_p	plasticity index (Attenberg)
i	flow gradient
J	Diffusion flux
j_1	Diffusion flux pr. unit area
k	permeability [m/s]
m	mass [kg]
m_s	mass of solid [kg]
m_w	mass of water [kg]
n	porosity
n	is the number of electrons transported in the reaction
Q	Amount of water (volume)
q_t	tip resistance for CPT
R	resistance [Ohm (Ω)]
ρ	resistivity [Ωm]

ρ	density [kg/m^3]
ρ_s	density of the solid [kg/m^3]
S_t	Sensitivity
σ	conductance [1/Ωm=siemens/m]
T	temperature [K]
t	time
τ	Shear strength [kPa]
u	Pore pressure [kPa]
V	volume
V	potential difference [Volt]
v	the rate of flow in Darcy's law [m/s]
w_L	Liquid Limit. The water content where fine graded soil changes from liquid to plastic state (NGF, 1982a)
w_P	Plastic limit. The water content where fine graded soil gets too dry to be in a plastic state (NGF, 1982a)
z	Normal term for the distance from the surface to certain level down in the soil

Attachment 1 Raw data from the resistivity measurements

Time	Drive_1 [V]	Top [V]	Drive_2 [V]	Current [mA]	Pin_1 [V]	Pin_2 [V]	Pin_3 [V]	Pin_4 [V]	Pin_5 [V]	MODE
-----------------------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
19.04.2016 17:30	4,92655	4,90985	0,000741	0,016699	4,76189	4,76714	4,77764	4,78665	4,79559	Tube 1
19.04.2016 17:30	4,90261	4,47965	0,012333	0,422962	0,613242	0,856604	1,13086	1,38876	1,63466	Tube 2
19.04.2016 17:30	4,9091	4,83236	0,00185	0,076742	3,33218	3,36481	3,40265	3,44371	3,49775	Tube 3
20.04.2016 05:30	4,92778	4,92785	0,000208	-0,00007	4,92566	4,92382	4,92718	4,92733	4,92739	Tube 1
20.04.2016 05:30	4,89483	4,46438	0,012539	0,430451	0,564229	0,812371	1,09388	1,35894	1,61175	Tube 2
20.04.2016 05:30	4,90818	4,83041	0,001862	0,077769	3,39311	3,42676	3,46585	3,50782	3,56383	Tube 3
20.04.2016 10:13	4,92761	4,92766	0,000212	-0,00005	4,92525	4,92367	4,92704	4,92702	4,92713	Tube 1
20.04.2016 10:13	4,89905	4,4634	0,012709	0,435652	0,551507	0,802803	1,08782	1,35634	1,61235	Tube 2
20.04.2016 10:13	4,9088	4,83098	0,001875	0,077821	3,39236	3,4257	3,46548	3,50778	3,56382	Tube 3
20.04.2016 10:13	4,92768	4,9277	0,000224	-0,00003	4,92539	4,92382	4,92704	4,92716	4,92724	Tube 1
20.04.2016 10:13	4,89954	4,46377	0,012703	0,435773	0,555269	0,806768	1,09199	1,36067	1,61691	Tube 2
20.04.2016 10:13	4,90884	4,83199	0,001843	0,076846	3,38569	3,41905	3,45789	3,50001	3,55622	Tube 3
20.04.2016 10:16	4,92749	4,92742	0,000228	0,00007	4,92416	4,92235	4,92577	4,92599	4,9262	Tube 1
20.04.2016 10:16	4,89918	4,46205	0,012761	0,437131	0,542345	0,794115	1,07971	1,34884	1,60534	Tube 2
20.04.2016 10:16	4,90886	4,83136	0,001845	0,077507	3,37414	3,40752	3,44674	3,48855	3,5443	Tube 3
20.04.2016 10:16	4,92765	4,92756	0,000235	0,000097	4,92434	4,92298	4,92594	4,9263	4,92635	Tube 1
20.04.2016 10:16	4,89941	4,46457	0,012682	0,434843	0,550541	0,803111	1,08938	1,35906	1,61617	Tube 2
20.04.2016 10:16	4,90898	4,83368	0,001794	0,075305	3,35704	3,39057	3,43006	3,4724	3,52864	Tube 3
20.04.2016 10:17	4,92747	4,92734	0,000232	0,00013	4,92364	4,92184	4,92531	4,92562	4,92587	Tube 1
20.04.2016 10:17	4,89914	4,46203	0,012748	0,437109	0,545038	0,796894	1,08258	1,35168	1,60831	Tube 2
20.04.2016 10:17	4,90891	4,83252	0,001833	0,076392	3,34055	3,37365	3,41237	3,45363	3,5091	Tube 3
20.04.2016 10:17	4,92741	4,92732	0,00024	0,000086	4,92373	4,92243	4,92539	4,92552	4,92585	Tube 1
20.04.2016 10:17	4,89932	4,46497	0,01267	0,434356	0,552656	0,80521	1,09148	1,36114	1,61828	Tube 2
20.04.2016 10:17	4,90904	4,83477	0,001762	0,074275	3,31789	3,35128	3,39023	3,43243	3,48816	Tube 3
20.04.2016 10:20	4,9269	4,91776	0,000517	0,009133	4,8359	4,83814	4,84582	4,85094	4,85621	Tube 1
20.04.2016 10:20	4,89949	4,46083	0,012801	0,438654	0,532057	0,784506	1,07084	1,34058	1,59783	Tube 2
20.04.2016 10:20	4,90902	4,83254	0,001827	0,076475	3,32887	3,36202	3,40086	3,44244	3,49735	Tube 3
20.04.2016 10:20	4,92669	4,91591	0,000573	0,010787	4,82041	4,82323	4,83135	4,83745	4,84374	Tube 1
20.04.2016 10:20	4,8993	4,46399	0,012693	0,435316	0,533762	0,788058	1,07634	1,34782	1,6067	Tube 2
20.04.2016 10:20	4,90914	4,83499	0,00177	0,074152	3,30135	3,33431	3,37282	3,4142	3,46931	Tube 3

Time	Drive_1 [V]	Top [V]	Drive_2 [V]	Current [mA]	Pin_1 [V]	Pin_2 [V]	Pin_3 [V]	Pin_4 [V]	Pin_5 [V]	MODE
21.04.2016 01:33	4,89844	4,40084	0,015478	0,497593	0,371523	0,537509	0,772365	1,04208	1,32134	Tube 1
21.04.2016 01:33	4,89359	4,449	0,012961	0,444589	0,508407	0,763267	1,05289	1,3257	1,58592	Tube 2
21.04.2016 01:33	4,90845	4,83006	0,001875	0,07839	3,38104	3,41503	3,45482	3,49677	3,5531	Tube 3
21.04.2016 13:33	4,89819	4,39144	0,015773	0,506746	0,363769	0,505276	0,742548	1,01493	1,29863	Tube 1
21.04.2016 13:33	4,89536	4,4439	0,013177	0,451467	0,482801	0,739811	1,03315	1,30951	1,57319	Tube 2
21.04.2016 13:33	4,90907	4,83004	0,001902	0,079026	3,3814	3,41582	3,4556	3,498	3,55448	Tube 3
22.04.2016 01:33	4,89724	4,38329	0,015984	0,513956	0,359976	0,479876	0,719218	0,99422	1,28204	Tube 1
22.04.2016 01:33	4,89299	4,43744	0,013259	0,455546	0,461983	0,718598	1,01547	1,29522	1,56227	Tube 2
22.04.2016 01:33	4,90799	4,82863	0,001909	0,079365	3,38113	3,41613	3,45648	3,49898	3,55592	Tube 3
22.04.2016 13:33	4,89742	4,37769	0,016183	0,519727	0,360553	0,462216	0,702258	0,978987	1,27	Tube 1
22.04.2016 13:33	4,89234	4,43169	0,013422	0,460647	0,442916	0,695561	0,995897	1,279	1,54928	Tube 2
22.04.2016 13:33	4,90844	4,8286	0,001929	0,079848	3,38126	3,4168	3,45694	3,49982	3,55717	Tube 3
23.04.2016 01:33	4,89644	4,37177	0,016322	0,524669	0,356685	0,443036	0,682974	0,9622	1,25699	Tube 1
23.04.2016 01:33	4,89126	4,42827	0,013504	0,462984	0,431526	0,677018	0,980845	1,26733	1,54077	Tube 2
23.04.2016 01:33	4,90758	4,82772	0,001922	0,079854	3,38302	3,419	3,45952	3,50258	3,56033	Tube 3
23.04.2016 13:33	4,89652	4,37324	0,016503	0,523275	0,356839	0,430241	0,668483	0,949901	1,24831	Tube 1
23.04.2016 13:33	4,88905	4,42283	0,013563	0,466217	0,422158	0,657501	0,964314	1,25371	1,53	Tube 2
23.04.2016 13:33	4,90741	4,82721	0,001939	0,080201	3,38288	3,41876	3,45954	3,5031	3,56088	Tube 3
24.04.2016 01:33	4,89605	4,36117	0,016668	0,534876	0,355384	0,417752	0,651904	0,934923	1,23618	Tube 1
24.04.2016 01:33	4,88807	4,41833	0,013668	0,469738	0,417906	0,641323	0,9509	1,24314	1,5222	Tube 2
24.04.2016 01:33	4,90692	4,82635	0,001929	0,080566	3,38399	3,42047	3,46191	3,50549	3,56374	Tube 3
24.04.2016 13:33	4,89576	4,3569	0,016779	0,538863	0,354146	0,407473	0,635939	0,920722	1,22493	Tube 1
24.04.2016 13:33	4,88724	4,41524	0,013725	0,471998	0,410442	0,621118	0,933238	1,22842	1,51043	Tube 2
24.04.2016 13:33	4,90676	4,8261	0,001923	0,080662	3,38281	3,42018	3,46149	3,50552	3,5639	Tube 3
25.04.2016 01:33	4,89566	4,35173	0,016924	0,543933	0,355055	0,400939	0,622067	0,908021	1,21458	Tube 1
25.04.2016 01:33	4,88699	4,4111	0,013841	0,475898	0,409128	0,606314	0,920043	1,2177	1,50198	Tube 2
25.04.2016 01:33	4,90657	4,82545	0,001942	0,081114	3,3856	3,4234	3,4651	3,50908	3,56755	Tube 3
25.04.2016 13:33	4,8956	4,34342	0,017181	0,552182	0,354691	0,39468	0,607914	0,894998	1,20421	Tube 1
25.04.2016 13:33	4,88717	4,40569	0,014008	0,481479	0,40745	0,591059	0,905581	1,20546	1,492	Tube 2
25.04.2016 13:33	4,90691	4,82505	0,001945	0,081864	3,38387	3,4216	3,4639	3,50823	3,56694	Tube 3

Time	Drive_1 [V]	Top [V]	Drive_2 [V]	Current [mA]	Pin_1 [V]	Pin_2 [V]	Pin_3 [V]	Pin_4 [V]	Pin_5 [V]	MODE
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26.04.2016 13:33	4,8953	4,33166	0,01752	0,563637	0,354702	0,3857	0,580326	0,869601	1,18393	Tube 1
26.04.2016 13:33	4,88821	4,3991	0,014233	0,489107	0,411208	0,568839	0,8831	1,18768	1,47882	Tube 2
26.04.2016 13:33	4,908	4,82496	0,00199	0,083035	3,38454	3,42316	3,46601	3,51051	3,57016	Tube 3
27.04.2016 01:33	4,89452	4,32583	0,017697	0,568684	0,355071	0,38274	0,567383	0,857442	1,17385	Tube 1
27.04.2016 01:33	4,88423	4,39188	0,014321	0,492347	0,412504	0,557926	0,870398	1,17692	1,46997	Tube 2
27.04.2016 01:33	4,90646	4,82306	0,002008	0,083397	3,38546	3,42479	3,46744	3,51206	3,57175	Tube 3
27.04.2016 13:33	4,8945	4,32125	0,017813	0,573257	0,356464	0,381499	0,556248	0,847258	1,16593	Tube 1
27.04.2016 13:33	4,88428	4,38867	0,014404	0,495615	0,412506	0,546763	0,85709	1,166	1,46142	Tube 2
27.04.2016 13:33	4,90682	4,82304	0,002018	0,083779	3,38398	3,42376	3,46675	3,51134	3,57172	Tube 3
28.04.2016 01:33	4,89407	4,31408	0,018021	0,579995	0,357107	0,379908	0,544767	0,836028	1,15678	Tube 1
28.04.2016 01:33	4,88349	4,38405	0,014522	0,499438	0,421545	0,545121	0,851322	1,16153	1,45839	Tube 2
28.04.2016 01:33	4,90643	4,82192	0,002018	0,084509	3,38473	3,42507	3,46834	3,51332	3,57382	Tube 3
28.04.2016 13:33	4,89406	4,30631	0,018232	0,587752	0,360025	0,38102	0,536129	0,826853	1,1492	Tube 1
28.04.2016 13:33	4,88451	4,37867	0,014724	0,505833	0,42036	0,534445	0,836521	1,14876	1,44766	Tube 2
28.04.2016 13:33	4,90738	4,82202	0,002037	0,085354	3,38569	3,42605	3,46959	3,51477	3,57511	Tube 3
29.04.2016 01:33	4,89387	4,29899	0,018471	0,594879	0,360103	0,379601	0,525231	0,814575	1,1391	Tube 1
29.04.2016 01:33	4,88322	4,37289	0,014853	0,510326	0,427645	0,532749	0,829305	1,14272	1,44313	Tube 2
29.04.2016 01:33	4,90716	4,82104	0,002086	0,086114	3,38496	3,42564	3,46943	3,51475	3,57566	Tube 3
29.04.2016 13:33	4,89392	4,29556	0,018553	0,598361	0,360458	0,378626	0,515319	0,803257	1,13023	Tube 1
29.04.2016 13:33	4,88447	4,37231	0,014902	0,512156	0,430793	0,528028	0,819229	1,13464	1,43744	Tube 2
29.04.2016 13:33	4,90812	4,8218	0,002091	0,08632	3,38327	3,42622	3,46918	3,51577	3,57605	Tube 3
30.04.2016 01:33	4,89319	4,26919	0,019333	0,624	0,36166	0,378745	0,506547	0,789972	1,11705	Tube 1
30.04.2016 01:33	4,88551	4,35136	0,015572	0,534151	0,430015	0,520119	0,804101	1,11991	1,42335	Tube 2
30.04.2016 01:33	4,90929	4,81996	0,002172	0,089334	3,38487	3,42655	3,47073	3,51574	3,57628	Tube 3
30.04.2016 13:33	4,89351	4,25833	0,01967	0,635179	0,36168	0,377756	0,497507	0,7789	1,10783	Tube 1
30.04.2016 13:33	4,88816	4,34573	0,01581	0,542437	0,438712	0,522273	0,799372	1,11661	1,42201	Tube 2
30.04.2016 13:33	4,91098	4,81988	0,002247	0,091097	3,39137	3,43388	3,47812	3,52382	3,58493	Tube 3
01.05.2016 01:33	4,89285	4,24855	0,019946	0,6443	0,364758	0,379882	0,491408	0,768806	1,09857	Tube 1
01.05.2016 01:33	4,88679	4,33818	0,016007	0,548612	0,440582	0,517868	0,786369	1,10346	1,40968	Tube 2
01.05.2016 01:33	4,9105	4,81876	0,002249	0,091741	3,38367	3,42685	3,47099	3,51647	3,57799	Tube 3

Time	Drive_1 [V]	Top [V]	Drive_2 [V]	Current [mA]	Pin_1 [V]	Pin_2 [V]	Pin_3 [V]	Pin_4 [V]	Pin_5 [V]	MODE
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02.05.2016 01:33	4,89207	4,23572	0,020325	0,656351	0,367148	0,380656	0,477873	0,74675	1,07967	Tube 1
02.05.2016 01:33	4,88584	4,32858	0,016266	0,55726	0,444259	0,511366	0,764114	1,08302	1,39317	Tube 2
02.05.2016 01:33	4,90985	4,81715	0,002296	0,092699	3,38005	3,42404	3,46856	3,51469	3,57623	Tube 3
02.05.2016 13:33	4,89279	4,23505	0,02034	0,657741	0,366545	0,379433	0,470532	0,735542	1,071	Tube 1
02.05.2016 13:33	4,88762	4,33004	0,016284	0,557576	0,449481	0,512383	0,75783	1,07822	1,39133	Tube 2
02.05.2016 13:33	4,91128	4,81801	0,002315	0,093265	3,3848	3,42992	3,47528	3,52187	3,58383	Tube 3
03.05.2016 13:33	4,89216	4,21125	0,021045	0,680902	0,371247	0,382947	0,462498	0,714974	1,05081	Tube 1
03.05.2016 13:33	4,88695	4,31288	0,016776	0,574068	0,455072	0,510326	0,738143	1,05647	1,37142	Tube 2
03.05.2016 13:33	4,91148	4,81613	0,002356	0,095344	3,38143	3,42723	3,47249	3,51929	3,58099	Tube 3
04.05.2016 13:33	4,89156	4,20611	0,0212	0,685455	0,372074	0,38281	0,452791	0,69433	1,03249	Tube 1
04.05.2016 13:33	4,88511	4,30844	0,016834	0,576667	0,459401	0,508515	0,720727	1,03857	1,35796	Tube 2
04.05.2016 13:33	4,91135	4,81572	0,002385	0,095629	3,37935	3,42534	3,47147	3,51859	3,58058	Tube 3
05.05.2016 13:33	4,89081	4,19536	0,021493	0,695453	0,374965	0,384944	0,446694	0,675761	1,01474	Tube 1
05.05.2016 13:33	4,88395	4,30184	0,017003	0,58211	0,463212	0,507244	0,703841	1,01908	1,34202	Tube 2
05.05.2016 13:33	4,91048	4,81453	0,002367	0,095949	3,37706	3,42396	3,47054	3,51772	3,58065	Tube 3
06.05.2016 13:33	4,89042	4,18992	0,02166	0,700495	0,375588	0,384848	0,439595	0,655745	0,994317	Tube 1
06.05.2016 13:33	4,88296	4,29848	0,01705	0,584476	0,467593	0,507365	0,689514	1,00124	1,32776	Tube 2
06.05.2016 13:33	4,91081	4,81472	0,002359	0,096098	3,37498	3,42285	3,47001	3,5178	3,58141	Tube 3
07.05.2016 13:33	4,88978	4,17786	0,021999	0,711925	0,378166	0,386984	0,435841	0,638918	0,975585	Tube 1
07.05.2016 13:33	4,88072	4,28915	0,017268	0,591568	0,471836	0,508129	0,676696	0,983288	1,31254	Tube 2
07.05.2016 13:33	4,91033	4,81344	0,002375	0,096897	3,37509	3,42359	3,47126	3,5195	3,5827	Tube 3
08.05.2016 13:33	4,88946	4,16391	0,022422	0,725551	0,378314	0,386683	0,430647	0,620819	0,954639	Tube 1
08.05.2016 13:33	4,88141	4,2813	0,017514	0,600113	0,477469	0,510859	0,666792	0,967138	1,29863	Tube 2
08.05.2016 13:33	4,91089	4,81283	0,002405	0,098063	3,37154	3,42141	3,46889	3,51718	3,5813	Tube 3
09.05.2016 13:33	4,88958	4,15156	0,022797	0,738019	0,37965	0,387608	0,42748	0,604932	0,934514	Tube 1
09.05.2016 13:33	4,88087	4,27218	0,017746	0,608695	0,481274	0,512188	0,656608	0,949922	1,28335	Tube 2
09.05.2016 13:33	4,91176	4,81245	0,002458	0,09931	3,36837	3,4189	3,46699	3,5162	3,58043	Tube 3
10.05.2016 13:33	4,88876	4,13796	0,023199	0,750803	0,381049	0,388693	0,425091	0,590479	0,915284	Tube 1
10.05.2016 13:33	4,88069	4,26461	0,017974	0,616084	0,485395	0,514271	0,648069	0,933541	1,26842	Tube 2
10.05.2016 13:33	4,9114	4,81123	0,002481	0,100174	3,36795	3,41899	3,4681	3,51706	3,5818	Tube 3

Time	Drive_1 [V]	Top [V]	Drive_2 [V]	Current [mA]	Pin_1 [V]	Pin_2 [V]	Pin_3 [V]	Pin_4 [V]	Pin_5 [V]	MODE
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12.05.2016 13:33	4,88722	4,11928	0,023742	0,767945	0,384187	0,391332	0,422352	0,565551	0,877607	Tube 1
12.05.2016 13:33	4,8787	4,25526	0,018217	0,623441	0,489913	0,515407	0,630967	0,899501	1,236	Tube 2
12.05.2016 13:33	4,91043	4,80999	0,002467	0,100438	3,35852	3,4108	3,46113	3,51046	3,57589	Tube 3
13.05.2016 13:33	4,88638	4,11896	0,023714	0,76742	0,386067	0,392989	0,421918	0,555437	0,860895	Tube 1
13.05.2016 13:33	4,87802	4,25943	0,018052	0,618591	0,493534	0,51761	0,625322	0,885103	1,22209	Tube 2
13.05.2016 13:33	4,91	4,81058	0,002441	0,099427	3,35446	3,40758	3,45813	3,5083	3,57373	Tube 3
14.05.2016 13:33	4,88537	4,10274	0,024171	0,782627	0,38748	0,394534	0,421708	0,545856	0,842786	Tube 1
14.05.2016 13:33	4,87575	4,25174	0,018216	0,624011	0,496658	0,519477	0,619696	0,868992	1,20346	Tube 2
14.05.2016 13:33	4,90913	4,80891	0,002447	0,100223	3,35082	3,40557	3,45595	3,5064	3,57178	Tube 3
15.05.2016 13:33	4,88478	4,09038	0,02456	0,794403	0,387375	0,394223	0,419854	0,535666	0,824118	Tube 1
15.05.2016 13:33	4,87505	4,24735	0,018308	0,6277	0,498146	0,51989	0,613472	0,852997	1,1853	Tube 2
15.05.2016 13:33	4,90911	4,80845	0,002461	0,100652	3,35161	3,4062	3,45763	3,50763	3,57416	Tube 3
16.05.2016 13:33	4,88402	4,07877	0,024864	0,805251	0,391198	0,398009	0,422349	0,530104	0,809221	Tube 1
16.05.2016 13:33	4,87429	4,2417	0,018463	0,632591	0,501177	0,52202	0,609894	0,84039	1,17078	Tube 2
16.05.2016 13:33	4,909	4,80799	0,002474	0,10101	3,34549	3,40112	3,45233	3,50295	3,56935	Tube 3
17.05.2016 13:33	4,88326	4,06505	0,025264	0,818209	0,393095	0,399664	0,422837	0,52347	0,793227	Tube 1
17.05.2016 13:33	4,87433	4,23426	0,01866	0,640076	0,503415	0,523507	0,606363	0,828429	1,15696	Tube 2
17.05.2016 13:33	4,90889	4,80719	0,002488	0,101704	3,33567	3,39184	3,44376	3,49489	3,56116	Tube 3
18.05.2016 13:33	4,88323	4,05512	0,025565	0,828111	0,393131	0,39977	0,421937	0,516004	0,776509	Tube 1
18.05.2016 13:33	4,87342	4,2287	0,018807	0,64472	0,508006	0,5274	0,605677	0,819432	1,14585	Tube 2
18.05.2016 13:33	4,90896	4,80692	0,002491	0,102047	3,33522	3,39258	3,44491	3,49614	3,56353	Tube 3
19.05.2016 13:33	4,88229	4,03886	0,026053	0,843431	0,395334	0,401967	0,423282	0,511305	0,762024	Tube 1
19.05.2016 13:33	4,87327	4,21999	0,019065	0,653287	0,511543	0,530316	0,604438	0,810044	1,13358	Tube 2
19.05.2016 13:33	4,90891	4,80603	0,00249	0,10288	3,33181	3,38927	3,4425	3,4937	3,56109	Tube 3
20.05.2016 13:33	4,88244	4,02576	0,026436	0,856681	0,397054	0,404312	0,42477	0,507374	0,74838	Tube 1
20.05.2016 13:33	4,87384	4,2126	0,01931	0,661246	0,517308	0,535491	0,605773	0,803252	1,12312	Tube 2
20.05.2016 13:33	4,91032	4,80639	0,002538	0,103922	3,33633	3,39452	3,44825	3,49971	3,56777	Tube 3
21.05.2016 13:33	4,88119	4,00673	0,026982	0,874463	0,399613	0,405232	0,424986	0,502474	0,733486	Tube 1
21.05.2016 13:33	4,87192	4,20102	0,019604	0,670897	0,52314	0,540849	0,607558	0,797039	1,11258	Tube 2
21.05.2016 13:33	4,90954	4,80465	0,002552	0,104889	3,32769	3,38683	3,44037	3,49266	3,56013	Tube 3

22.05.2016 13:33	4,88107	3,9936	0,027384	0,887466	0,400879	0,407356	0,426481	0,499348	0,720861	Tube 1
22.05.2016 13:33	4,87211	4,19335	0,019818	0,678763	0,525114	0,542387	0,605965	0,788223	1,09996	Tube 2
22.05.2016 13:33	4,91009	4,80468	0,002592	0,105405	3,33072	3,39105	3,44499	3,49755	3,56545	Tube 3
23.05.2016 13:33	4,88067	3,98154	0,02773	0,89913	0,403327	0,409783	0,428366	0,497259	0,709911	Tube 1
23.05.2016 13:33	4,87201	4,18729	0,019996	0,684715	0,530337	0,547236	0,607877	0,783131	1,09047	Tube 2
23.05.2016 13:33	4,91072	4,80454	0,002588	0,106179	3,33761	3,39782	3,45278	3,5058	3,57377	Tube 3
24.05.2016 13:33	4,88026	3,96639	0,028175	0,913875	0,405225	0,411655	0,429745	0,494756	0,698208	Tube 1
24.05.2016 13:33	4,87193	4,17881	0,020264	0,693123	0,532157	0,548635	0,606569	0,775055	1,07774	Tube 2
24.05.2016 13:33	4,91096	4,80432	0,002603	0,106646	3,32615	3,3867	3,44189	3,4949	3,5637	Tube 3
25.05.2016 13:33	4,87909	3,95263	0,028567	0,926457	0,408159	0,41451	0,43212	0,49372	0,688521	Tube 1
25.05.2016 13:33	4,87122	4,17281	0,020409	0,698405	0,53736	0,553494	0,60895	0,770818	1,06848	Tube 2
25.05.2016 13:33	4,91058	4,8036	0,002608	0,106984	3,31593	3,3772	3,43277	3,48593	3,5548	Tube 3
26.05.2016 13:33	4,87852	3,93227	0,029187	0,946242	0,409978	0,41632	0,433546	0,491992	0,678332	Tube 1
26.05.2016 13:33	4,87097	4,16215	0,020726	0,708816	0,540868	0,556683	0,609904	0,765439	1,0576	Tube 2
26.05.2016 13:33	4,91057	4,80269	0,002641	0,107876	3,31542	3,3774	3,43324	3,48681	3,55561	Tube 3
27.05.2016 12:52	4,87948	3,91342	0,029759	0,966065	0,412217	0,418524	0,435425	0,49125	0,669774	Tube 1
27.05.2016 12:52	4,86756	4,1481	0,021021	0,71946	0,545986	0,561512	0,61268	0,762226	1,04849	Tube 2
27.05.2016 12:52	4,91176	4,80248	0,002679	0,109278	3,31712	3,37982	3,43609	3,48993	3,5597	Tube 3

Time	Pin_6 [V]	Pin_7 [V]	Pin_8 [V]	Screw_1 [V]	Screw_2 [V]	Screw_3 [V]	Screw_4 [V]	Screw_5 [V]	MODE
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19.04.2016 17:30	4,80498	4,81516	4,82587	4,76393	4,77037	4,78666	4,80567	4,82567	Tube 1
19.04.2016 17:30	1,89186	2,13369	2,39671	0,617747	0,86983	1,40442	1,88902	2,39428	Tube 2
19.04.2016 17:30	3,54402	3,59077	3,63574	3,33426	3,36593	3,44409	3,54353	3,63517	Tube 3
20.04.2016 05:30	4,9273	4,92757	4,92735	4,92722	4,92739	4,92732	4,92758	4,92754	Tube 1
20.04.2016 05:30	1,87593	2,12462	2,39512	0,568147	0,825911	1,3753	1,87299	2,39275	Tube 2
20.04.2016 05:30	3,61128	3,65988	3,7069	3,3961	3,42882	3,50883	3,61149	3,70579	Tube 3
20.04.2016 10:13	4,92716	4,92723	4,92696	4,92708	4,92711	4,92721	4,92723	4,92716	Tube 1
20.04.2016 10:13	1,87998	2,13187	2,40577	0,555371	0,816451	1,37299	1,87692	2,40331	Tube 2
20.04.2016 10:13	3,61183	3,66023	3,70732	3,39466	3,42798	3,50858	3,61154	3,70661	Tube 3
20.04.2016 10:13	4,92716	4,92722	4,92718	4,92727	4,92711	4,92713	4,92734	4,92732	Tube 1
20.04.2016 10:13	1,88472	2,13676	2,41089	0,559169	0,820424	1,37734	1,88167	2,4084	Tube 2
20.04.2016 10:13	3,60394	3,65248	3,69883	3,38805	3,42068	3,50045	3,6038	3,69811	Tube 3
20.04.2016 10:16	4,92633	4,92642	4,92646	4,92591	4,926	4,92625	4,92637	4,92653	Tube 1
20.04.2016 10:16	1,87347	2,12596	2,40046	0,546209	0,807855	1,36549	1,87054	2,39804	Tube 2
20.04.2016 10:16	3,59241	3,64061	3,68739	3,37663	3,40935	3,48911	3,59192	3,68634	Tube 3
20.04.2016 10:16	4,92638	4,92649	4,92663	4,92602	4,92608	4,92626	4,92643	4,92674	Tube 1
20.04.2016 10:16	1,88507	2,13803	2,4132	0,55448	0,816708	1,37576	1,882	2,41063	Tube 2
20.04.2016 10:16	3,57695	3,62538	3,67249	3,35952	3,39255	3,47333	3,57665	3,6715	Tube 3
20.04.2016 10:17	4,92593	4,92601	4,92597	4,92535	4,92552	4,92587	4,92587	4,92594	Tube 1
20.04.2016 10:17	1,87649	2,12897	2,40357	0,548935	0,810602	1,36839	1,8735	2,40116	Tube 2
20.04.2016 10:17	3,5562	3,60403	3,65045	3,34323	3,37561	3,4544	3,55577	3,64877	Tube 3
20.04.2016 10:17	4,92593	4,92609	4,92602	4,92528	4,92535	4,92578	4,92591	4,9262	Tube 1
20.04.2016 10:17	1,88712	2,14006	2,4152	0,5566	0,818803	1,37783	1,88407	2,41265	Tube 2
20.04.2016 10:17	3,53565	3,58367	3,63017	3,32083	3,35341	3,4331	3,53502	3,62874	Tube 3
20.04.2016 10:20	4,86136	4,86685	4,8729	4,83788	4,84178	4,85123	4,86145	4,87289	Tube 1
20.04.2016 10:20	1,86669	2,1198	2,39507	0,535947	0,798197	1,35734	1,86371	2,39266	Tube 2
20.04.2016 10:20	3,54443	3,59231	3,63835	3,3314	3,36349	3,44305	3,54433	3,63733	Tube 3
20.04.2016 10:20	4,84989	4,85645	4,86349	4,82178	4,82653	4,8379	4,85009	4,86364	Tube 1
20.04.2016 10:20	1,87741	2,132	2,4091	0,537818	0,801747	1,36463	1,87433	2,40647	Tube 2
20.04.2016 10:20	3,51643	3,56373	3,60996	3,30327	3,33591	3,41504	3,51588	3,60882	Tube 3

Time	Pin_6 [V]	Pin_7 [V]	Pin_8 [V]	Screw_1 [V]	Screw_2 [V]	Screw_3 [V]	Screw_4 [V]	Screw_5 [V]	MODE
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21.04.2016 01:33	1,60163	1,90465	2,22776	0,369253	0,531094	1,0458	1,60766	2,23004	Tube 1
21.04.2016 01:33	1,85794	2,11409	2,39257	0,511519	0,77715	1,34252	1,85492	2,39027	Tube 2
21.04.2016 01:33	3,60149	3,65037	3,69768	3,38399	3,41697	3,49783	3,60138	3,69635	Tube 3
21.04.2016 13:33	1,58361	1,89181	2,2205	0,365724	0,494583	1,01865	1,58974	2,22286	Tube 1
21.04.2016 13:33	1,84875	2,1083	2,39043	0,485117	0,753832	1,32662	1,84572	2,38814	Tube 2
21.04.2016 13:33	3,60282	3,65209	3,69977	3,38349	3,41791	3,49894	3,60271	3,69865	Tube 3
22.04.2016 01:33	1,57148	1,88457	2,21857	0,360908	0,467663	0,997892	1,57764	2,22103	Tube 1
22.04.2016 01:33	1,84143	2,1042	2,39006	0,463704	0,732615	1,31257	1,83826	2,38767	Tube 2
22.04.2016 01:33	3,60465	3,65428	3,70205	3,38399	3,41823	3,49996	3,60443	3,70099	Tube 3
22.04.2016 13:33	1,56301	1,88025	2,21863	0,360844	0,45071	0,982486	1,56934	2,22108	Tube 1
22.04.2016 13:33	1,8318	2,09784	2,38728	0,444187	0,709732	1,29663	1,82862	2,38485	Tube 2
22.04.2016 13:33	3,60592	3,65607	3,70442	3,38373	3,41863	3,50076	3,6059	3,70319	Tube 3
23.04.2016 01:33	1,55415	1,8761	2,21944	0,356457	0,433465	0,965707	1,56058	2,22195	Tube 1
23.04.2016 01:33	1,8266	2,0958	2,38861	0,432414	0,691264	1,28505	1,82339	2,38617	Tube 2
23.04.2016 01:33	3,60947	3,65989	3,70849	3,38521	3,42081	3,50357	3,60916	3,7074	Tube 3
23.04.2016 13:33	1,54953	1,87595	2,2242	0,356339	0,422712	0,953409	1,55604	2,22677	Tube 1
23.04.2016 13:33	1,81883	2,0908	2,38671	0,422841	0,671849	1,27166	1,81555	2,38425	Tube 2
23.04.2016 13:33	3,61063	3,66158	3,71066	3,38519	3,42105	3,5042	3,61059	3,70943	Tube 3
24.04.2016 01:33	1,54066	1,87077	2,22308	0,35489	0,412027	0,938444	1,54724	2,22566	Tube 1
24.04.2016 01:33	1,81395	2,08871	2,3876	0,418413	0,655756	1,26131	1,81068	2,38506	Tube 2
24.04.2016 01:33	3,6141	3,66466	3,71438	3,38643	3,42271	3,50638	3,61379	3,71301	Tube 3
24.04.2016 13:33	1,53291	1,86702	2,2236	0,353589	0,403239	0,924176	1,53958	2,22629	Tube 1
24.04.2016 13:33	1,8052	2,08282	2,38488	0,410826	0,635522	1,24681	1,80196	2,38238	Tube 2
24.04.2016 13:33	3,61431	3,66574	3,71558	3,38502	3,42215	3,50636	3,61393	3,71414	Tube 3
25.04.2016 01:33	1,52546	1,8628	2,22286	0,354346	0,397918	0,911502	1,53216	2,2256	Tube 1
25.04.2016 01:33	1,79926	2,07924	2,38381	0,409371	0,620699	1,23619	1,79601	2,3813	Tube 2
25.04.2016 01:33	3,61864	3,67025	3,72042	3,38808	3,4253	3,51011	3,61831	3,71918	Tube 3
25.04.2016 13:33	1,51809	1,85892	2,22283	0,353937	0,39253	0,898346	1,52489	2,22552	Tube 1
25.04.2016 13:33	1,79164	2,07388	2,38098	0,407593	0,60531	1,22411	1,78836	2,37841	Tube 2
25.04.2016 13:33	3,61804	3,66997	3,71991	3,38617	3,424	3,50852	3,61764	3,71904	Tube 3

Time	Pin_6 [V]	Pin_7 [V]	Pin_8 [V]	Screw_1 [V]	Screw_2 [V]	Screw_3 [V]	Screw_4 [V]	Screw_5 [V]	MODE
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26.04.2016 13:33	1,50401	1,85192	2,22346	0,353849	0,384586	0,872927	1,51098	2,22634	Tube 1
26.04.2016 13:33	1,78323	2,07001	2,382	0,411175	0,582525	1,20658	1,77991	2,37937	Tube 2
26.04.2016 13:33	3,62178	3,67451	3,72557	3,38667	3,4253	3,51129	3,62155	3,72412	Tube 3
27.04.2016 01:33	1,49663	1,84763	2,22256	0,35414	0,381926	0,8608	1,50362	2,22551	Tube 1
27.04.2016 01:33	1,77642	2,0652	2,37929	0,412383	0,571197	1,19603	1,7731	2,37666	Tube 2
27.04.2016 01:33	3,62353	3,67659	3,7277	3,38772	3,42655	3,51288	3,62333	3,72677	Tube 3
27.04.2016 13:33	1,49158	1,84589	2,22434	0,355397	0,380856	0,850851	1,49869	2,22732	Tube 1
27.04.2016 13:33	1,77038	2,06154	2,37821	0,412349	0,559628	1,18526	1,76697	2,3756	Tube 2
27.04.2016 13:33	3,62348	3,67699	3,72847	3,38597	3,42544	3,51218	3,62345	3,72726	Tube 3
28.04.2016 01:33	1,48497	1,84231	2,22406	0,355993	0,379427	0,839634	1,49213	2,22709	Tube 1
28.04.2016 01:33	1,76879	2,06128	2,37945	0,421395	0,557428	1,18098	1,76538	2,37686	Tube 2
28.04.2016 01:33	3,62623	3,67987	3,73146	3,38743	3,42706	3,51428	3,62588	3,73022	Tube 3
28.04.2016 13:33	1,4796	1,83944	2,224	0,358944	0,380579	0,830462	1,48682	2,22703	Tube 1
28.04.2016 13:33	1,76039	2,055	2,37552	0,420155	0,546218	1,16829	1,757	2,3729	Tube 2
28.04.2016 13:33	3,62798	3,68171	3,73336	3,38806	3,42821	3,51563	3,6276	3,73243	Tube 3
29.04.2016 01:33	1,47213	1,83507	2,22299	0,359104	0,379294	0,818166	1,47943	2,22607	Tube 1
29.04.2016 01:33	1,75733	2,05334	2,37545	0,42737	0,543952	1,16241	1,75394	2,37281	Tube 2
29.04.2016 01:33	3,62845	3,68259	3,73482	3,38657	3,42769	3,51567	3,6284	3,73394	Tube 3
29.04.2016 13:33	1,46634	1,83276	2,22452	0,359411	0,37838	0,806934	1,47372	2,22767	Tube 1
29.04.2016 13:33	1,7541	2,05253	2,37718	0,430504	0,538684	1,15452	1,75082	2,37462	Tube 2
29.04.2016 13:33	3,62948	3,68356	3,73616	3,38669	3,42756	3,51615	3,62923	3,73484	Tube 3
30.04.2016 01:33	1,45337	1,82049	2,2131	0,360716	0,378506	0,793439	1,46087	2,21627	Tube 1
30.04.2016 01:33	1,74071	2,03968	2,36503	0,429672	0,530275	1,13982	1,73732	2,3624	Tube 2
30.04.2016 01:33	3,6298	3,68353	3,73612	3,38717	3,42852	3,51676	3,6296	3,73521	Tube 3
30.04.2016 13:33	1,44671	1,81649	2,21171	0,360748	0,377558	0,782603	1,4542	2,21489	Tube 1
30.04.2016 13:33	1,74127	2,04178	2,3685	0,438355	0,531891	1,13668	1,73785	2,3658	Tube 2
30.04.2016 13:33	3,63869	3,69309	3,74604	3,3933	3,43559	3,52489	3,6383	3,74492	Tube 3
01.05.2016 01:33	1,43921	1,81141	2,2094	0,363782	0,379681	0,772389	1,44679	2,21267	Tube 1
01.05.2016 01:33	1,73002	2,03177	2,36031	0,440222	0,526939	1,12361	1,72666	2,35757	Tube 2
01.05.2016 01:33	3,63111	3,68624	3,73841	3,38657	3,42868	3,5178	3,63118	3,73718	Tube 3

Time	Pin_6 [V]	Pin_7 [V]	Pin_8 [V]	Screw_1 [V]	Screw_2 [V]	Screw_3 [V]	Screw_4 [V]	Screw_5 [V]	MODE
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02.05.2016 01:33	1,42548	1,80365	2,20815	0,366212	0,38052	0,749952	1,43317	2,2116	Tube 1
02.05.2016 01:33	1,71775	2,02354	2,35642	0,443866	0,519395	1,10339	1,7143	2,3537	Tube 2
02.05.2016 01:33	3,63016	3,68517	3,73816	3,38268	3,42585	3,51565	3,62993	3,73737	Tube 3
02.05.2016 13:33	1,42036	1,80246	2,21082	0,365598	0,379327	0,739164	1,42814	2,2144	Tube 1
02.05.2016 13:33	1,71887	2,0272	2,36253	0,449101	0,519996	1,09889	1,7153	2,35984	Tube 2
02.05.2016 13:33	3,63845	3,69398	3,74764	3,38727	3,43162	3,52259	3,63827	3,74668	Tube 3
03.05.2016 13:33	1,4033	1,78962	2,20297	0,370312	0,382846	0,718493	1,4112	2,20657	Tube 1
03.05.2016 13:33	1,70112	2,01171	2,34986	0,454668	0,517145	1,07744	1,69761	2,34707	Tube 2
03.05.2016 13:33	3,63498	3,69102	3,74457	3,38383	3,42866	3,51989	3,63529	3,74347	Tube 3
04.05.2016 13:33	1,39071	1,78378	2,20444	0,371168	0,382777	0,698125	1,39872	2,20815	Tube 1
04.05.2016 13:33	1,69233	2,00733	2,35019	0,458956	0,514643	1,05981	1,68889	2,34737	Tube 2
04.05.2016 13:33	3,63544	3,69189	3,74618	3,38163	3,42702	3,51945	3,63582	3,7452	Tube 3
05.05.2016 13:33	1,37816	1,77775	2,20557	0,374098	0,384919	0,679584	1,38642	2,20944	Tube 1
05.05.2016 13:33	1,68063	1,99991	2,34737	0,462721	0,512746	1,04058	1,67725	2,34445	Tube 2
05.05.2016 13:33	3,63584	3,69253	3,74758	3,37911	3,42591	3,51867	3,63593	3,74649	Tube 3
06.05.2016 13:33	1,36267	1,76866	2,20361	0,374673	0,384888	0,659529	1,37105	2,20761	Tube 1
06.05.2016 13:33	1,67077	1,99425	2,34638	0,467091	0,512404	1,02298	1,66733	2,34336	Tube 2
06.05.2016 13:33	3,63686	3,69442	3,74968	3,37748	3,4247	3,51858	3,63674	3,74856	Tube 3
07.05.2016 13:33	1,3481	1,75972	2,20105	0,377305	0,387009	0,642646	1,35662	2,20518	Tube 1
07.05.2016 13:33	1,65917	1,98622	2,34224	0,471332	0,512682	1,00515	1,65579	2,33934	Tube 2
07.05.2016 13:33	3,63923	3,69633	3,75198	3,37725	3,42533	3,52032	3,63879	3,75116	Tube 3
08.05.2016 13:33	1,33116	1,74867	2,19657	0,377421	0,386772	0,62448	1,33977	2,2007	Tube 1
08.05.2016 13:33	1,6487	1,97907	2,33874	0,476966	0,515059	0,989017	1,6452	2,33576	Tube 2
08.05.2016 13:33	3,63768	3,69558	3,75186	3,37365	3,42273	3,51843	3,63757	3,7509	Tube 3
09.05.2016 13:33	1,31448	1,73743	2,19153	0,378786	0,38766	0,608397	1,32324	2,19583	Tube 1
09.05.2016 13:33	1,63691	1,97071	2,33423	0,480746	0,516057	0,971773	1,63343	2,33116	Tube 2
09.05.2016 13:33	3,63709	3,69564	3,75213	3,37048	3,42006	3,51684	3,63713	3,75133	Tube 3
10.05.2016 13:33	1,29851	1,72746	2,18836	0,380144	0,388758	0,593924	1,30747	2,19275	Tube 1
10.05.2016 13:33	1,62542	1,96259	2,32983	0,484894	0,517838	0,955317	1,62189	2,32681	Tube 2
10.05.2016 13:33	3,63937	3,69766	3,75479	3,37076	3,42046	3,51847	3,63915	3,75364	Tube 3

	Pin_6	Pin_7	Pin_8	Screw_1	Screw_2	Screw_3	Screw_4	Screw_5	
Time	[V]	[V]	[V]	[V]	[V]	[V]	[V]	[V]	MODE
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12.05.2016 13:33	1,26738	1,70885	2,18422	0,383387	0,391435	0,568733	1,27655	2,18882	Tube 1
12.05.2016 13:33	1,59996	1,94423	2,31931	0,48943	0,518581	0,921038	1,59648	2,31622	Tube 2
12.05.2016 13:33	3,63373	3,69277	3,7508	3,36062	3,41283	3,5116	3,63296	3,74934	Tube 3
13.05.2016 13:33	1,2542	1,70324	2,18732	0,385248	0,39309	0,558542	1,26351	2,19214	Tube 1
13.05.2016 13:33	1,58977	1,93791	2,3173	0,493153	0,52053	0,906531	1,58626	2,31422	Tube 2
13.05.2016 13:33	3,63209	3,69173	3,75022	3,35659	3,40943	3,50953	3,63155	3,74885	Tube 3
14.05.2016 13:33	1,23724	1,69176	2,1826	0,386929	0,394639	0,548797	1,24667	2,18744	Tube 1
14.05.2016 13:33	1,57203	1,92149	2,3025	0,496242	0,522214	0,890067	1,5685	2,2994	Tube 2
14.05.2016 13:33	3,63031	3,69043	3,74868	3,35383	3,40703	3,50733	3,62997	3,74764	Tube 3
15.05.2016 13:33	1,21977	1,68042	2,17894	0,386939	0,394499	0,538401	1,22934	2,18388	Tube 1
15.05.2016 13:33	1,55563	1,9074	2,29086	0,497716	0,522485	0,873633	1,55208	2,28779	Tube 2
15.05.2016 13:33	3,63242	3,69254	3,75152	3,35381	3,40788	3,50888	3,63216	3,75016	Tube 3
16.05.2016 13:33	1,20499	1,671	2,17648	0,390775	0,398236	0,53271	1,21463	2,18152	Tube 1
16.05.2016 13:33	1,5436	1,89848	2,28544	0,500775	0,52451	0,860647	1,53997	2,28237	Tube 2
16.05.2016 13:33	3,62775	3,68838	3,74714	3,34779	3,40243	3,50405	3,62773	3,74638	Tube 3
17.05.2016 13:33	1,18869	1,6603	2,17317	0,392525	0,399846	0,525911	1,19844	2,1783	Tube 1
17.05.2016 13:33	1,53282	1,89138	2,28238	0,503069	0,525898	0,848422	1,52915	2,27938	Tube 2
17.05.2016 13:33	3,62021	3,68132	3,74034	3,33833	3,3933	3,49587	3,62009	3,73945	Tube 3
18.05.2016 13:33	1,17146	1,64904	2,16989	0,392666	0,399956	0,51835	1,18129	2,17518	Tube 1
18.05.2016 13:33	1,52456	1,88684	2,2821	0,507645	0,529691	0,8388	1,52085	2,27893	Tube 2
18.05.2016 13:33	3,62209	3,6838	3,74287	3,33825	3,39432	3,49714	3,62188	3,742	Tube 3
19.05.2016 13:33	1,15515	1,63759	2,16566	0,394975	0,402163	0,513529	1,165	2,17103	Tube 1
19.05.2016 13:33	1,51474	1,88065	2,28005	0,511152	0,532514	0,829071	1,51102	2,27685	Tube 2
19.05.2016 13:33	3,62042	3,68181	3,74166	3,33444	3,39102	3,49496	3,61991	3,74076	Tube 3
20.05.2016 13:33	1,13906	1,62629	2,16167	0,397428	0,40453	0,509464	1,14894	2,16712	Tube 1
20.05.2016 13:33	1,50615	1,87521	2,27829	0,51694	0,537698	0,821805	1,50236	2,27502	Tube 2
20.05.2016 13:33	3,62722	3,68913	3,74919	3,33863	3,39624	3,50059	3,62668	3,7483	Tube 3
21.05.2016 13:33	1,12036	1,61117	2,15291	0,398354	0,405468	0,5045	1,13029	2,15851	Tube 1
21.05.2016 13:33	1,49678	1,86852	2,27478	0,522827	0,542936	0,815119	1,49303	2,27154	Tube 2
21.05.2016 13:33	3,61992	3,68231	3,74202	3,33023	3,38838	3,49355	3,61995	3,74149	Tube 3

22.05.2016 13:33	1,10403	1,59912	2,14836	0,400505	0,407565	0,501275	1,11401	2,15404	Tube 1
22.05.2016 13:33	1,48618	1,86168	2,27231	0,524816	0,544454	0,805828	1,48244	2,26904	Tube 2
22.05.2016 13:33	3,62529	3,68791	3,74804	3,33396	3,39207	3,49854	3,62476	3,74703	Tube 3
23.05.2016 13:33	1,08946	1,58925	2,14673	0,402996	0,41005	0,499219	1,09947	2,15258	Tube 1
23.05.2016 13:33	1,47835	1,85737	2,27207	0,530071	0,549214	0,800215	1,47456	2,26874	Tube 2
23.05.2016 13:33	3,6345	3,69694	3,75807	3,34014	3,39898	3,50661	3,63348	3,75726	Tube 3
24.05.2016 13:33	1,07276	1,57588	2,14076	0,404873	0,411869	0,496743	1,08286	2,14667	Tube 1
24.05.2016 13:33	1,46687	1,84944	2,26852	0,531805	0,550571	0,791619	1,46302	2,26521	Tube 2
24.05.2016 13:33	3,62396	3,68671	3,74809	3,32884	3,38798	3,49598	3,62396	3,74704	Tube 3
25.05.2016 13:33	1,05803	1,56483	2,13781	0,407719	0,414721	0,495601	1,06816	2,14384	Tube 1
25.05.2016 13:33	1,45855	1,84447	2,26774	0,537018	0,555369	0,786857	1,45465	2,26448	Tube 2
25.05.2016 13:33	3,61571	3,67898	3,74033	3,31886	3,37877	3,48679	3,61568	3,73945	Tube 3
26.05.2016 13:33	1,04179	1,55096	2,13101	0,40957	0,416541	0,493764	1,05195	2,13713	Tube 1
26.05.2016 13:33	1,44777	1,83651	2,2635	0,540513	0,558501	0,781012	1,44389	2,26028	Tube 2
26.05.2016 13:33	3,61668	3,67977	3,74141	3,31836	3,37897	3,48782	3,61644	3,74036	Tube 3
27.05.2016 12:52	1,02718	1,53834	2,12542	0,411776	0,418754	0,492981	1,03723	2,13165	Tube 1
27.05.2016 12:52	1,43802	1,82901	2,25897	0,545646	0,563327	0,777266	1,43416	2,25576	Tube 2
27.05.2016 12:52	3,62035	3,6843	3,74558	3,32042	3,38184	3,49113	3,6207	3,74488	Tube 3

Attachment 2 Index test

Index test		
Length of sample:	65	cm
Volume of sample, 23,2*L:	1508	cm^3
Mass, cylinder w/sample:	3291,8	g
Mass, empty cylinder:	382,3	g
Mass, sample:	2909,5	g
Avarge density, $\bar{\rho}$	1,93	g/cm^3
Unit weight of soil, $\bar{\gamma} = \bar{\rho} \cdot g$	18,93	kN/m^3

Water content w(%)		**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
Cup no.		63,37	60,79	66,6	63,61
Total wet mass	**g**	110,45	106,42	114,57	119,43
Total dry mass	**g**	98,38	97,3	102,73	104,93
Mass, water	**g**	12,07	9,12	11,84	14,5
Mass, cup	**g**	63,37	60,79	66,6	63,51
Mass, dry sample	**g**	35,01	36,51	36,13	41,42
Water content, w	**%**	34,48	24,98	32,77	35,01
Water content w(%)		**Sample 5**	**Sample 6**	**Sample 7**	**Sample 8**
Cup no.		78	86	75	80
Total wet mass	**g**	93,99	87,55	94,62	86,86
Mass dry mass	**g**	82,99	76,37	82,51	76,26
Mass, water	**g**	11	11,18	12,11	10,6
Mass, cup	**g**	49,82	45,69	48,36	45,18
Mass, dry sample	**g**	33,17	30,68	34,15	31,08
Water content, w	**%**	33,162	36,441	35,461	34,106

Water content w(%)		**Sample 9**	**Sample 10**	**Sample 11**	**Sample 12**
Cup no.		73	72	77	74
Total wet mass	**g**	90,5	91,55	135,11	138,24
Mass dry mass	**g**	80,61	81,83	123,57	123,73
Mass, water	**g**	9,89	9,72	11,54	14,51
Mass, cup	**g**	50,09	48,87	86,72	86,03
Mass, dry sample	**g**	30,52	32,96	36,85	37,7
Water content, w	**%**	32,40	29,49	31,32	38,49
Water content w(%)		**Sample 13**	**Sample 14**	**Sample 15**	**Sample 16**
Cup no.		71	98	63,75	60
Total wet mass	**g**	129,15	128,41	110,81	71,75
Mass dry mass	**g**	118,43	117,22	99,86	59,63
Mass, water	**g**	10,72	11,19	10,95	12,12
Mass, cup	**g**	89,15	85,43	63,74	21,96
Mass, dry sample	**g**	29,28	31,79	36,12	37,67
Water content, w	**%**	36,61	35,20	30,32	32,17

Plasticity limit				
Water content w(%)	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
Cup no.	167	164	168	160
Total wet mass	45,57	44,95	46,96	50,3
Total dry mass	40,19	39,7	41,8	43,44
Mass, water	5,38	5,25	5,16	6,86
Mass, cup	18,89	18,38	19,5	19,35
Mass, dry sample	21,3	21,32	22,3	24,09
Water content, wp	25,26	24,62	23,14	28,48

Plasticity limit				
Water content w(%)	**Sample 5**	**Sample 6**	**Sample 7**	**Sample 8**
Cup no.	157	158	163	211
Total wet mass	45,86	49,76	53,59	45,02
Total dry mass	40,27	44,37	47,72	42,22
Mass, water	5,59	5,39	5,87	2,8
Mass, cup	18,1	20,03	19,2	27,59
Mass, dry sample	22,17	24,34	28,52	14,63
Water content, wp	25,21	22,14	20,58	19,14

Plasticity limit				
Water content w(%)	**Sample 9**	**Sample 10**	**Sample 11**	**Sample 12**
Cup no.	213	161	169	241
Total wet mass	46,51	39,37	40,79	45,06
Total dry mass	43,27	36,15	37,11	41,35
Mass, water	3,24	3,22	3,68	3,71
Mass, cup	26,51	18,43	18,9	24,06
Mass, dry sample	16,76	17,72	18,21	17,29
Water content, wp	19,33	18,17	20,21	21,46

Plasticity limit				
Water content w(%)	**Sample 13**	**Sample 14**	**Sample 15**	**Sample 16**
Cup no.	150	151	153	156
Total wet mass	46,09	45,7	41,36	48,02
Total dry mass	40,2	39,25	36,57	41,74
Mass, water	5,89	6,45	4,79	6,28
Mass, cup	19,67	17,97	18,91	18,43
Mass, dry sample	20,53	21,28	17,66	23,31
Water content, wp	28,69	30,31	27,12	26,94

Attachment 3 Calculations of Effective Diffusion Length

cA(z,t)=0,5 g/L K+ c0=125 g/L K+

c(z,t)	**0,5**
c1	0
c0	125
Dk+	1,7209E-09
e	0,486
De (m2/s)	8,3637E-10
erfcξ	0,004
erfξ	0,996
	0,992016
	-0,007984
	-4,83031574
ξ	1,9477477

z(cm)	**t(s)**	**Time (days)**
0	0	0
1	7879,08386	0,0911931
2	31516,3355	0,3647724
3	70911,7548	0,8207379
4	126065,342	1,4590896
5	196977,097	2,27982751
6	283647,019	3,28295161
7	386075,109	4,46846191
8	504261,367	5,83635842
9	638205,793	7,38664112
10	787908,386	9,11931003
11	953369,147	11,0343651
12	1134588,08	13,1318064
13	1331565,17	15,4116339
14	1544300,44	17,8738477
15	1772793,87	20,5184476
16	2017045,47	23,3454337
17	2277055,24	26,354806
18	2552823,17	29,5465645
19	2844349,27	32,9207092
20	3151633,55	36,4772401
21	3474675,98	40,2161572
22	3813476,59	44,1374605
23	4168035,36	48,24115
24	4538352,31	52,5272258
25	4924427,41	56,9956877
26	5326260,69	61,6465358
27	5743852,14	66,4797701
28	6177201,75	71,4953906
29	6626309,53	76,6933973
30	7091175,48	82,0737902
31	7571799,59	87,6365694
32	8068181,88	93,3817347
33	8580322,33	99,3092862

cB(z,t)=0,5 g/L K+ c0=62,5 g/L K+

c(x,t)	**0,5**
c1	0
c0	62,5
Dk+	1,7209E-09
e	0,486
De (m2/s)	8,3637E-10
erfcξ	0,008
erfξ	0,992
	0,984064
	-0,015936
	-4,13917458
ξ	1,80302527

z(cm)	**t(s)**	**Time (days)**
0	0	0
1	9194,69862	0,10642012
2	36778,7945	0,42568049
3	82752,2876	0,95778111
4	147115,178	1,70272197
5	229867,466	2,66050307
6	331009,15	3,83112443
7	450540,233	5,21458603
8	588460,712	6,81088787
9	744770,589	8,62002996
10	919469,862	10,6420123
11	1112558,53	12,8768349
12	1324036,6	15,3244977
13	1553904,07	17,9850008
14	1802160,93	20,8583441
15	2068807,19	23,9445277
16	2353842,85	27,2435515
17	2657267,9	30,7554155
18	2979082,35	34,4801198
19	3319286,2	38,4176644
20	3677879,45	42,5680492
21	4054862,09	46,9312742
22	4450234,13	51,5073395
23	4863995,57	56,2962451
24	5296146,41	61,2979908
25	5746686,64	66,5125769
26	6215616,27	71,9400031
27	6702935,3	77,5802696
28	7208643,72	83,4333764
29	7732741,54	89,4993234
30	8275228,76	95,7781107
31	8836105,38	102,269738
32	9415371,39	108,974206
33	10013026,8	115,891514