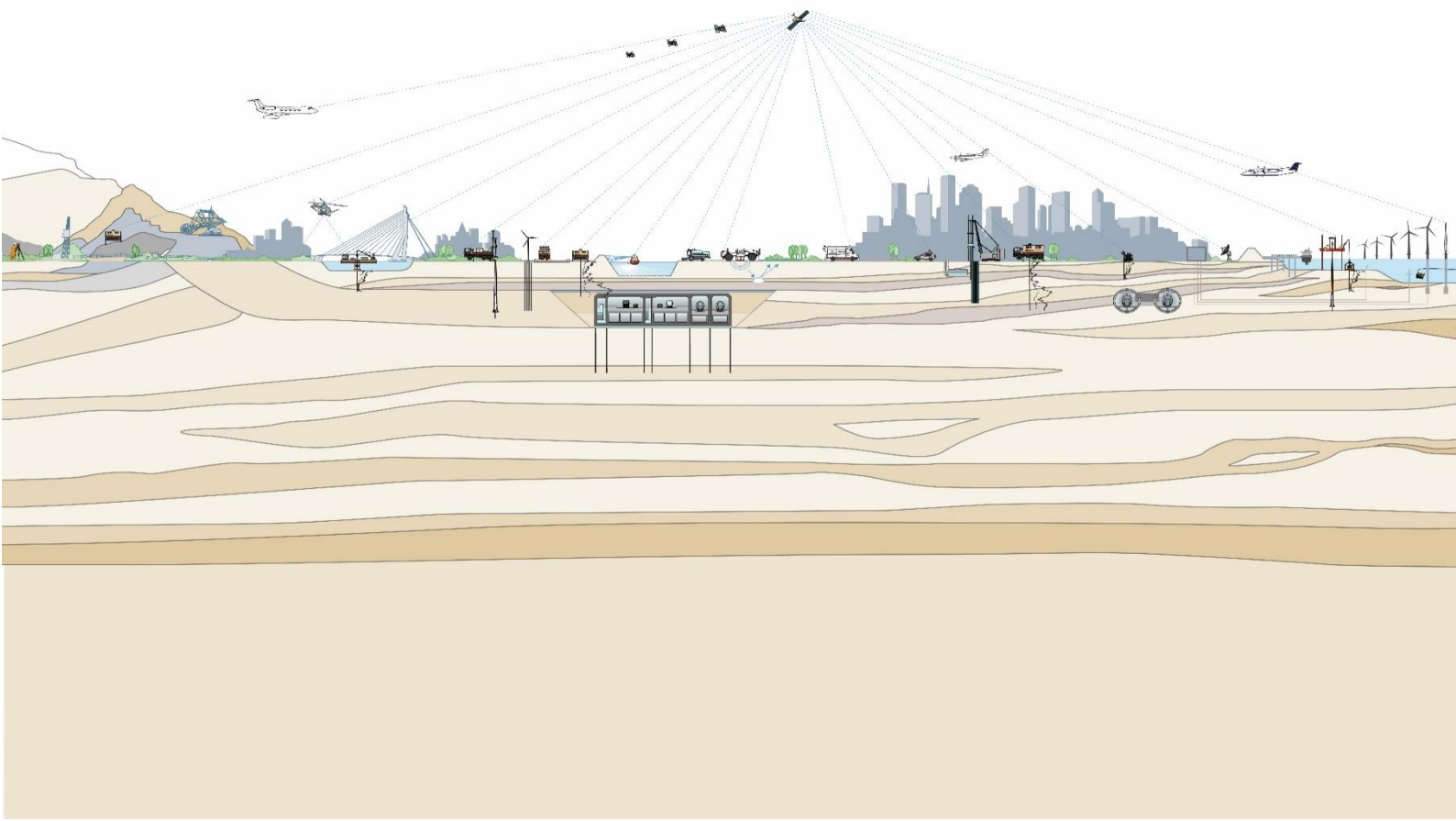


The influence of water content in clay on electrical conductivity measurements

A bachelor thesis
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Preface

The aim of this study is to look into the effect of water content in clays on the electrical conductivity as obtained from measurements of an frequency domain electromagnetic induction survey and a laboratory resistivity test. The laboratory test results are compared to theoretical conductivity models. The focus is hereby on determining the relationship between decreasing water content in clay and the electrical conductivity. The research has been performed in collaboration with the land geophysics department at Fugro.

I would like to thank Veerle Steenhuisen for giving me the opportunity to carry out this research at Fugro and Serkan Elgun for supervising my thesis on behalf of Fugro. I also want to thank Evert Slob and Dominique Ngan-Tillard for the help on academic level and supervising my thesis.

Abstract

The importance of water on the apparent conductivity of rocks and soils was empirically found by Archie in 1942 (Archie, 1942). However, when dealing with clay particles, this relation does not hold according to Waxman and Smits (1968), due to the cation exchange capacity of clay minerals. Thus not only water but also the clay influences the apparent conductivity of a soil. Four saturated remolded clay samples are collected from a pond located on the floodplain between the Waal and a dyke in the western part of the Netherlands to be tested in the laboratory on their resistivity. The samples are tested six to seven times over the timespan of ten days to see the effect drying has on the clay conductivity. All samples give an empirical linear relationship, but with different slopes. All these linear relationships can be added together to give a spectrum of conductivities characteristic specifically for this area. The size of the spectrum becomes smaller till 15.9% gravimetric water content, where the conductivity of the samples differs no more than 2.8 mS/m, from that point onward, the spectrum gets larger again with increasing water content to a size as high as 14.3 mS/m around 60% gravimetric water content. The uncertainties of this study are mainly caused by the remolding of the sample. This restructuring of the sample leads to variation in the measured resistance and has measured to go up to differences of 4.9 mS m⁻¹. The empirical relationship as tested in this experiment is only validated for the interval of 10.5% to 65.5% water content, where the conductivity covers an interval of 35.4 mS/m. This shows the significant importance of water on the clay conductivity. When comparing the lab data to four existing electrical conductivity models, it is found that these fit with an R-squared between 0.88 and 0.89, independent from the fact if the CEC is taken into account in the model. This concludes that the clay minerals have a minimal influence on the soil conductivity, opposite of water which is the main source of soil conductivity.

Table of contents

Preface.....	2
Abstract	2
1. Introduction	4
2. Materials and methods.....	5
2.1 The research area.....	6
2.2 Fieldwork.....	6
2.3 Electrical resistivity lab measurements	6
2.4 Electrical conductivity models	8
3. Results	9
3.1 Fieldwork results	9
3.2 Laboratory results.....	11
3.2.1 The clay before, during and after drying	11
3.2.2 Resistivity test results	13
3.3 Model Results.....	15
3.3.1 Model parameters and constants	15
3.3.2 Statistical fitting	16
4. Discussion	16
4.1 Electrical conductivity at high water content	16
4.2 Error analysis.....	17
4.3 Deviations in clay structure and water content.....	18
4.4 Porosity in conductivity models	18
4.5 Further research	19
5. Conclusion.....	19
6. Stakeholder assessment	20
6.1 Improvement of the model	20
6.2 Quality, Health, Safety and Environment.....	20
References	22
Appendix A: Borehole classification.....	24
Appendix B: Laboratory results	26
Appendix C: Model parameters and statistics	28

1. Introduction

The Dutch soil is suitable for shallow geophysical electromagnetic induction surveys due to its predominant sand-clay layering with, in general, sand having a relatively low conductivity and clay a relatively high conductivity. However, these values strongly depend on the presence and quality of the water. Salty groundwater in sandy soil will result in higher bulk conductivity than fresh water, while dry sand has barely any conductivity at all according to NEN 5774 (Nederlandse norm, 1990).

In general, the conductivity of soils is electrolytic and takes place through the water-filled pores and passages in the soil (McNeil, 1980). Aside from water to conduct the electricity, clay minerals have the ability, due to their structure and Cation Exchange Capacity (CEC), to let the current pass through them (McPhee et al, 2015). The CEC is caused by imperfections in the clay mineral lattice, such as vacancies, substitutions and interstices (Bergaya, 2006). McNeil (1980) states that, when neglecting organic matter and external factors such as fertilizer and conductive fences, the soil conductivity is assumed to be a function of clay and water content.

Through the course of the past 80 years, there have been many different approaches to examine the effect water has on the electrical conductivity of the soil. Archie (1942) for example created an often used empirical relationship where the formation factor F and water conductivity C_w are used to determine the bulk conductivity C_o of the soil when all pores are filled with water. Equation [1] shows this relationship and is called *Archie's law*. Archie's law is usually written in terms of resistivity, but here it has been chosen to write it in terms of conductivity. The formation factor is defined by Winsauer (1952) as a function of porosity ϕ , cementation factor m and scaling constant a as can be seen in equation [2],

$$C_o = F^{-1} \cdot C_w, \quad [1] \quad (\text{Archie, 1942})$$

$$F = a \cdot \phi^{-m}. \quad [2] \quad (\text{Winsauer, 1952})$$

The water conductivity C_w represents, amongst other things, the quality of the water, since it depends mostly on the Total Dissolved Solids (TDS) in the water (Kirsch, 2006). The quantity of the water, aside from the porosity, is not taken into account in this definition of Archie, but is generally implemented in more complex models with the aid of the saturation degree S_w .

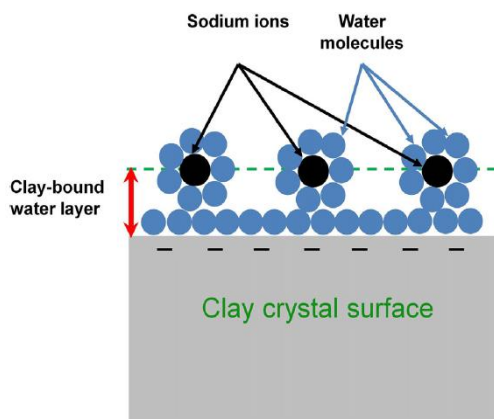


Figure 1: a schematic representation of the clay bound water layer in an ionic double layer model (McPhee, 2015).

Equations [1] and [2] however assume that the matrix is nonconductive, which is not the case with clay minerals. Ions can be transported through the Clay Bound Water structures (CBW), leading to a conductive matrix. The cation exchange capability of clay can be explained by an ionic double layer. The surface of the clay particles are negatively charged, which attracts the cations dissolved in the formation water. Again the anions in the formation water are attracted by the cations, leading to a double layer on the surface of the clay particles, the so called CBW (McPhee, 2015). A schematic drawing of the CBW is illustrated in Figure 1. Due to the fine grainsize of clay minerals, the surface area, and thus the accompanied CBW, is large compared to sand, leading to a high CEC (Budhu, 2015).

Waxman and Smits (1968) modified Archie's law by adding a component C_e which takes the conductive clay matrix into account. The extra clay conductivity component cannot simply be added to the equation [1], the formation factor also needs to be corrected for the Cation Exchange Capacity of the clay, leading to the symbol F^* . The Waxman and Smits equation is given by equation [3],

$$C_o = \frac{1}{F^*} \cdot (C_w + C_e). \quad [3] \quad (\text{Waxman \& Smits, 1968})$$

McNeil (1980) states that clay is an insulator and has thus barely any conductivity when there is no water around for the cation and anion exchange. Clay et al (2001) found that for glacial till the relationship between water content and apparent conductivity is linear. However, the tested material barely contains any clay particles. Hanson and Kaita (1997) also found a linear relationship between the two for a soil which has a clay content between 16 and 21%, showing that water with higher conductivity leads to steeper slopes in the conductivity-water content graph. Both do not show much influence of the CEC of clay on the results.

With these assumptions, the hypothesis of this study is created, which assumes that with decreasing water content, the measured conductivity should decrease as well. Furthermore, it is expected that the conductivity and water content have a linear relationship. Lastly, it is expected that the CEC of the clay does not affect the model. To test these hypotheses a case study is carried out which examines river clay with the aid of frequency domain electromagnetic surveys, resistivity lab test and conductivity modeling. The second chapter will focus on the methodology and the used equipment. In the third chapter, the results will be discussed, followed by a discussion about the results in chapter five. The conclusion and stakeholder assessment will close up the report in chapters five and six.

2. Materials and methods

The study consists of three parts, namely in-situ research, laboratory research and theoretical modelling. First, the research field is in situ examined with the aid of a frequency domain electromagnetic induction survey (FDEM). The electromagnetic induction survey is conducted with a CMD explorer from GF instruments (GF instruments, 2016). With the aid of the FDEM data, clay samples are recovered from the research area with an Edelman auger. Second, the collected clay samples are investigated further in the laboratory by measuring the conductivity with a Wenner probe system DET4TCR2 from Megger (Megger, n.d.). Third, the results retrieved from the laboratory tests will be fitted in several theoretical conductivity models. These theoretical models are generally created for petrophysical research and are thus not made for clay-layers but rather for clean and shaly sands. The CMD explorer is pictured in Figure 2 and the DET4TCR2 Megger in Figure 3.



Figure 2: The CMD explorer is made waterborne by a surfboard construction for this study



Figure 3: The Megger wenner probe consists of a resistance meter, four electrodes and an EC box

2.1 The research area

A suitable research area for this research should contain a thick clay layer with high water content. The thickness of the layer is important since enough clay material is needed for the lab measurements later on. A high water content is preferable, so the effect of water on the clay conductivity can be examined with natural in-situ water, instead of adding artificial water. For these reasons, the research area is chosen to be a pond, indicating the soil below is well saturated. The pond is located on the floodplain between the river Waal and a dyke in the western part of the Netherlands and has an area of approximately 10.857 m² (33x329 m). Since the research area is a pond located at the toe of dyke, it is expected that the clay layer is thick. The electromagnetic induction survey together with the borehole data will give an indication of how thick the clay layer is exactly.

2.2 Fieldwork

The CMD explorer from GF instruments uses multiple-intercoil distances to measure the bulk apparent conductivity over several depth intervals. The three transmitter coils are all located at different constant distances from the receiver coil. With the aid of a CMD inversion program, it is possible to determine the bulk apparent conductivity over the depths 0.00 m – 2.20 m, 0.00 m – 4.20 m and 0.00 m – 6.70 m below the surface of the pond when set in vertical mode. It is assumed that the water column is not measured as the CMD explorer is set on a factory calibration to neglect the first meter of the measurement. With the aid of these three datapoints, a two layered model can be made. The instrument measures at a constant unchangeable frequency (GF instruments, 2016).

Afterwards, the bulk apparent conductivities are visualized with ArcGIS to determine the most suitable hand drill locations. The hand drill locations are selected in such way that the whole spectrum of measured bulk conductivities is covered. That way, the calibration for the electromagnetic induction survey, the laboratory tests and the theoretical modeling should be suitable for the whole research area.

The hand drills are performed with the aid of an Edelman auger on a boat. The borehole has a depth of 5.00 m starting from the boat. Unlike the electromagnetic induction survey, the water column is included in the depth range. The samples are collected in plastic bags to preserve the water in the samples. Generally, each plastic bag contains one meter of soil.

2.3 Electrical resistivity lab measurements

First, all collected samples are classified according to NEN 5104 (Nederlandse norm, 1989). This way it can be determined which of the samples are clay and thus usable for this study. The clay samples originating from the same clay layer and recovered from the same borehole shall be mixed to create a large enough test volume. It is assumed that the clay samples are saturated and thus no water will be added to the clay paste.

The clay samples collected from the area are tested on their conductivity with a Wenner probe system with four electrodes. The voltage of the probe is set on 50 V with a test frequency of 128 Hz. The four electrode pins are located at a constant equal distance of 29.2 mm at a depth of 45 mm. Since the samples are remolded and to make sure the same volume of clay is measured with each test, the sample is placed in an EC box with dimensions 140x70x70 mm (L x W x D). The EC box consists of a non-conductive plastic material. The lid, made of the same non-conductive material, has 4 holes to put the electrodes through to make sure they are always placed at an equal distance of 29.2 mm. The experiment set-up is shown in Figure 4 below, but instead of field measurements, the test was performed on a small scale in the laboratory. After the tests, the samples are laid down to air dry under an extractor hood.

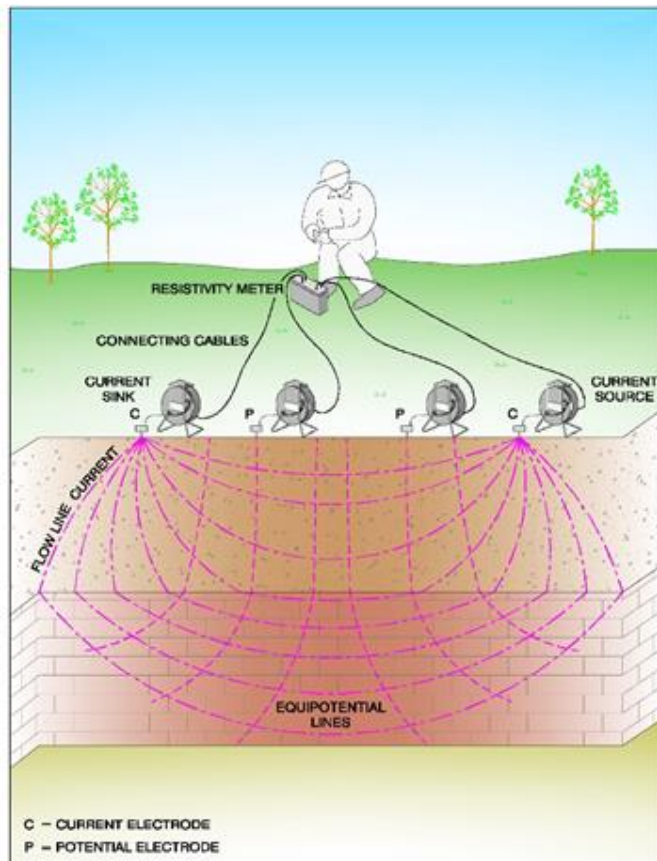


Figure 4: The Wenner probe electrical resistivity test (Fugro, 2020).

The Wenner probe only measures the resistance in Ω the electrical current experiences as it passes through the sample. To calculate the conductivity of the sample, equation [4] is used. The equation depends on the probe spacing in cm (a), the probe depth in cm (b), the temperature of the sample in $^{\circ}\text{C}$ (T) and the determined resistance in Ω (R). The specific conductivity at 20 $^{\circ}\text{C}$ (σ_{20}) is used to minimize the influence of temperature differences between tests and samples,

$$\sigma_{20} = \frac{40\,000 \cdot \left(1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}\right)}{(20+T)4\pi a R}. \quad [4]$$

To determine the water content of the clay for each test, a small fragment of the sample is weighted, dried in the oven for 16 hours at 110 $^{\circ}\text{C}$ and then reweighted according to NEN-EN-ISO 17892-1 (Nederlandse Norm, 2014). This standard assumes the difference between wet weight and dry weight of the sample is equal to the evaporated free water in the specimen.

With the aid of both the wet weight M_{wet} and dry weight M_{dry} , the gravimetric water content w can be determined by using equation [5]. It is assumed that the fragment is a good representation of the sample as a whole and has the same water content,

$$w = \frac{M_{water}}{M_{solid}} = \frac{M_{wet} - M_{dry}}{M_{dry}}. \quad [5]$$

Das (2016) states that a fragment of 20 g is enough to determine the gravimetric water content for a sample with a maximum grainsize of 0.425 mm. When taking the possibility into account that the sample could contain sand particles, a fragment of 50 g should be used. During the laboratory testing it will be determined how large the fragment will be, based on how much can be missed to continue testing, but it will be at least more than 20 g and it is aimed to be even over 50 g.

The volumetric water content θ can also be calculated with equation [6], however this equation is based on more assumptions than equation [5] and is thus more likely to contain errors. Aside from assuming the fraction has the same water content as the whole sample like assumed for equation [5], it is also assumed the box is well filled with no air bubbles and an assumption of the water density needs to be made,

$$\theta = \frac{V_{water}}{V_{solid}} = \frac{M_{water}/\rho_{water}}{V_{box} - \frac{M_{water}}{\rho_{water}}} = \frac{\frac{M_{wet} - M_{dry}}{\rho_{water}}}{V_{box} - \frac{M_{wet} - M_{dry}}{\rho_{water}}}. \quad [6]$$

The water density varies depending on the temperature and the salinity of the water (ILRI, 1972). Therefore, the volumetric water content is ignored and the gravimetric water content is used to keep possible errors as small as possible. Furthermore, it has been decided not to calculate the particle density and the porosity, since it is unknown what fraction of the sample is occupied by air.

2.4 Electrical conductivity models

Lastly, the laboratory data will be compared to theoretical conductivity models, which mostly originate from petrophysical research and empirical relationships. First, the water conductivity needs to be determined at 20 °C, so it is on the same line as the measured laboratory conductivities. Equation [7] is used to calculate the water conductivity $C_{w,20}$ at 20 °C. Here, $C_{w,25}$ is the conductivity as measured at 25°C, T is the temperature to which it needs to be converted and a is constant equal to 0.0191 according to Clesceri et al. (1998),

$$C_{w,20} = C_{w,25}[1 + a(T - 25)]. \quad [7] \quad (\text{Hayashi, 2004})$$

Up till today, no universal method has been found which accurately and effectively models the bulk conductivity (Cai et al, 2017). Most models use similar elements, whereas the most important ones are porosity ϕ , cementation factor m , scaling factor a , water conductivity C_w and saturation degree S_w .

The models used in this study are portrayed in equations [8] till [11]. Archie's equation [8] does not take the conducting ability of clay into account unlike the other three models. The other models use parameters as B , Q_v and the soil conductivity C_s . Since only a few parameters of the soil have been determined during the laboratory tests, the other parameters must be calculated or estimated.

$$C_o = \frac{\phi^m}{a} C_w S_w^n, \quad [8] \quad (\text{Archie, 1942})$$

$$C_o = S_w^n \cdot \phi^m \left(C_w + \frac{B Q_v}{S_w^n} \right), \quad [9] \quad (\text{Waxman and Smits, 1968})$$

$$C_o = \frac{1}{a} \cdot C_w \cdot S_w^n \cdot \phi^m + C_s, \quad [10] \quad (\text{Frohlich and Parke, 1989})$$

$$C_o = \frac{\phi^m}{a} \cdot \left[S_w^n C_w + \left(\frac{a}{\phi^m} - 1 \right) \cdot C_s \right]. \quad [11] \quad (\text{Linde et al., 2006})$$

The laboratory tests relates gravimetric water content with electrical conductivity. In theoretical models however, the saturation degree S_w is generally chosen to relate to the conductivity not the water content. In this study, it is also chosen to work with the saturation degree for the theoretical models only. The saturation degree can be calculated with the volume of the water, the porosity and the total volume,

$$S_w = \frac{V_{water}}{\phi \cdot V_{total}}. \quad [12]$$

The water volume will be calculated using a constant estimated water density of 1 g/cm³. Furthermore, it will be assumed that the EC-box is completely filled and the volume of the box is equal to the total volume of the sample. The porosity of the test samples are determined with the aid of equation [13]. For this equation, the matrix volume is calculated with the dry weight M_{dry} and the grain density ρ_g , which is assumed to be 2.65 g cm⁻³,

$$\phi = \frac{V_{total} - V_{matrix}}{V_{total}} = \frac{V_{total} - \left(\frac{M_{dry}}{\rho_g}\right)}{V_{total}}. \quad [13]$$

Both m and n can be calculated using the logarithmic relation between bulk conductivity with porosity and saturation degree respectively. These relations are shown in equation [14] and [15],

$$\log(C_o) \sim m \cdot \log(\phi), \quad [14]$$

$$\log(C_o) \sim n \cdot \log(S_w). \quad [15]$$

The other parameters B and Q_v can be calculated with equations [16] and [17] (McPhee et al., 2015). Both temperature T and water resistivity R_w are known to calculate B . For calculating Q_v , the cation exchange capacity CEC is unknown and has to be estimated. The grain density ρ_g is again assumed to be 2.65 g cm⁻³. Lastly, the soil conductivity C_s cannot be calculated either and has to be estimated.

$$B = \frac{-1.28 + 0.225T - 0.0004059T^2}{1 + R_w^{1.23} \cdot (0.045T - 0.27)}, \quad [16]$$

$$Q_v = \frac{CEC(1-\phi)\rho_g}{100\phi}. \quad [17]$$

3. Results

After the tests both in the field as well as in the lab are performed, the data is processed in the office. The field data is mainly processed by ArcGIS to interpret and visualize the lithology. The lab data on the other hand is processed by excel to visualize relationships. Lastly, the modelling is done in MATLAB.

3.1 Fieldwork results

An electromagnetic induction survey on the water was performed during a dry period in November 2019. The pond water level generally varied between 0.50m and 1.00m. Figure 5 shows the bulk apparent conductivity over three depth intervals by the CMD explorer. The apparent conductivity between 0.00 m and 6.70 m below surface, presented on the right side of the figure shows a homogeneous soil content over the lateral extent of the research area with values varying between 32 mS/m and 49 mS/m. However, the shallow apparent conductivity, 0.00 m to 2.20 m below surface, shows a lot more variation. These variations could be caused by several factors, one of them is that the top soil layer is not as homogeneous as the layers below, for example due to the presence of a sludge layer at some locations. Another option is that the water has still had influence on the measurements.

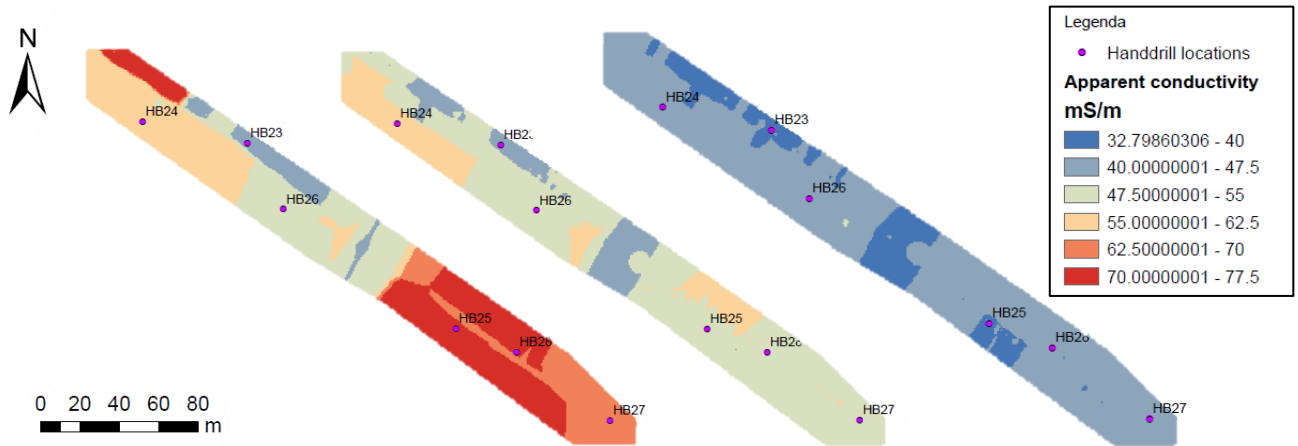


Figure 5: The apparent conductivity of the research area over a depth of 0.00 m-2.20 m (left), 0.00 m-4.20 m (middle) and 0.00 m-6.70 m (right)

To calibrate the EM data, six hand drills were performed with the aid of the Edelman auger. The soil is classified according to NEN 5104 and shows a homogeneous clay layer of at least 2m thick with only minimal variation in organic matter. In general, the soil of each borehole is classified as slightly silty and slightly humus. The hand drill only dug up till a depth of 2.65m below the bottom of the pond, it was impossible to collect samples any deeper due to the high-water level and the high water content of the clay. The classification of borehole HB23 can be seen in figure 6. The other borehole classifications can be found in Appendix A.

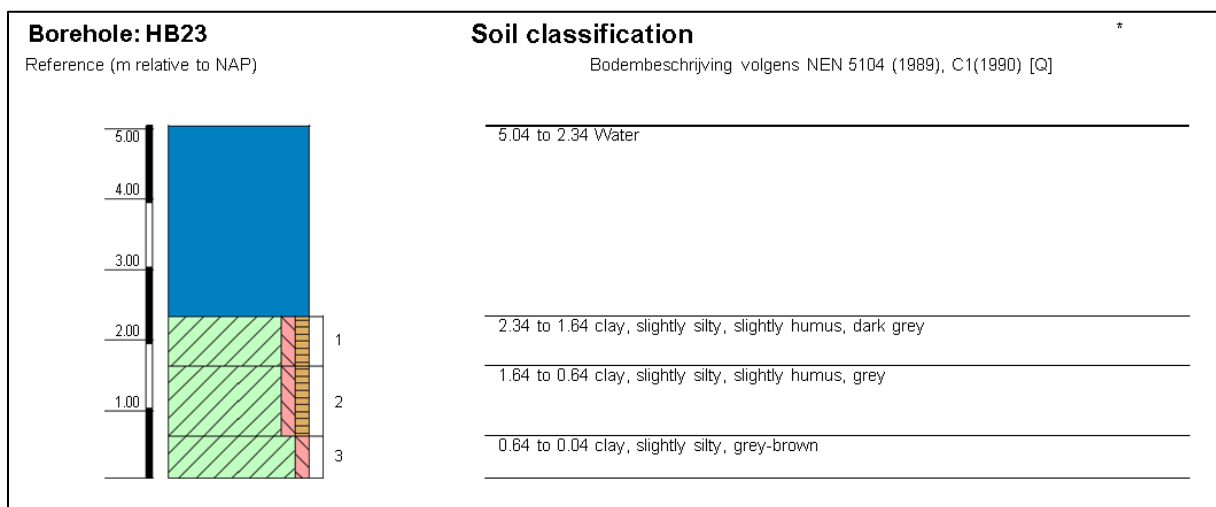


Figure 6: Soil classification of borehole HB23.

It should be noted that the water column at the times the boreholes were performed was much larger than at the time the EM data was collected. The exact difference is unknown, but it is estimated to be around 2m. The soil classification indicates no lateral variation in the soil, just as the apparent conductivity over a depth of 0.00 m-4.20 m and 0.00 m-6.70 m below surface shows. The high variations in the apparent conductivity from 0.00 m-2.20 m below surface cannot be explained with this soil classification, however sludge layers are not sampled for the soil classification and could thus be the reason for these variations.

With the aid of the borehole classifications and the EM data, the lithology of the area can be mapped. Figure 7 shows the interpretation based on a minimum clay thickness, assuming the clay layer ends at the end of the borehole. Since it is uncertain that the bottom of the clay layer matches the bottom of the borehole, it is possible that the clay layer is even thicker. Also, this two-layered model assumes the area consists only of clay and sand. The water column as measured during the electromagnetic survey is used for the cross section. Since the water column was not measured near HB27, this part in the cross section has been left blank.

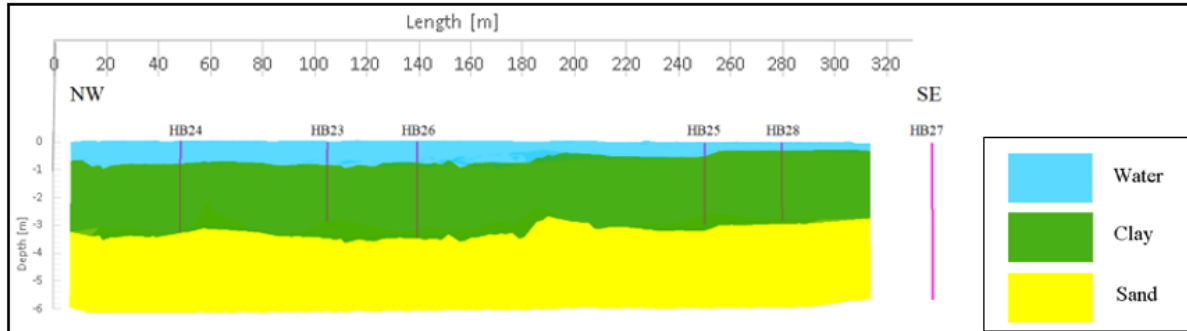


Figure 7: Two layered cross section based on the minimum known thickness of the clay layer.

Furthermore, the electrical conductivity of the water was measured with a CTD diver around the same time as the soil samples were taken. It is possible the rainfall has decreased the water conductivity, by increasing the water volume while the ion concentration remained mostly constant. The surface water was measured to have a conductivity of 38 mS m^{-1} with an accuracy of 2 mS m^{-1} at $11 \text{ }^\circ\text{C}$ and a conductivity of 52 mS m^{-1} with an accuracy of 1 mS m^{-1} at a temperature of $25 \text{ }^\circ\text{C}$. It should be noted that it is not possible to compare the water conductivity directly with the bulk conductivity, as there is a temperature difference between both measurements.

3.2 Laboratory results

Before the resistivity test results can be discussed. It is first important to look at the characteristics of the clay, since these characteristics can help to explain the results of the resistivity test. The clay will be examined and characterized before, during and after drying for ten days. For the laboratory tests, only the samples HB23, HB24, HB25, HB26 and HB27 are used. HB28 is not used for these tests and serves as a back-up sample. Furthermore, the samples are not tested every day, but only on days one, three, six, eight, nine and ten.

3.2.1 The clay before, during and after drying

All collected samples are transported in plastic bag so the original water content is maintained as much as possible. Due to the high water content of the samples, the samples behave like a viscous fluid rather than a solid. The Atterberg limits can be used to determine the phase transition of soils based on the water content of samples (Atterberg, 1911). Although the Atterberg limits, consisting of the shrinkage, plastic and liquid limit, are not determined for the samples, it is assumed from this observation that the samples are all above the liquid limit on day one. This assumption and the following assumptions about the soil states are based on Budhu (2010).

Two days later, the next sequence of resistivity tests are performed. The soil samples have dried to become harder, but they are still easy deformable without any cracks occurring. The plastic behavior also continues on at the tests which are performed on day six. At day eight, the plasticity limit seems

to be reached as cracks start to form when molding the sample. At the end of the ten days drying period, it cannot be determined without further testing if the shrinkage limit has been reached. It is still possible to scratch the sample with a fingernail. A picture of the samples on day one, three and eight are portrayed in Figure 8.

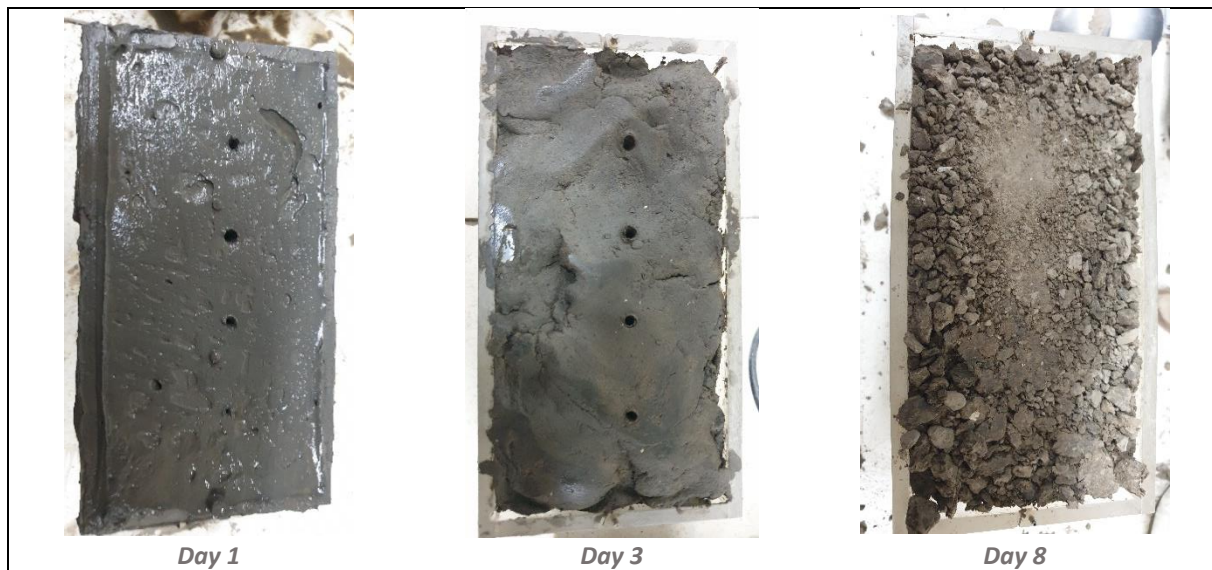


Figure 8: The remolded clay sample in the EC box on day one, three and eight.

The gravimetric water content is plotted against the drying time in Figure 9. For this graph, not all datapoints are used, since sometimes a sample got mixed with a wetter sample to ensure enough test volume. Assuming the observation about the liquid limit and plastic limit are right, this would indicate according to the graph that the liquid limit is between 65.6% and 89.8% and the plastic limit is between the 20.1% and 28.4%. Both these assumptions are supported by literature (Budhu, 2015). From Figure 9, it can be noted that the decrease in water content went faster in the first few days than the last few days, leading to a flattening of the curve near the end of the drying period. The median trendline is plotted to visualize the trend.

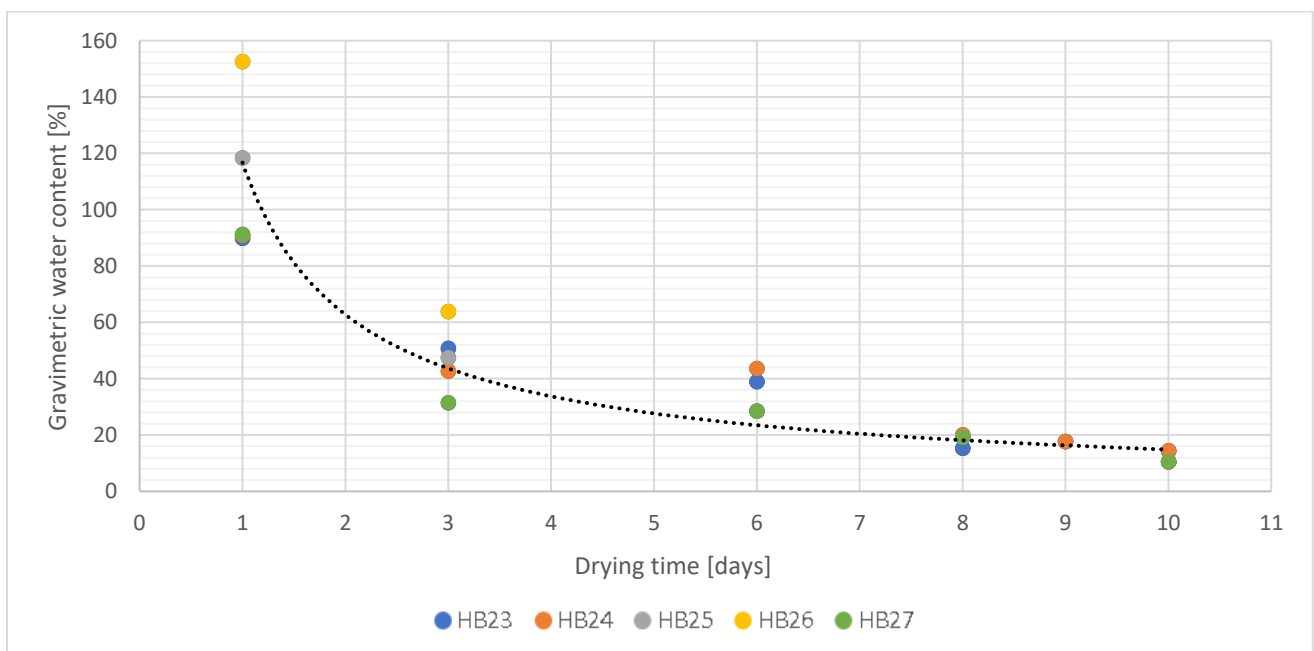


Figure 9: The drying curve of the clay samples over the timespan of 10 days.

3.2.2 Resistivity test results

A total of 22 resistivity tests are performed over a time span of ten days. All test results are plotted in Figure 10, where the different colours each stand for an individual sample. However there are six cases where some samples got mixed as the original sample did not have enough material to continue working with. Two of these six mixed tests consist of a combination between HB23 and HB24 and the other four are a combination of HB25 and HB27. The mixed tests are illustrated with the two colours of the original samples. An overview of the results of the tests are furthermore given in table B1 of appendix B.

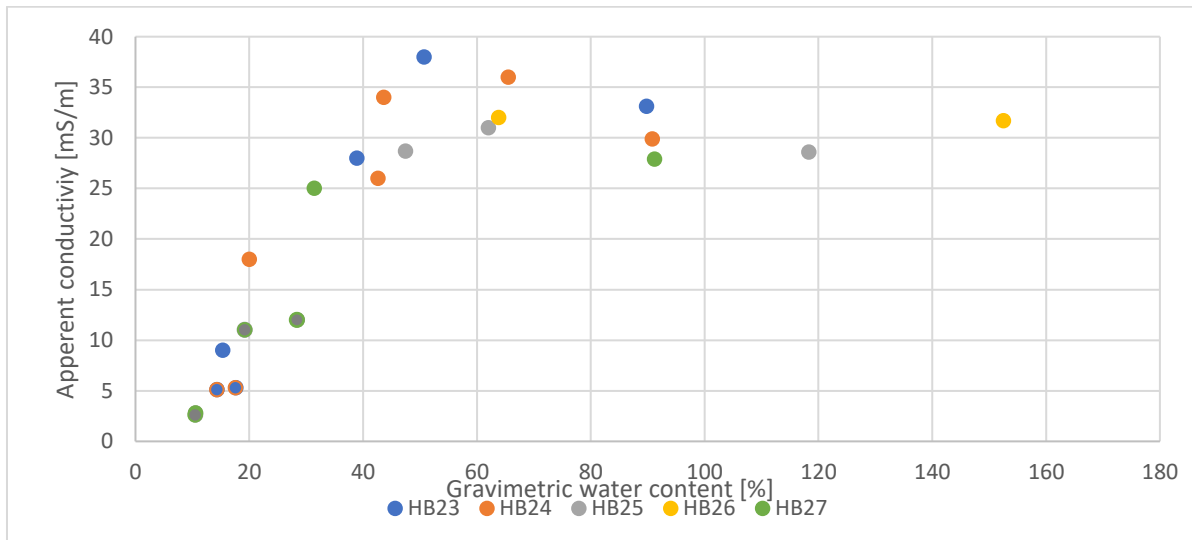


Figure 10: The apparent conductivity of the lab samples with respect to the water content.

In general, six to seven tests are performed on each sample, these numbers include the mixed sample tests. Only sample HB26 has been tested twice, since this sample was too small. The results of sample HB26 will not be discussed any further; with only two tests it is not possible to define a reliable conclusion.

Figure 10 shows an overview of all test results. To examine the results of each test in more detail, Figure 11 is created to show the results of HB23, HB24, HB25 and HB27 each in a separate graph. The graphs in Figure 11 all have the same scale to make it easy to analyze and compare them. Although the values vary amongst the samples, the outline of the graphs is identical. All samples have one outlier with a high gravimetric water content but not a significantly high conductivity while the other test results are more or less on the same line.

The data of these outliers in table B1 show that all of these tests have been performed on the first day of the laboratory tests, making it more likely there was a structural error rather than a coincidental error. Since the outliers have all been tested on the same day, it could be the case that there was something wrong with the equipment. However, it has also been stated that these samples are assumed to be above the liquid limit, indicating possible difficulties and inaccuracies during the measurements.

The aberrant results will be left out from now on as they are deemed unreliable, leaving the test results between 10.5% and 65.5% gravimetric water content to work with. The remaining test results can be fitted well around a linear line with a R-squared between 0.832 for HB27 and 0.981 for HB23. The linear relationship of each sample does however not have the same slope. HB23 has a significantly steeper slope than HB25.

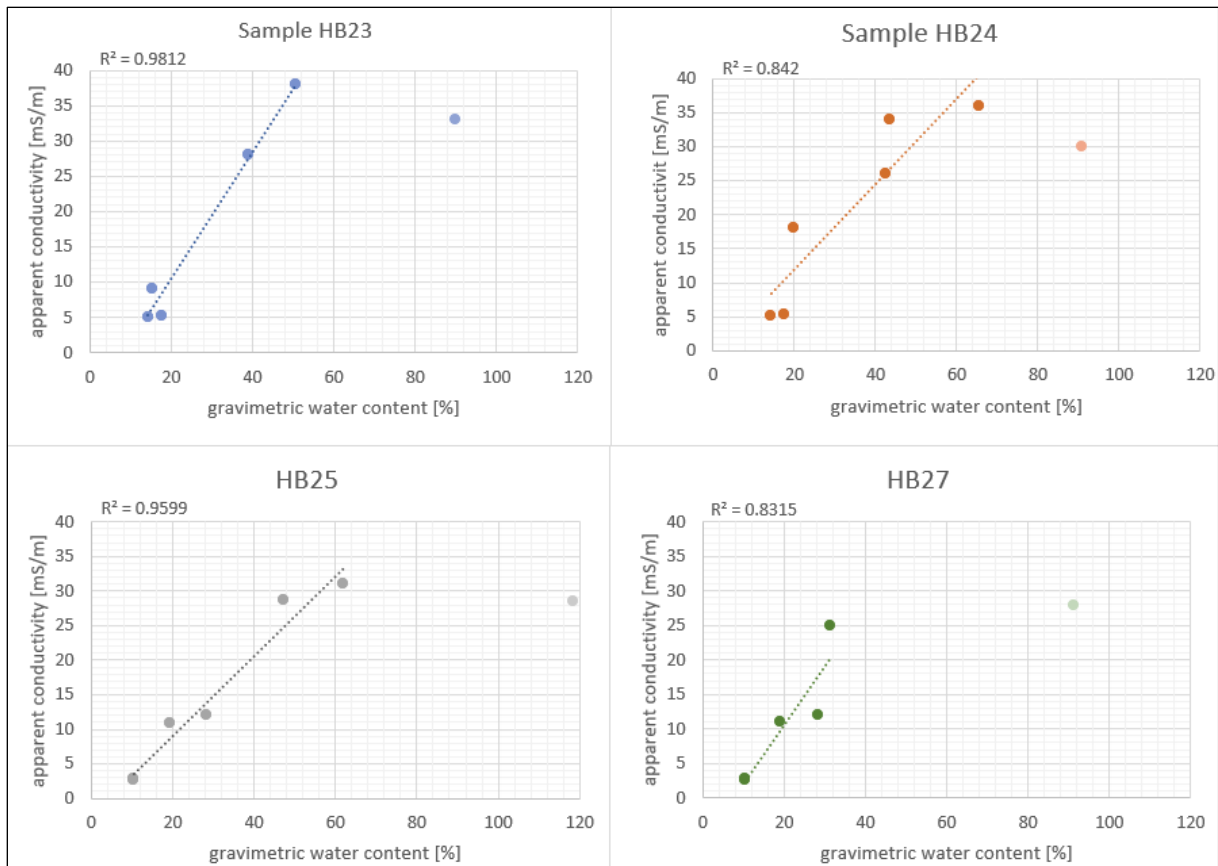


Figure 11: The results of HB23, HB24, HB25 and HB27 each in a separate graph. The linear relation between the test result of each sample is plotted in a dotted line. The R-squared is given to represent the fit of the linear line.

All four linear relations can be plotted into one graph. This graph, portrayed in Figure 12, gives the range of relationships the gravimetric water content has on the different clay samples. An average estimation is added, which is created with the test results of all samples minus the outliers and HB26 are used. The HB23 line and the HB25 line show, for the most part, the upper and lower boundary. The relationships used in Figure 12, which include the individual as well as an average relationships, are written down in equation [18] to [22],

$$C_{HB23} = 0.9027 \cdot w - 7.6167 \quad [18]$$

$$C_{HB24} = 0.6229 \cdot w - 0.4038 \quad [19]$$

$$C_{HB25} = 0.5791 \cdot w - 2.4976 \quad [20]$$

$$C_{HB27} = 0.8534 \cdot w - 6.3875 \quad [21]$$

$$C_{avg} = 0.6740 \cdot w - 2.9762 \quad [22]$$

At 15.9% gravimetric water content, the conductivity spectrum is smallest with a variance between the upper and lower bound of 2.79 mS m^{-1} . With an increase of 40% in the water content, the conductivity increases on average with 27 mS m^{-1} and maximal 35 mS m^{-1} , showing the large influence the water content has on the conductivity. The standard deviation of the tested samples and their matching linear relationships are maximum 2.40 mS m^{-1} . When comparing the test results with the average line within the tested range, the maximum standard deviation is 2.59 mS m^{-1} .

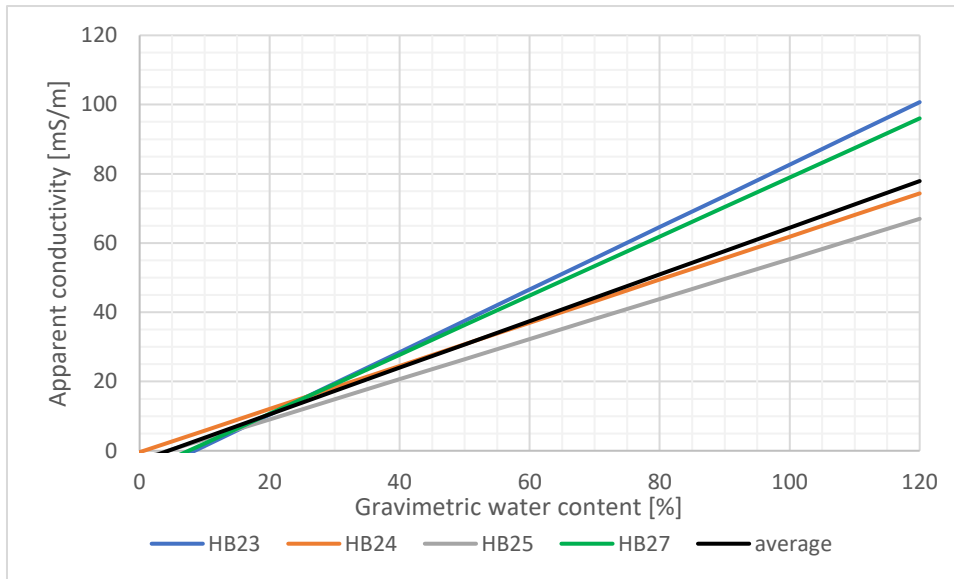


Figure 12: The linear relationship between water content and clay conductivity.

3.3 Model Results

McWhorter and Sunada (1977) found that clays generally have a porosity between 0.35 and 0.58. For this study, the porosity for this clay was determined with the aid of equation [13]. This showed that the porosity varies amongst the tests between 0.46 and 0.66. It has been chosen to enlarge this spectrum by using values of namely 0.4, 0.5, 0.6 and 0.7. The 0.4 and 0.7 are chosen to serve as upper and lower boundaries.

For each porosity value, the constants m and n will first be determined with the aid of equations [8], [14] and [15]. The values for m and n found with Archie's formula will be used for all models. This means that for Waxman and Smits' model, the formation factor will not be corrected for the conducting matrix, which is generally accepted (Greve et al., 2013).

3.3.1 Model parameters and constants

To simplify the models, it is assumed that scaling constant a is equal to 1.0 (Cai et al., 2017). This way it is easier to determine both cementation factor m and saturation degree exponent n . When calculating the saturation degree exponent n , 50%, 60% and 70% all give the same value of 1.73, while 40% has only a value of 1.71. For 50% to 70%, the mean value of 1.73 is used, while 40% porosity uses its own value of 1.71.

With the calculation of m , it can immediately be noted that the porosity of 70% is indeed too high of an estimate, since m has a meaningless negative value of -0.0613 . The 70% porosity model will not be continued. m has a value of 1.00, 0.809 and 0.480 at a porosity of 40%, 50% and 60%, respectively. These values of m lead to formation factors of 2.51 for 40%, 1.75 for 50% and 1.28 for 60% porosity, which is within the bounds as defined by NEN 5774 (Nederlandse Norm, 1990).

Aside from Archie's model, the other models all take the conducting matrix into account, either in the form of cation exchange capacity CEC or surface conductivity C_s . A code is written to determine at which value of CEC and C_s the R-squared is highest. The CEC of Waxman and Smits is calculated to be 3.50 and 3.84 for a porosity of 50% and 60%. Forhlich and Parke (1989) and Linde et al. (2006) both use the soil conductivity in their model. Both have different values for C_s . Forhlich and Parke shows that the clay conductivity is 0.161 mS/m for both porosity values of 50% and 60% whereas

Linde et al. finds values of 0.375 and 0.742 mS/m. For the 40% porosity case, both the CEC and C_s return values of 0.00. An overview of the calculated and estimated parameters is given in Table C1 in appendix C.

3.3.2 Statistical fitting

For Archie's model, all variables are calculated and thus lead to the best possible fit. The other models are expected to improve Archie's model. Figure 13 shows that this is true in the case of a porosity of 50% and 60%, but does not apply on the model with the 40% porosity. Even when more significant numbers are added, the R-squared for the 40% porosity model remains constant at 0.885.

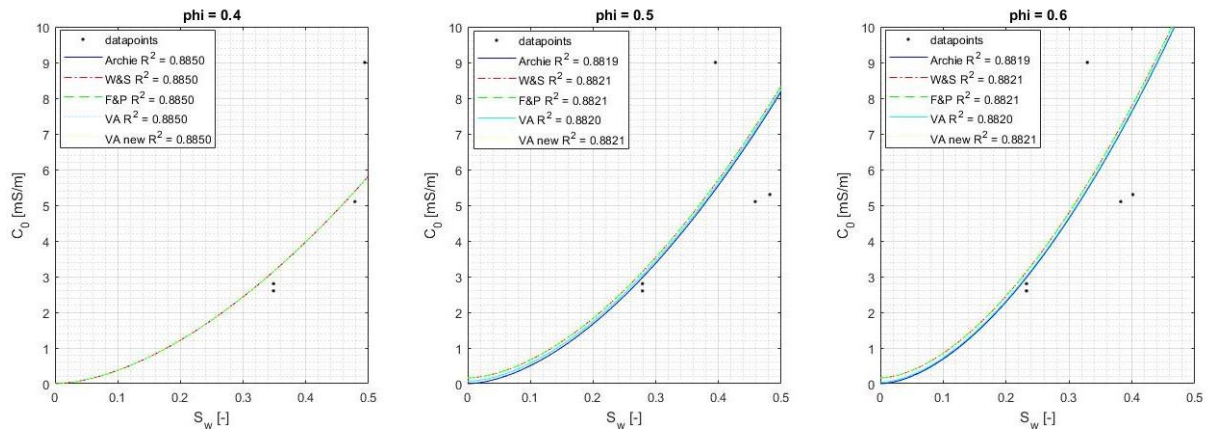


Figure 13: All four models are portrayed with the calculated or estimated values. Linde et al. is plotted two times; the original model uses the C_s value from Frohlich & Parke and the new model uses the re-calculated value for C_s .

For a porosity of 50% and 60%, the R-squared for all models are rounded off to 0.882, indicating there is only a small difference between the four models. Archie has the least fit of the four models, which was expected as it doesn't take the clay conductivity into account. However the difference with the best fitting model is only small. When the porosity is 50%, the Frohlich and Parke model has the best fit, the Waxman and Smits on the other hand gives the best fit on a porosity of 60%. In both cases, the difference in R-squared with Archie is no more than $1.72 \cdot 10^{-4}$. The calculated R-squared can be found in Table C2 of Appendix C

4. Discussion

The laboratory tests show an evidential linear relationship between the clay conductivity and the gravimetric water content. Clay et al (2001) and Hanson & Kaita (1997) have found a similar linear relationship for soils with low clay contents. It can be concluded from this research that the presence and amount of clay doesn't change the fact that the relationship between water content and soil conductivity is linear. Moreover, from the theoretical modelling, it can be observed that the clay conductivity barely effects the models at all.

4.1 Electrical conductivity at high water content

A total of five tests out of 22 tests show significantly different results. These tests were performed with samples which are assumed to be above the liquid limit on the first day of measurements. The liquid limit is there for estimated to be somewhere between 65.6% and 89.8%. A smaller interval was not determined as there have been no tests in between this range.

According to Bai et al (2013) at a certain level of high water content, the electrical conductivity remains constant. This conclusion is based on lateritic soil and it is not stated if this high water content relates to the liquid limit of the material. However, when looking at the graphs in Figure 10, this theory could make a valid fit as the tests on days one and three both show similar conductivity values. This can best be seen at samples HB25, HB26 and HB27. To make sure this theory is valid, it is recommendable to do more tests in the high water content region.

From this study, the linear relationship is only validated for a water content between 10.5% and 65.5%. For values outside this range, more testing needs to be done to check if the linear relationship remains valid.

4.2 Error analysis

The laboratory tests are subject to several different errors, both in the equipment as well as human errors. Table B1 in appendix B shows the uncertainty in the conductivity. These uncertainties are calculated with equation [23],

$$\delta\sigma = \sqrt{(\delta\sigma_{r_{avg}})^2 + (\delta\sigma_{T=20.5})^2 + (\delta\sigma_{T=21.5})^2} . \quad [23]$$

For equation [23], it is assumed that the error in the conductivity calculations only depends on the difference between the measured resistance $\delta\sigma_{r_{avg}}$ and the great inaccuracy the thermostat has, $\delta\sigma_{T=20.5}$ and $\delta\sigma_{T=21.5}$. Both the electrode spacing of 29.2 mm and depth of 45 mm are kept constant and it is assumed that no deviations have occurred here. From table B1, it can be concluded that the error is generally of order 10^{-1} with some exceptions. These exceptions are mostly caused by the difference in order of the conductivity. The relative error is calculated with equation [24] to make it easier to compare the reliability of the tests and is displayed in a separate column in table B1,

$$\frac{\delta\sigma}{\sigma} = \sqrt{\left(\frac{\delta\sigma_{avg}}{\sigma_{avg}}\right)^2 + \left(\frac{\delta\sigma_{T=20.5}}{\sigma_{T=20.5}}\right)^2 + \left(\frac{\delta\sigma_{T=21.5}}{\sigma_{T=21.5}}\right)^2} . \quad [24]$$

The relative error varies between $2.45 \cdot 10^{-2}$ and $8.52 \cdot 10^{-2}$. Both the maximum and minimum relative error are of the same order, indicating none of the tests is more unreliable than the other. The largest uncertainty is caused by the thermostat, since the thermostat only gives rounded values, leading to an uncertainty of 1 °C. Replacing this equipment with a more accurate thermostat can increase the accuracy significantly.

The uncertainty in the gravimetric water content is difficult to determine. The rounding error of the used scales definitely plays a role. Two scales are used in this experiment. One scale has an error of 0.05g and is used to weight the sample used for the resistivity test, which is generally around 1000g. The second scale has a rounding error of 0.0005 and is used to weight the fraction of the sample to determine the water content, which is generally around 30g. These errors are rather small compared to the uncertainties caused by inhomogeneous water distribution in the clay.

Since this study is performed with clay, the small fraction taken from the sample to determine the water content should have a minimal weight of 20g to get reliable information, assuming the material consist only of clay. The fractions used in this research are generally around the 30g, which satisfies if it is assumed the soil only consists of clay and is not mixed with sand. In case this sample includes some sand, the sample should have been at least 50g, this could cause an uncertainty (Das, 2016).

4.3 Deviations in clay structure and water content

Some more tests are performed with the unused sample HB28 to look into the water distribution, sample structure and its deviations on the conductivity by performing the resistivity test several times at the same water content. Before each test, the sample gets remolded, this way it is possible to see the effect of restructuring the clay on the conductivity. Furthermore, the whole sample is divided into six smaller fractions to determine the water content of the sample. It should be noted that this test is only performed on a sample with high water content, the deviations caused by structure and inhomogeneous water content are not determined for a sample with low water content.

Both the weight and the measured conductivity show that the six tests with the same sample at supposed constant water content are different. The conductivity varies between 44.5 and 49.4 mS m⁻¹. Assuming the probe spacing and depth, the temperature and water content remains the same over the six tests, the deviation of 4.9 mS m⁻¹ is caused by remolding the sample and compacting it differently.

The weight of the sample varies by 76.8 g. From this it can be concluded that not the same force is applied to put the sample in the EC-box, which has influences on the structure of the clay too. It is not possible to determine a correlation between the weight of the sample and the conductivity. The large conductivity variance shows however that remolding the sample creates a much larger uncertainty than caused by the temperature and measurement uncertainty as discussed in paragraph 4.2.

The fractions used to determine the water content are around 200g to ensure reliability. Table B2 in Appendix B shows that the water content of the fractions varies with 7%. Four out of the six water content measurements result in a water content between 93.5% and 93.8%, leading to an estimated water content of 93.65% where the two outliers are neglected. For the smaller fractions of 30g used in this study, the chance that the measured water content is not representable for the complete sample is statistically higher than for the 200g fractions. To determine the size of this uncertainty, several samples of 30g should be tested to determine the variation.

4.4 Porosity in conductivity models

All four theories fit with at least an R-squared of 0.88 for all three tested porosities. The clear difference between 40% porosity and 50% & 60% can however not go unnoticed. Not only has the 40% porosity model a constant R-squared for all individual models, it also states that the soil conductivity and CEC are equal to zero.

The study immediately eliminated the possibility that the clay would have a 70% porosity since the m turned out to be negative. From the fact that both the CEC and C_s are zero for the 40% porosity model indicates that 40% porosity is an unrealistic low estimate. It is however interesting to see that the lower bound and upper bound respond differently. The maximum porosity for these models and samples have not been determined, but will most likely be marked by the tipping point of m going from positive to negative. The minimum porosity can be found by looking at the CEC and C_s . Both are expected to be around the 0.46 and 0.66 respectively.

In the end, the graph indicates that there is no difference between the 50% and 60% model, meaning it does not matter which porosity within this interval is chosen, as all of them will result in an accurate model.

4.5 Further research

The deviations which occur due to remolding the sample can lead to more significant uncertainties than the uncertainties occurring due to equipment and rounding errors. To keep the original structure intact and use this same structure for the whole of the laboratory measurements, it is recommended to start with an undisturbed sample, or, if that is not possible, to keep the sample in the EC-box over the complete length of the experiment. In both cases, the electrodes are supposed to remain in the sample to prevent air from coming between the electrode and the sample.

If the remolding technique is however the only option as it was in this study, it would be recommendable to perform the same test several times while remolding the sample in between the tests. This way a spectrum of values can be achieved which can serve as error bars. The time it takes to measure a remolded sample is however long and it is more challenging to test samples with considerably high and low water content.

Furthermore, to determine the water content of the sample during the test, it is important to use larger fractions or even multiple large fractions. That way, the uncertainty of the water content can be plotted with error bars too. To make this work however, it is important that a large amount of material is collected to have enough material.

To determine why the relationship between water content and clay conductivity varies among the samples, it could be interesting to look at other properties of the samples, for example on the microscopic scale, and see where they are different. The borehole classification in appendix A shows a generally homogeneous clay layer on the macro scale. The resistivity laboratory measurements however show that the samples are different. Determining the liquid limit could furthermore help to determine if the samples were indeed above the liquid limit on the first day. This way the behavior of the conductivity can better be explained at high water content.

Lastly, determining the CEC in the laboratory can help to improve the electrical conductivity models. With the CEC of the sample, it can be help to more accurately determine the other parameters as there is one parameter less to be determined by the code. Moreover, it can help to determine the minimum porosity usable for the theoretical models.

5. Conclusion

The laboratory resistance measurements show a linear relationship between the gravimetric water content and the conductivity for each sample. All linear relationships together show a spectrum characteristic for this research area, where HB25 shows the lowest increase in conductivity and HB23 experiences the highest increase in conductivity as the water content increases. The spectrum is smallest at a water content of 15.9%, but from there on the spectrum increases. It can be concluded that the influence the amount of water content has on the conductivity is significantly. The conductivity for this specific clay increases on average 27 mS m^{-1} with a 40% water content increase.

All samples have been collected from locations with each a different bulk apparent conductivity according to FDEM data. Although the bulk apparent conductivity is incomparable with the laboratory measurements directly, it gives an indication that the conductivity spectrum is likely to be applicable to the entire clay layer. Since the average linear relationship has a standard deviation similar to the individual lines, the average line is sufficient for large scale research such as this.

The empirical relationship has only been tested to be valid for the clay if it has a gravimetric water content between 10.5% to 65.5%. Outside this range, including below shrinkage limit and above liquid limit, has not been tested and its behavior can thus not be concluded.

When comparing the dataset to theoretical electrical conductivity models, it can be concluded that it does not matter which theory is used, even if it does not take the conducting matrix into account, since all models have an R-squared around 0.882. The differences between the models in R-squared is at maximum $1.72 \cdot 10^{-4}$. Moreover, the R-squared shows that the influence of the porosity is minimum, as long as it is chosen within a reasonable and logical interval. This interval should best be determined by porosity measurements first.

In the end, the combination of the laboratory tests and the theoretical model shows that the water content in the clay plays a significant role for the conductivity of the clay. The results also indicate that the matrix conductivity as caused by the clay minerals is neglectable.

6. Stakeholder assessment

A better understanding of the large influence water has on the measured bulk conductivity of clay is not only beneficial for the party conducting the research and its client, but spreads wider to, amongst others, locals, landowners, governmental bodies and environmental organizations. The benefit of this research for each stakeholder will be examined with respect to scientific, economic, environmental, societal and safety aspects.

6.1 Improvement of the model

The study is carried out on behalf of Fugro, but can be used by other engineering companies who use resistivity tests to determine soil characteristics as well. The knowledge and new perspectives gained during the study have yet to be translated into a usable tool for an engineering company, but it is expected that the study will be beneficial mainly in terms of economical as well as scientific impact.

The existing inversion model used to interpret the data can be improved by taking the water component into account. The improvement is supposed to increase the accuracy and helps to take away uncertainties more easily and efficient. The model will request two extra measurements on top of the ones which are already performed, to determine the water conductivity and groundwater level. During the fieldwork, it was shown that these extra tests do not take more than a few extra minutes, assuming the fieldworker knows how to use the equipment. Furthermore, it is expected that the model requires less calibration boreholes, decreasing the fieldwork time and thus saving on the project costs for both client and engineering company. It should be noted that the processing in the office is assumed to take the same amount of time.

The client can make good use of these more accurate results by improving their own calculations and models. Delivering a reliable and accurate report, can help the engineering company to gain more status. Also the client and engineering company can both improve their status with the aid of platforms such as LinkedIn or (local) newspaper where reports on the successful project can be posted.

6.2 Quality, Health, Safety and Environment

QHSE is of paramount importance in this line of work. It is important that a risk assessment is made every time before a project starts, but also when a new technique or model is made. The fieldwork is the most sensitive part of the project for hazards, both for employees as well as local residents passing by and the environment. Both the CMD explorer and CTD Diver are overall deemed non-hazardous, although minor accidents can occur. Hand-drilling on the other hand is more accident sensitive. The risk for the company and the employee decreases by performing less hand-drillings.

Not only does the new model benefit the safety of the employee, but also that of the local environment. Animals can experience nuisance from the operation. In case the research area is a meadow, the cattle cannot go outside during the measuring. On the other hand, the wildlife can get disturbed due to the drilling, disordering the local ecosystem for a short amount of time. The hand-drillings already have, compared to CPT's, a much lighter footprint. But if the drilling time could be decreased even further, the impact it has on the ecosystem reduces even further. After drilling, the borehole gets filled up with natural material leaving the area seemingly untouched as much as possible. It should be noted however that it is uncertain how much the amount of hand-drills will be decreased and since the footprint is already low, the positive influence on the ecosystem shall only be small.

In the end, the knowledge about the water management in the area and an accurate and reliable model can help the client to continue their project in a safer way and lead to stable end results. Keeping in mind this model was contrived with dyke projects in mind, safety is of key importance for the end results.

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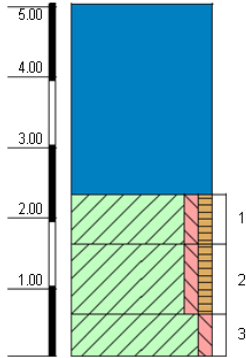
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Appendix A: Borehole classification

Borehole: HB23

Reference (m relative to NAP)



Soil classification

Bodembeschrijving volgens NEN 5104 (1989), C1(1990) [Q]

5.04 to 2.34 Water

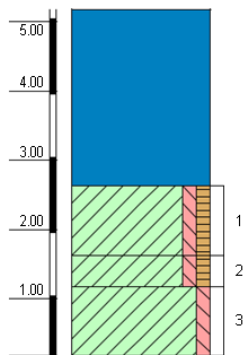
2.34 to 1.64 clay, slightly silty, slightly humus, dark grey

1.64 to 0.64 clay, slightly silty, slightly humus, grey

0.64 to 0.04 clay, slightly silty, grey-brown

Borehole: HB24

reference (m relative to NAP)



Bodembeschrijving volgens NEN 5104 (1989), C1(1990) [Q]

5.18 to 2.63 Water

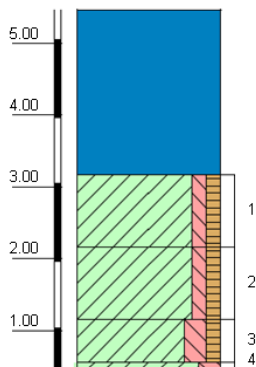
2.63 to 1.63 clay, slightly silty, slightly humus, dark grey

1.63 to 1.18 clay, slightly silty, slightly humus grey

1.18 to 0.18 clay, slightly silty, grey

Borehole: HB25

Reference (m relative to NAP)



Bodembeschrijving volgens NEN 5104 (1989), C1(1990) [Q]

5.46 to 3.16 Water

3.16 to 2.16 clay, slightly silty, slightly humus, dark grey

2.16 to 1.16 clay, slightly silty, slightly humus, grey

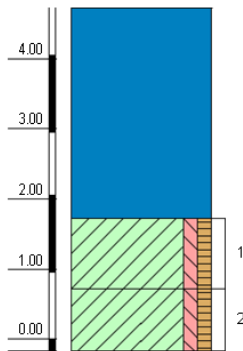
1.16 to 0.56 clay, moderately silty, slightly humus, brown

0.56 to 0.46 Clay, moderately silty, grey

Borehole: HB26

Reference (m relative to NAP)

Bodembeschrijving volgens NEN 5104 (1989), C1(1990) [Q]

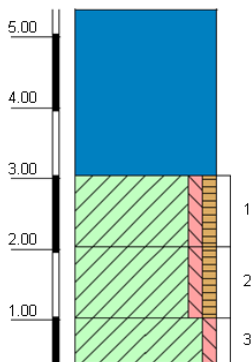


4.72 to 1.72	Water
1.72 to 0.72	Clay, slightly silty, slightly humus, dark grey
0.72 to -0.18	Clay, slightly silty, slightly humus grey

Borehole: HB27

Reference (m relative to NAP)

Bodembeschrijving volgens NEN 5104 (1989), C1(1990) [Q]

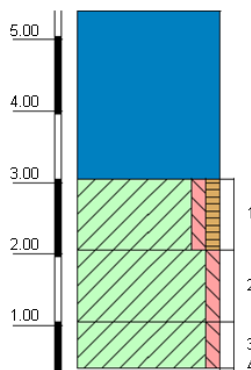


5.39 to 3.04	Water
3.04 to 2.04	Clay, slightly silty, slightly humus, dark grey
2.04 to 1.04	Clay, slightly silty, slightly humus, grey-brown
1.04 to 0.39	Clay, slightly silty, grey

Borehole: HB28

Reference (m relative to NAP)

Bodembeschrijving volgens NEN 5104 (1989), C1(1990) [Q]



5.40 to 3.05	Water
3.05 to 2.05	Clay, slightly silty, slightly humus, dark grey
2.05 to 1.05	Clay, slightly silty, dark grey
1.05 to 0.40	Clay, slightly silty, grey

Appendix B: Laboratory results

Table B1: The conductivity and water content of each measurement.

Borehole sample	Day	Conductivity [$\frac{mS}{m}$]	Relative conductivity error	Water content [$\frac{W_{wet}}{W_{dry}}$ %]	Bulk density [$\frac{g}{cm^3}$]	Dry density [$\frac{g}{cm^3}$]
HB23	1	33.1 $\pm 0.86 \cdot 10^{-1}$	$2.86 \cdot 10^{-2}$	89.9	1.56	0.82
	3	38.3 $\pm 0.89 \cdot 10^{-1}$	$2.65 \cdot 10^{-2}$	50.7	1.67	1.11
	6	27.9 ± 1.1	$4.12 \cdot 10^{-2}$	38.9	1.65	1.19
	8	7.97 ± 0.14	$4.12 \cdot 10^{-2}$	15.3	1.49	1.29
HB23 + HB24	9	5.26 $\pm 9.1 \cdot 10^{-2}$	$4.99 \cdot 10^{-2}$	17.6	1.53	1.30
	10	5.08 $\pm 8.7 \cdot 10^{-2}$	$5.09 \cdot 10^{-2}$	14.3	1.53	1.34
HB24	1	31.6 ± 3.1	$8.52 \cdot 10^{-2}$	90.8	1.61	0.84
	3	25.6 ± 0.49	$2.68 \cdot 10^{-2}$	42.6	1.58	1.11
	3	36.3 ± 0.69	$2.36 \cdot 10^{-2}$	65.5	1.64	0.99
	6	34.6 ± 0.60	$2.25 \cdot 10^{-2}$	43.6	1.65	1.15
	8	18.1 ± 0.35	$3.05 \cdot 10^{-2}$	20.0	1.54	1.29
	HB25	1	28.6 ± 0.71	$2.41 \cdot 10^{-2}$	118.3	1.48
3		28.7 ± 0.54	$2.53 \cdot 10^{-2}$	47.4	1.71	1.16
6		31.3 ± 0.77	$2.87 \cdot 10^{-2}$	62.0	1.67	1.03
HB25 + HB27	6	12.1 ± 0.21	$3.42 \cdot 10^{-2}$	28.4	1.50	1.17
	8	10.6 ± 0.18	$3.62 \cdot 10^{-2}$	19.2	1.50	1.25
	10	2.76 $\pm 5.1 \cdot 10^{-2}$	$7.06 \cdot 10^{-2}$	10.5	1.47	1.33
	10	2.62 $\pm 4.5 \cdot 10^{-2}$	$6.98 \cdot 10^{-2}$	10.5	1.47	1.33
HB26	1	31.7 ± 0.57	$2.39 \cdot 10^{-2}$	152.5	1.39	0.55
	3	31.8 ± 0.60	$2.45 \cdot 10^{-2}$	63.8	1.48	0.90
HB27	1	27.9 $\pm 6.7 \cdot 10^{-4}$	$3.01 \cdot 10^{-2}$	91.2	1.60	0.84
	3	20.3 ± 0.36	$2.80 \cdot 10^{-2}$	31.4	1.87	0.94

Table B2: The conductivity water content, dry density and particle density of the test sample HB28.

Sample #	Conductivity $\frac{mS}{m}$	Wet Weight [g]	Bulk density $\frac{g}{cm^3}$	Watercontent %	Dry density $\frac{g}{cm^3}$
28.01	46.5	969.29	1.42	93.8	0.73
				93.7	0.73
				93.5	0.73
				94.2	0.73
				93.6	0.73
				100.5	0.70
28.02	46.3	1031.89	1.50	93.8	0.78
				93.7	0.78
				93.5	0.78
				94.2	0.77
				93.6	0.78
				100.5	0.75
28.03	49.1	1046.09	1.52	93.8	0.79
				93.7	0.79
				93.5	0.79
				94.2	0.79
				93.6	0.79
				100.5	0.76
28.04	44.5	990.49	1.44	93.8	0.75
				93.7	0.75
				93.5	0.75
				94.2	0.75
				93.6	0.75
				100.5	0.72
28.05	49.4	998.09	1.45	93.8	0.75
				93.7	0.75
				93.5	0.75
				94.2	0.75
				93.6	0.75
				100.5	0.73
28.06	45.6	1025.79	1.50	93.8	0.77
				93.7	0.77
				93.5	0.77
				94.2	0.77
				93.6	0.77
				100.5	0.75

Appendix C: Model parameters and statistics

Model	Parameter	$\phi = 0.4$	$\phi = 0.5$	$\phi = 0.6$	$\phi = 0.7$
General	m	1.00	0.81	0.48	- 0.0613
	F	2.51	1.75	1.28	0.978
	n	1.71	1.73	1.73	1.73
Waxman and Smits	CEC	0.00	3.50	3.84	-
Frohlich and Parke	C_s	0.00	0.161	0.161	-
Linde et al.	C_s	0.00	0.375	0.742	-

Table C1: Calculated and estimated parameters for each of the four models.

Model	$\phi = 0.4$	$\phi = 0.5$	$\phi = 0.6$
Archie	0.8850	0.8819	0.8819
Waxman and Smits	0.8850	0.8821	0.8821
Frohlich and Parke	0.8850	0.8821	0.8821
Linde et al.	0.8850	0.8820	0.8820
Linde et al. New C_s	0.8850	0.8821	0.8821

Table C2: The R-squared with each porosity and theory.