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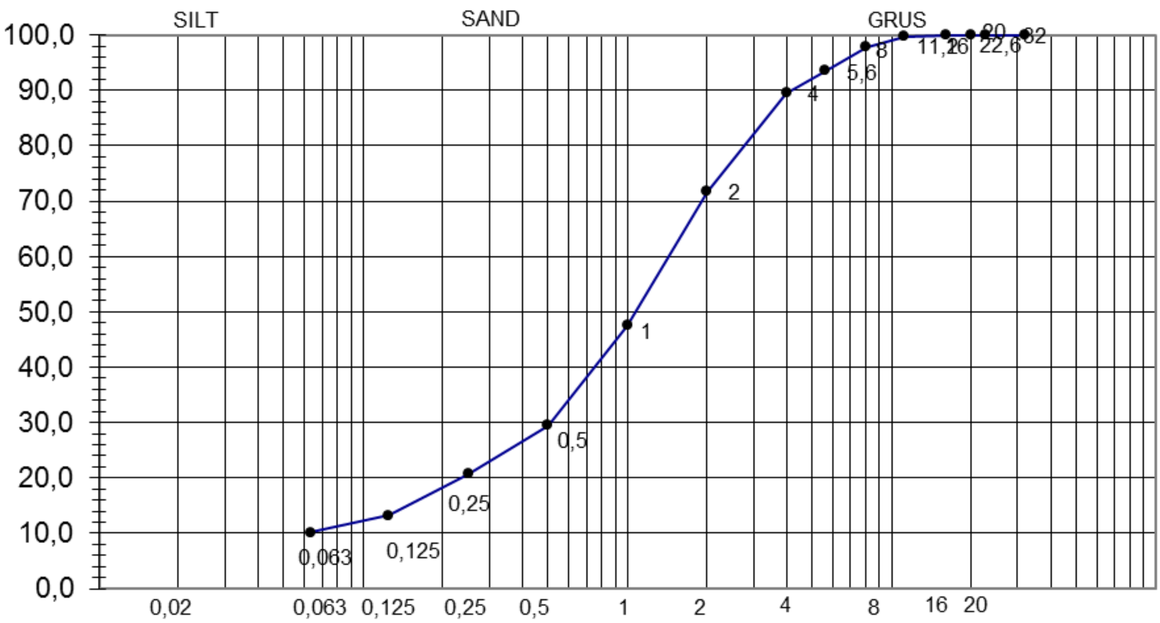

Estimation of Hydraulic Conductivity from Grain Size Analyses

A comparative study of different sampling and calculation methods focusing on Västlänken

Master of Science Thesis in the Master's Programme Geo and Water Engineering

ANDREA SVENSSON

Department of Civil and Environmental Engineering
Division of GeoEngineering

Engineering Geology Research Group

CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014
Master's Thesis 2014:1

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Cover:
Grain size curve from borehole OC4008-1 at Skansen Lejonet. The results are interpreted in chapter 8.

Department of Civil and Environmental Engineering
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ABSTRACT

The purpose of this thesis is to evaluate different methods to calculate hydraulic conductivity, as well as to compare the methods to obtain soil samples used in the project Västlänken, with sampling methods used in this thesis. Soil samples from two locations, Skansen Lejonet and Korsvägen, were taken. Laboratory work such as grain size analyses and different porosity measurements were used on these samples. By using a version of the Kozeny-Carman method to calculate hydraulic conductivity, the results were compared to the most common methods, Hazen and Gustafson. The values from the previous sampling in the project were also used to calculate hydraulic conductivity with Kozeny-Carman. The three methods were compared to each other and the results from the previous soil sampling were compared with the results from the current sampling performed in this thesis. The results from grain size analyses were also compared with slug tests and pumping tests performed in the project Västlänken. The results showed that the Kozeny-Carman equation generally gives a lower conductivity than the Hazen and Gustafson equation, but may be more in line with the results from the hydraulic tests. The results also showed that there were very small differences between the more limited sampling method used previously and the sampling methods used in this thesis. The conclusion drawn from these results was that for test sites with fairly homogenous soil like Korsvägen and especially Skansen Lejonet the limited sampling method is accurate enough. The more elaborate laboratory work needed to use the Kozeny-Carman method may discourage the use of this method. However, if some work were performed on classifying the degree of compaction of a soil sample easily, the Kozeny-Carman method would be easier to use. The conclusion is that the Kozeny-Carman method could be useful to evaluate the hydraulic conductivity from grain size analyses with more accuracy.

KEY WORDS: hydraulic conductivity, grain size analysis, Kozeny-Carman equation, soil sampling, porosity, Västlänken.

Contents

Handledarens förord

Syftet med föreliggande examensarbete har varit att i projektet Västlänken belysa skillnader i resultat vid användning av olika metoder för beräkning av hydraulisk konduktivitet från siktanalyser. Även provtagningsmetodikens betydelse för jordprovets sammansättning har varit av intresse.

I projekt Västlänken har jordlagrens genomsläpplighet till viss del karaktäriserats genom siktanalyser av jordprov. Grundvattenrör med 8 mm hål har drivits ned till friktionsjorden, jordprov har tagits på material som spolats upp och dessa har sedan siktats. I grundvattenrören har även slugtester utförts och i två fall har provpumpningar i filterbrunnar genomförts.

I flertalet fall har resultat från siktanalyser och slugtester haft dålig överensstämmelse, då det trängt in fint jordmaterial i grundvattenrören, vilket innebär att rören har satt igen. Vid tolkningen av jordlagrens genomsläpplighet har siktanalyserna bedömts som mer trovärdiga. Beräkning av hydraulisk konduktivitet har utförts på tidigare siktade prover och prov tagna under examensarbetet. Beräkningarna har utförts med ekvationer av Kozeny-Carman (vidareutvecklad av Bengt Åhlén), Hazen och Gustafson.

Två kompletterande jordprovtagningar har utförts med ambition att få med såväl fraktioner grövre än 8 mm som de finaste fraktionerna. Resultaten har jämförts med de tidigare provtagningarna.

Trafikverket har bistått med finansiering av jordprovtagning och tillhandahållit data. Trafikverkets ansvarige hydrogeolog i projekt Västlänken Tekn Lic Bengt Åhlén har bistått med expertkunskap och resultat från sin forskning gällande beräkningar av hydraulisk konduktivitet från siktanalyser samt deltagit i att formulerat frågeställningarna. SGUs geolog Docent Tore Påsse har ställt upp med tid och beräkningsunderlag för hur siktkurvor kan kompenseras för bortfall av grövre fraktioner i provtagningen.

Andrea Svensson har självständigt och entusiastiskt genomfört examensarbetet. Arbetet för Andrea har inneburit många utmaningar med att söka relevant information och lösningar för att ta reda på efterfrågade parametrar som legat till grund för beräkningarna, vilket hon har genomfört på ett beundransvärt sätt.

Extern handledare

Bergab – Berggeologiska Undersökningar AB

Annika Nilsson

Preface

This master thesis has been carried out at the department of Civil and Environmental Engineering, Division of GeoEngineering at Chalmers University of Technology. It was initiated by Bengt Åhlen at the Swedish Transport Administration and Annika Nilsson at Bergab – Berggeologiska Undersökningar AB. Supervisors have been Annika Nilsson at Bergab and Lars Rosén at Chalmers. Examiner has been Lars Rosén at Chalmers. The Swedish Transport Administration have made the sampling possible.

I would especially like to thank my supervisor Annika Nilsson for guidance and support during the entity of this project. I also want to thank Lars Rosén for his comments and help. Further I would like to thank Bengt Åhlén who has been a source of expert knowledge in this thesis, Peter Hedborg and Mona Pålsson in the geotechnical and environmental chemistry laboratory at Chalmers for help with the laboratory investigations, and Tore Påsse at SGU for his time and guidance. I also want to express my appreciation to everyone at Bergab for their interest and encouragement.

Finally, my thanks goes to my family, especially Robert Lanzky, for their endless support, encouragement and constructive criticism.

Gothenburg, March 2014

Andrea Svensson

Notations

Roman upper case letters

A = Area	$[cm^2]$
A_0= See Åberg, 1993	
A_C=Cross sectional area of channel	$[m^2]$
A_s = Cross sectional area of sample	$[m^2]$
B_0= See Åberg, 1993	
C_H = Empirical constant	*[-]*
C_u = Coefficient of uniformity	*[-]*
d= Degree of compaction	*[-]*
d_e= Effective grain size diameter	*[mm]*
d_h/d_l = Hydraulic gradient	*[-]*
d_{10} = The particle size for which 10% of the material is finer	*[mm]*
d_{20} = The particle size for which 20% of the material is finer	*[mm]*
d_{50} = The particle size for which 50% of the material is finer	*[mm]*
d_{60} = The particle size for which 60% of the material is finer	*[mm]*
E = See Andersson et. al 1984	
e = Euler's number, mathematical constant	*[-]*
$E(C_U)$ = See Andersson et. al 1984	
$G(C_U)$ = See Andersson et. al 1984	
h = Height of water pillar	*[cm]*
K = Hydraulic conductivity	*[m/s]*
k_0 = Constant	*[-]*
L = Length of test piece	*[m]*
L_1,L_2,L_3=Different levels of the test piece L	*[m]*
l = Length of sample	*[cm]*
L_e = Average length of capillaries	*[m]*
m = hydraulic radius	*[m]*
m_s = Mass of soil	*[g]*
m_{soil} = Weight of soil sample	*[g]*
m_w = Mass of water	*[g]*
m_1 = Weight of empty container	*[g]*
m_2 = Weight of container and mineral turpentine	*[g]*
m_3 = Weight of soil sample	*[g]*

m_4 = Weight of soil sample and mineral turpentine *[g]*

m_5 = Mass of cylinder *[g]*

m_6 = Mass of water up to mark and cylinder *[g]*

m_7 = Mass of soil up to mark and cylinder *[g]*

m_8 = Mass of water and soil up to mark and cylinder *[g]*

n = Porosity *[-]*

P=Wetted perimeter *[m^2]*

Q = Flow *[m^3/s]*

R = Coefficient of roughness *[-]*

R_e = Effective radial distance over which y is dissipated *[m]*

r_w = Radius of influence *[m]*

S=Particle surface for unit volume of the porous media *[-]*

S_0 = Specific grain surface of solids *[-]*

T = Transmissivity *[m^2/s]*

t = Time for water flowing through the sample *[s]*

V = Volume of water flowing through the sample *[cm^3]*

V_{soil} = Volume of soil sample *[cm^3]*

V_{py} = Volume of pycnometer *[cm^3]*

V_w = Volume of water *[cm^3]*

w = Water content *[%]*

y= Vertical difference between water level inside well and static water Table *[m]*

Greek letters

γ =Specific weight *[N/m^3]*

ε = Void ratio *[-]*

μ = Viscosity *[$(Ns)/m^2$]*

μ_G =Geometric mean *[mm]*

ρ = Bulk density of soil sample *[g/cm^3]*

ρ_s = Compact density of soil sample *[g/cm^3]*

ρ_1 = Density of mineral turpentine *[g/cm^3]*

σ =Geometric standard deviation *[mm]*

τ = Ratio of kinematic viscosity at 10°C and ground water temperature *[-]*

1 Introduction

When conducting a hydrogeological study, hydraulic conductivity is one of the most important parameters, but also a parameter that is difficult to determine. This master thesis will study hydraulic conductivity in soils, focusing on the project Västlänken in Gothenburg. Samples have been taken from two different locations along the Västlänken stretch, Korsvägen and Skansen Lejonet. These samples was tested in a laboratory and several different methods to calculate hydraulic conductivity was used and compared to each other and to the results from previous sampling in the project.

1.1 Background

The project Västlänken is a railway tunnel through central Gothenburg, see Figure 1. In addition to the existing station Centralstationen, two stations will be constructed at Korsvägen and Haga. Due to the sensitive urban environment there are many challenges that have to be solved in this project. As there are a lot of buildings in the vicinity and the ground has been drained previously, the ground is sensitive to settlements. Due to this, the hydrogeological properties, such as the hydraulic conductivity, are important to know. There can be different consequences both if the hydraulic conductivity is overestimated and if it is underestimated. In questions of leakage into for example a tunnel, an overestimation of the hydraulic conductivity is conservative, but in questions of infiltration the opposite is true. Misjudgements that lead to settlements or other damages can have great financial consequences and also legal repercussions.

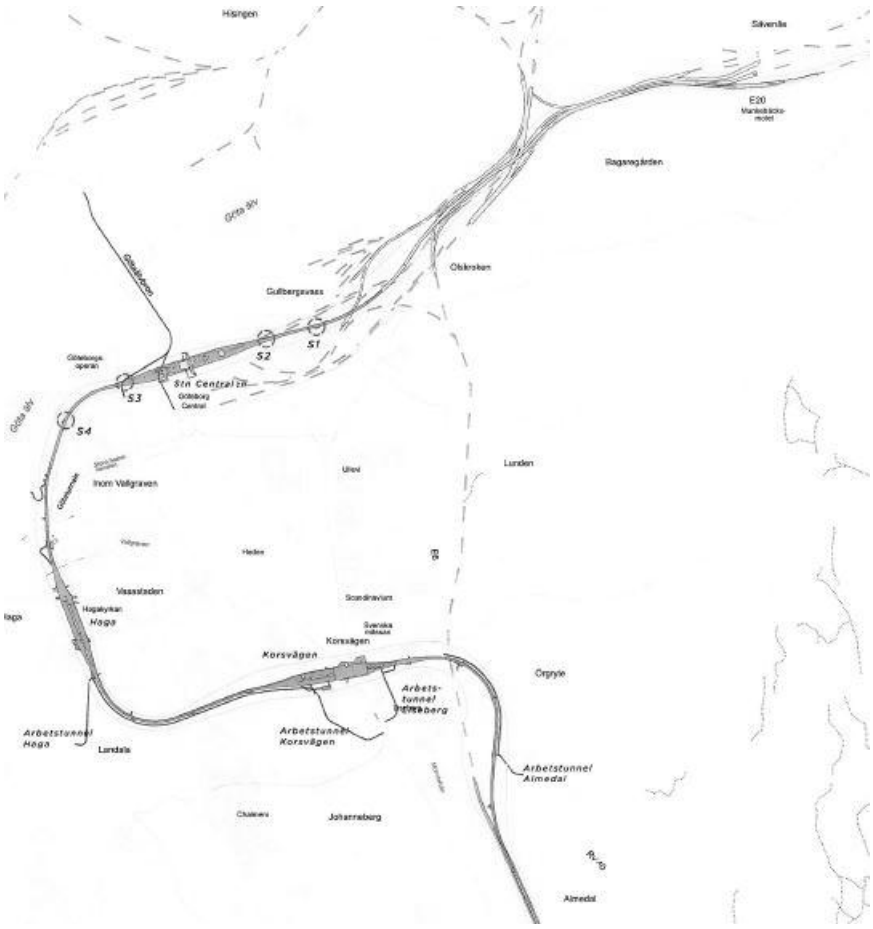

Figure 1 The stretch of the railway tunnel through central Gothenburg (Trafikverket, 2013)

Several different methods exist to estimate a hydraulic conductivity, both from laboratory work, indirect methods such as grain size analyses and from hydraulic tests. Besides the grain size, other parameters such as degree of compaction, porosity and shape of the grains all have an effect on the hydraulic conductivity. It is also important to be aware of and understand the hydrogeological environment, for example since the sedimentological environment determines the degree of compaction.

As changes in the groundwater Table, depending on the hydraulic conductivity, can affect the area in many ways, knowing if the estimated value is accurate is important. More theoretically, investigating how different soil parameters affect the hydraulic conductivity and what results different methods provide, can give an increased understanding of hydraulic conductivity and improve the accuracy when estimating it.

In the Västlänken project geological investigations have been made throughout the route. When studying the hydrogeology in the area, soil samples have been taken from boreholes and grain size analyses have been made on these samples to determine the hydraulic conductivity. Some hydraulic tests have also been made, such as slug tests and test pumping.

1.2 Aim and objections

The overall aim of this master thesis is to compare different methods to estimate hydraulic conductivity through grain size analyses and correlate it with results from hydraulic tests. The test methods to achieve a soil sample have different uncertainties that all affect the estimations of hydraulic conductivity. In the scope of this master thesis investigations of soil samples will be conducted to determine the hydraulic conductivity. A comparison of different sampling methods will be made.

The specific objective of this thesis focus on Västlänken, and will evaluate if the test methods used for sampling gives accurate results, or if more undisturbed sampling methods provide more accurate results. Conclusions will also be drawn on the applicability on several methods used to calculate hydraulic conductivity in this thesis.

1.3 Delimitations

The laboratory work on the soil samples have focused on grain size analysis and porosity. Grain shape, which also affect the hydraulic conductivity and might be interesting to look at in another study, have not be studied in this thesis. Another important factor is degree of compaction, but due to the limited amount of sample material this has not been part of the laboratory work to desired extent. As the thesis focuses on the project Västlänken, the soil samples is limited to samples from the area Korsvägen and Skansen Lejonet in Gothenburg.

2 Hydrogeological concepts

To understand the principles of hydraulic conductivity, some basic concepts are presented in this section. The flow of groundwater in a soil is determined by the material properties of the soil, as well as basic physical laws.

2.1 Darcy's law

The flow of groundwater depends on the hydraulic gradient and the hydraulic conductivity (Knutsson & Morfeldt, 2002). The flow of a fluid in porous medium can be described by Darcy's law, see equation 2.1.

$$Q = -KA\frac{d_h}{d_l} \qquad 2.1.$$

Q = Flow	[m³/s]
K = Hydraulic conductivity	[m/s]
A = Area	[m²]
d_h/d_l *= Hydraulic gradient*	[-]

The difference in height and length is represented by the hydraulic gradient, and is the reason for the negative sign as the water flows from higher to lower level. When describing ground water flow, Darcy's law is altered to describe all three dimensions. Often, this is simplified to describe 2-dimensional flow. Depending on type of aquifer, different partial differential equations are used to describe the flow, like the Laplace equation. To solve these equations analytically, idealized cases are used and the boundary conditions of the aquifer must be known. By using a conceptual model of a ground water system, reality can be translated and simplified into a manageable model.

2.2 Soil properties

The hydraulic conductivity varies in different soils. A sorted soil like an esker deposit has a high conductivity, and is therefore often used for ground water extraction. In Sweden, the most common soil type is glacial till, which is an unsorted soil (Knutsson & Morfeldt, 2002). It is often difficult to determine hydraulic conductivity in an unsorted soil due to the great variation in the composition of the soil. In a glacial till, the grain size varies a lot as well as the degree of compaction. Unsorted soils often show a high degree of anisotropy; the hydraulic conductivity depends on the direction of measurement. This means that the hydraulic conductivity is different in a horizontal orientation than in a vertical direction.

2.2.1 Grain size

The grain size distribution of a soil is one of the soil mechanic properties that affect the hydrogeological conductivity. A sorted soil with larger grains has a high hydraulic conductivity. If a sediment contains a mixture of grain sizes, a more multi-graded soil, the porosity will be lowered, and thus the hydraulic conductivity (Fetter, 2001). This is because the void between the larger grains is filled up with smaller grains.

2.2.2 Porosity

Porosity is defined as the relationship between the pore volume and the total volume, i.e. the air voids in a soil (Larsson, 2008). The porosity can be calculated indirectly by knowing the compact density of the soil and the dry density (Knutsson & Morfeldt, 2002). When calculating hydraulic conductivity, the interesting parameter is the effective porosity, the volume of the pores where water can move freely, as opposed to total porosity where closed pores also are calculated.

2.2.3 Degree of compaction

The porosity depends on the degree of compaction. The dry density of a soil compared to the maximum dry density where the material has been compacted in a laboratory is called the degree of compaction (Fagerström, 1973). Different degrees of compaction give different optimal water content, where the bulk density is the highest.

2.2.4 Grain shape

Hydraulic conductivity is also determined by the systems formed by the voids between the grains (Fetter, 2001). Well-rounded grains may be almost perfect spheres, but grains can also be very irregular. Different grain shapes create different ways for the water to move through, see Figure 2. In theory, grains are usually assumed to be spherical, which can become a source of error in estimations of hydraulic conductivity if the grains are very angular.

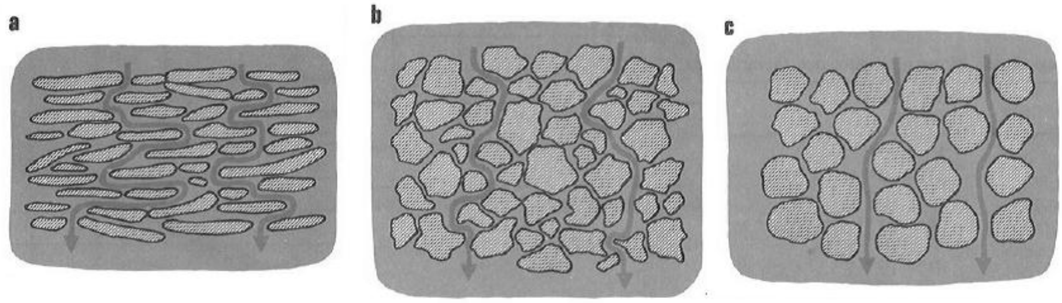

Figure 2 Different grain shape makes the water travel in different paths (Fagerström & Wiesel, 1972)(modified)

2.3 Hydraulic conductivity

In the field of hydrogeology, it is important to know how easy water (or other fluids) can move through a porous media, i.e. hydraulic conductivity. Hydraulic conductivity describes a material's ability to let water through. This is defined in terms of volume per area and time, $m^3/m^2/s$ = m/s, which should not be confused with meter per second as a velocity (Fetter, 2001). This parameter is not always easily measured, but often has to be predicted by using basic information and translating it into estimates of hydraulic conductivity. Hydraulic conductivity can be estimated by using methods based on grain size analysis or determined by the use of experimental in situ- or laboratory methods. The grain-size methods use coefficients that are estimated from empirical data, as well as some kind of representative value of the grain size. The experimental methods measure the flow in a soil material and calculate the hydraulic conductivity or transmissivity from the flow in different ways. The different methods will be described more in detail further on.

3 Literature review

It is common to determinate hydraulic conductivity from grain size analyses as the methods are cheap and easy to use. As there are simplifications in these methods, there are some uncertainties in how these methods reflect the reality.

Many authors have studied the hydraulic conductivity regarding what method are most accurate, comparing methods based on grain-size distributions to hydraulic tests, evolving the methods in different ways to make them more accurate or compare the methods to each other. This literature review is a selection of some of the studies that has been made. .

3.1 Comparison between field methods and grain size analyses

Vienken and Dietrich (2011) compared many different methods to evaluate hydraulic conductivity from grain size analyses with slug tests. They used sonic sampling to collect core samples for their laboratory work, to try to avoid the disturbances that typically occur during sampling. The sampling site was chosen for its high degree of heterogeneity and broad sedimentological spectrum of deposits and 108 samples were chosen. Grain size analyses were performed on the samples and factors like porosity and shape factor used in the Kozeny-Carman equation were estimated with formulas derived from the grain size analyses. When comparing the different methods to each other, several of the methods showed a high correlation but some methods such as the modified Kozeny-Carman equation, Kozeny-Köhler, see equation 3.1, showed larger differences.

$$K = \frac{\tau}{R} \cdot 405 \cdot \frac{\varepsilon^3}{(1+\varepsilon)} \cdot d_e^2 \qquad 3.1.$$

K = Hydraulic conductivity	[m/s]
τ = Ratio of kinematic viscosity at 10°C and ground water temperature	[-]
R = Coefficient of roughness	[-]
ε = Void ratio	[-]
d_e = Effective grain size diameter	[mm]

The slug test measures primarily horizontal conductivity, which in this site is primarily greater than the vertical conductivity. This is in contrast to the hydraulic conductivity from grain size data that measure a sort of cross between the horizontal and vertical conductivity, as the sieving process destroys the natural sediments. When comparing the hydraulic conductivity from grain size methods to the hydraulic conductivity from slug tests the correlation was rather high for most methods, however the grain size conductivity was usually smaller than the slug test conductivity. The methods that used porosity, like Kozeny-Köhler, showed less correlation to slug tests than the other methods. The authors concluded that the method applied to estimate porosity has a great impact on the result and should be chosen carefully.

Cheong et al. (2008) performed another study were hydraulic conductivity determined from grain size analyses were compared to hydraulic conductivity determined from slug test, pumping test and numeric modelling respectively. The numerical modelling was performed in MODFLOW to take into account heterogeneous, anisotropic aquifers and irregular boundary conditions. The authors argued that because of this, the values obtained by numerical modelling are more reasonable than the values from grain size analyses or aquifer tests. For the grain size analyses, 184 samples from eight boreholes were used. The porosity measurements were calculated by comparing the volume of dried samples to saturated samples. The friction soils in the studied area consist of upper fine, medium and lower fine sands, and a highly conductive sand/gravel layer. The sand/gravel layer is the main aquifer.

The results of the study showed varying results depending on the method and the studied layer. The horizontal hydraulic conductivity estimated from numerical modelling corresponded well to hydraulic conductivity estimated from grain size analysis when comparing the sand/gravel layers but not for the fine or medium sand layers. The hydraulic conductivity from pumping test was slightly smaller than the hydraulic conductivity from grain size analysis when comparing the medium sands and sand/gravel layers, but higher for the fine sand layers. The hydraulic conductivity from slug tests was smaller than both the hydraulic conductivity from pumping tests as well as grain size analyses.

3.2 Evaluation of the Kozeny-Carman equation

When using the Kozeny-Carman equation, more care must be taken to receive accurate results due to the fact that several parameters are included in the equation and thus more uncertainties than for example Gustafson's equation. Chapuis and Aubertin (2003) reviewed many test results from several studies and compared measured hydraulic conductivity to predicted hydraulic conductivity. They used permeameter tests to measure the hydraulic conductivity and the Kozeny-Carman equation to predict it. The specific surface is one important parameter in the Kozeny-Carman equation, which can be difficult to estimate. The authors estimated the specific surface from the gradation curve, by using an equation where the specific surface is calculated by using the percentage of each grain size together with the specific gravity of the material.

The authors found that when using the Kozeny-Carman equation correctly, especially with regards to the specific surface factor, the predictions corresponds fairly well to measured hydraulic conductivity. It is also important to take care when performing the permeameter test, for example as the material has to be fully saturated to reach a steady-state condition. Besides these practical reasons, there are also theoretical reasons when the results from the Kozeny-Carman equation show discrepancies, for example when the soil is anisotropic. They conclude that the Kozeny-Carman equation is a good predictive tool for any natural homogenous soil, and specialists in geotechnics and hydrogeology should use it more systematically.

3.3 Comparison between laboratory methods and grain size analyses

Eggleston and Rojstaczer (2001) compared in-situ measurements of hydraulic conductivity by the use of an air permeameter, to hydraulic conductivity calculated with the Hazen equation. In theory, hydraulic conductivity should increase with effective grain size and decrease with grain size variability. The authors have found this to be generally true but point out that the hydraulic conductivity is sensitive to other parameters such as sediment stratification, low weight percentage fines and cementation. The conclusions drawn in the article is that firstly, the hydraulic conductivity values achieved by the Hazen equation are much too high. The authors believe that the Hazen coefficients in order for the equation to be more accurate should be empirically fitted. Secondly, the values have less variability than they should, particularly if lower hydraulic conductivity values are not sampled. This means that in an aquifer where there is strong fine scale variability, as much as several hundred measurements may be needed to adequately characterize the aquifer.

Another article (Carrier, 2003) also finds uncertainties in the Hazen coefficient. The author argues that the coefficient varies from 1 up to 1000 in various geotechnical textbooks, which results in a large spread of the hydraulic conductivity when using Hazen. The author theoretically compares the Hazen equation to the Kozeny-Carman equation, and argues that the difficulties with the Kozeny-Carman equation, namely to determine the specific surface, is easier today when the use of computers is widespread. The conclusion is that the Kozeny-Carman equation is superior to the Hazen equation in terms of accuracy, and should be preferred.

Mbonimpa et al (2002) have also argued that the Hazen coefficient has limitations, and have proposed a function for determining this coefficient by using an extension of the Kozeny-Carman function. The aim of the study was to use pedotransfer functions, i.e. functions that translate readily available data into estimates of soil properties that are more difficult to determine, such as grain size and density, to determine hydraulic conductivity. The authors define the surface area by using the effective diameter and uniformity coefficient. The tests described in the article were conducted on reconstituted samples and used permeameters and triaxial cells to measure hydraulic conductivity experimentally. Results from using the function with data from several different studies have shown good agreement for a wide spectrum of materials. The conclusion is that the function may be used to obtain useful information about the hydraulic conductivity during the phase of preliminary analyses and also to check if a questionable test result is reasonable.

Boadu (2000) studied hydraulic conductivity and developed new models from grain size distribution based on multivariate regression analysis. Both the Hazen and Kozeny-Carman equation uses representative grain size diameters. The author argues that using the geometric mean of a grain size distribution does not work for all types of soil. If the soil has a significant fine content, the harmonic mean provides a more accurate hydraulic conductivity than the geometric mean. As the harmonic mean puts greater weight on smaller grain sizes and the geometric mean puts greater weight on larger sizes, it is important to choose the right representative grain size diameter. This also depends on the state of sorting and packing. In this study, soil samples were compacted similar to the standard Proctor compaction tests, and measurements of the hydraulic conductivity were made with both the falling head method and the constant head method. Sieve analyses were also made to provide grain size distributions. By using fractal analysis of the grain size distribution, a model to determine hydraulic conductivity based on fractal dimension, entropy, fractional porosity, percent of fine material and bulk density were developed. The author argues that Hazen and Kozeny-Carman were developed based on representative grain sizes of soil samples, and gives erroneous results when the grain size distribution is different, while this model compensate for these differences.

These studies all deal with methods of measuring hydraulic conductivity, although from different premises. Despite the fact that some authors draw the conclusion that using Kozeny-Carman equation is the best way to calculate hydraulic conductivity from grain size distributions, others believe that the multitude of parameters makes it more difficult to use and creates more uncertainties. The use of the Hazen equation, and in Sweden the Gustafson equation, is widespread. Their simplicity makes it unlikely that these methods will be abandoned, unless an application for the Kozeny-Carman equation is developed that makes it easier to use.

3.4 Porosity

Frings et al (2011) studied the accuracy of porosity predictors for fluvial sand-gravel deposits. They looked at several ways to measure porosity based on different parameters such as effective grain size, standard deviation, deviation of the grain size distribution from a type curve and theoretical predictors that take mixing processes into account and calculate porosity computationally. They used laboratory methods and in-situ experiments to calculate the porosity and compared this to different methods based on the parameters mentioned above. The uncertainty of the laboratory methods could lead to an overestimation of the porosity, mainly due to disturbance of the packing near the container walls, but the authors believed that this overestimation was probably small. In addition to the experimentally obtained results, the authors also used two porosity data sets from literature to compare to.

The results showed that empirical predictors based on the relation between median grain size and the porosity did not correspond very well to the laboratory results. In part, this is because the finer sediments of a grain size distribution often represents a small percentage of the entire distribution, and does not affect the median grain size a lot even though this has a great impact on the porosity. The conclusion was that there is no unique relation between grain size and porosity. The empirical methods could be useful in cases when the geological conditions mirrored the original conditions in which the methods were developed, but were not generally applicable. When looking at methods based on the other parameters the correlation was better, especially when using theoretical predictions, but the methods based on these parameters were still not able to produce highly accurate porosity predictions. The authors developed a tailor-made equation for the studied area with multivariate regression analysis, which used two independent parameters: the sediment standard deviation and the number of grains smaller than 0.5 mm. They were still not able to produce accurate predictors but could see trends such as downstream decreasing porosities, and concluded that porosity predictors are useful to provide insights in the spatial variation in porosity.

Sakata and Ikeda (2013) studied how hydraulic conductivity varied by depth in alluvial gravel deposits. The dependence of hydraulic conductivity on depth in sediments is mainly due to decreasing porosity because of compaction and other physical or chemical effects. The hydraulic conductivity in unconsolidated gravel deposits varies quite a lot with even a slight change in porosity. When using a model that represents the hydraulic conductivity as a function of the porosity and volume fraction of each component in a sediment mixture, the hydraulic conductivity can range over several orders of magnitude by these factors. The authors cite a study that showed that a very small change in porosity (a few percent) could cause greater than 10-fold changes in hydraulic conductivity. To obtain as undisturbed samples as possible, the authors used tube-samplers that had been improved for high-quality sampling of gravel deposits. Grain size analyses were made on these gravel cores and was compared to the results from slug tests. As indirect methods based on grain-size distribution create discrepancies due to the simplifications to only one parameter, the authors classified the samples according to a matrix packing level index, by viewing the sample. This index categorizes the packing in the gravel cores into four levels, from full to very loose. This refers to the cavities between the gravel and to which degree the cavities are filled with finer material. The authors measured how much of a core that were part of each level as a ratio of the entire core, defined as L1, L2, L3 and L4 for each of the levels. The hydraulic conductivity was calculated by using grain size diameter and the matrix packing level index as seen in equation 3.2:

$$K = 6.89\left(\frac{d_{20}}{1000}\right)^{1.9} \cdot (L_1 + L_2) + 0.0167 \cdot {L_3}^3 \qquad 3.2.$$

The L-values gives a form of visual way of measuring the porosity. The d_{20}-value was chosen because it produced the highest correlation to the slug tests. The authors concluded that there was a clear depth dependency, where an increase in depth of 1 meters corresponds to an approximately 10% decrease in hydraulic conductivity. However, the relations between the slug tests and the core properties were not sufficiently verified, and were only valid for this particular site. The slug tests showed a slightly lower hydraulic conductivity than the grain size analysis.

4 Hydrogeological environment

The Gothenburg region is characterised by thick layers of clay and several valleys stretching in various directions. One of these valleys stretches in a north-south direction, where the river Mölndalsån is situated. As the ground water aquifer in the city has been drained in previous constructions, the ground is very sensitive to settlements (Banverket, 2006).

Traces of the ice can be seen in the grooves that are usually found in a northeast/southwest direction (Adrielsson & Fredén, 1987). After the melting of the ice, glacial clay was deposited in the deep seabeds. The glacial clay on the west coast was deposited in salt water and lacks the typical varves that usually are seen in glacial clay. After the melted water from the ice sheet did no longer affect the area, glacial clay at shallow depth eroded and was deposited at greater depths. Most of Gothenburg is below the highest coastline, and was thus previously below water.

The layer sequence in the central area of Gothenburg is typically from top to bottom fill 1-7 meters, dry crust clay, post-glacial clay 8-15 meters, sand layer, glacial clay up to a 100 meters, gravel and sand, glacial till and finally bedrock (SWECO, 2013c). There are typically two ground water zones, an upper thinner zone on top of the clay in the fill, and a lower under the clay on top of the bedrock. The ground water formation is relatively small, less than 100 millimetres per year. The ground water levels in the city vary a lot, as the urban environment makes the hydrological situation quite complex. A typical layer sequence can be seen in Figure 3, this particular sequence is from borehole OC4001 at Skansen Lejonet. However the depth of the different layers varies.

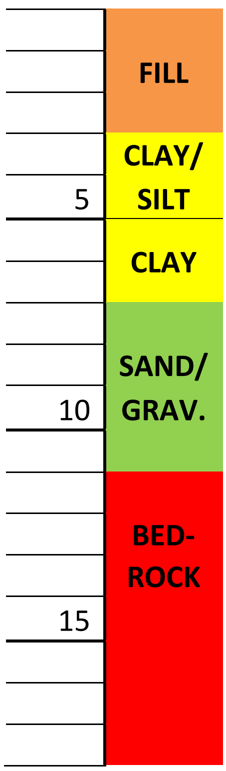

Figure 3 Example of typical layer sequence. The numbers marks depth in meters. Modified from (SWECO, 2013c).

4.1 Skansen Lejonet

Skansen Lejonet is a fortification from the 17th century, and stands on top of a mountain block about 20 meters above the ground, see Figure 4. The tunnel will probably pass through the mountain, marked with a red ellipse in the Figure. A vast layer of clay under fluvial sediments characterises the area around the railway yard, except around the fortification where there is an outcrop (SWECO, 2013c). The area was previously a wetland but was drained, piled and filled during the 19th century (Göteborgs Stad, 2013). Due to this, settlements have been occurring in the area ever since (SWECO, 2013c). North of Skansen, the soil consists of a fill of silty sand, sandy silt and silty clay. The fill is considered to be inclined to float and water bearing.

The area has two ground water zones, an upper in the fill on top of the clay and a lower in the friction material under the clay. There might be some contact between the zones where the clay layer thickness is small, the contact is otherwise assumed to be very limited. The hydrostatic pressure is higher in the upper zone than in the lower, which means that where contact exists, the flow will run downward.

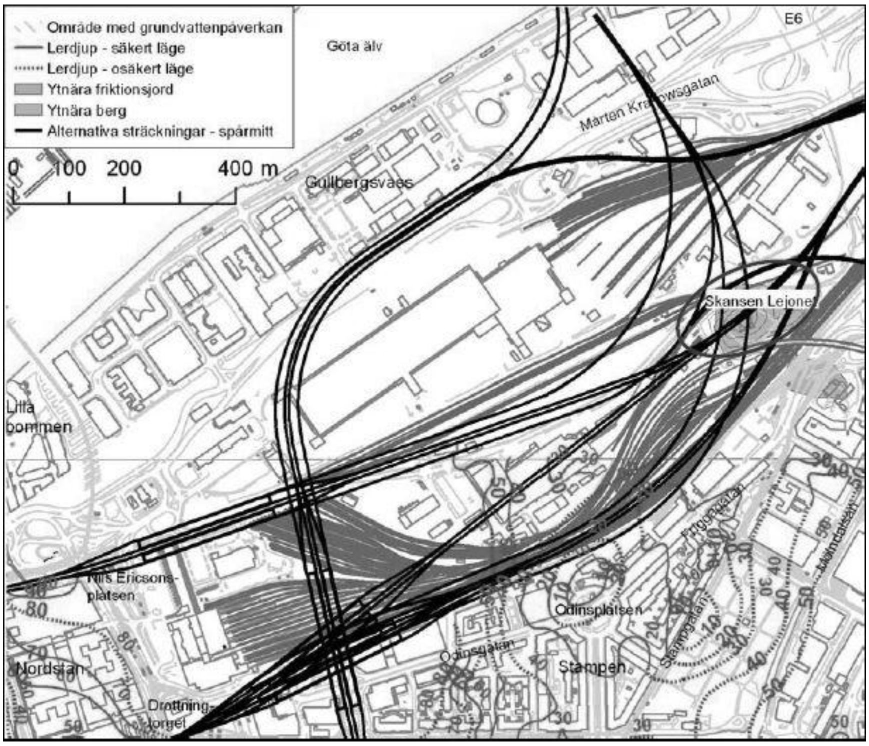

Figure 4 View over Skansen Lejonet. Possible tunnel stretches is marked in black (SWECO, 2013c).

4.2 Korsvägen

Korsvägen is situated in central Gothenburg, and the tunnel will be constructed from east to west through the area, see Figure 5.

Figure 5 Map over the area around Gothenburg, in the south central part of the town. The lines show the approximate corridor where the tunnel will be constructed (Google Maps, 2014)(Modified).

The area around Korsvägen is characterised by valleys and dips in the north-north-west direction. South of Korsvägen, along Södra vägen, there is a valley with a flat ground in this direction. The soil layers in the valley consist of glacial clay, which in the north is overlayed by postglacial clay. In the south, the thickness of this layer is less than ten meters, but increases to the north to over twenty meters. Below the clay there is a layer of friction soil, on top of bedrock. The bedrock in the area consists of schisted gneiss with a north-south strike.

To the west, parallel to this valley, there is another dip. The layers are similar to the valley. The layer of friction soil in this valley is approximately two meters thick in the south and approximately six meters thick in the north, around Carlandersplatsen.

Many construction projects have been executed around the area. Several of the urban areas are sensitive to settlements, for example the gardens in Johannebergs Landeri. Previous investigations have shown that the area south of Carlandersplatsen and around Södra vägen can tolerate a lowering of the ground water table up to one meter, but the area north of Carlandersplatsen cannot tolerate any lowering of the ground water Table.

The soil depths at Korsvägen can be seen in Figure 6, and means that the foundation of the tunnel will be constructed in part bedrock and part soil.

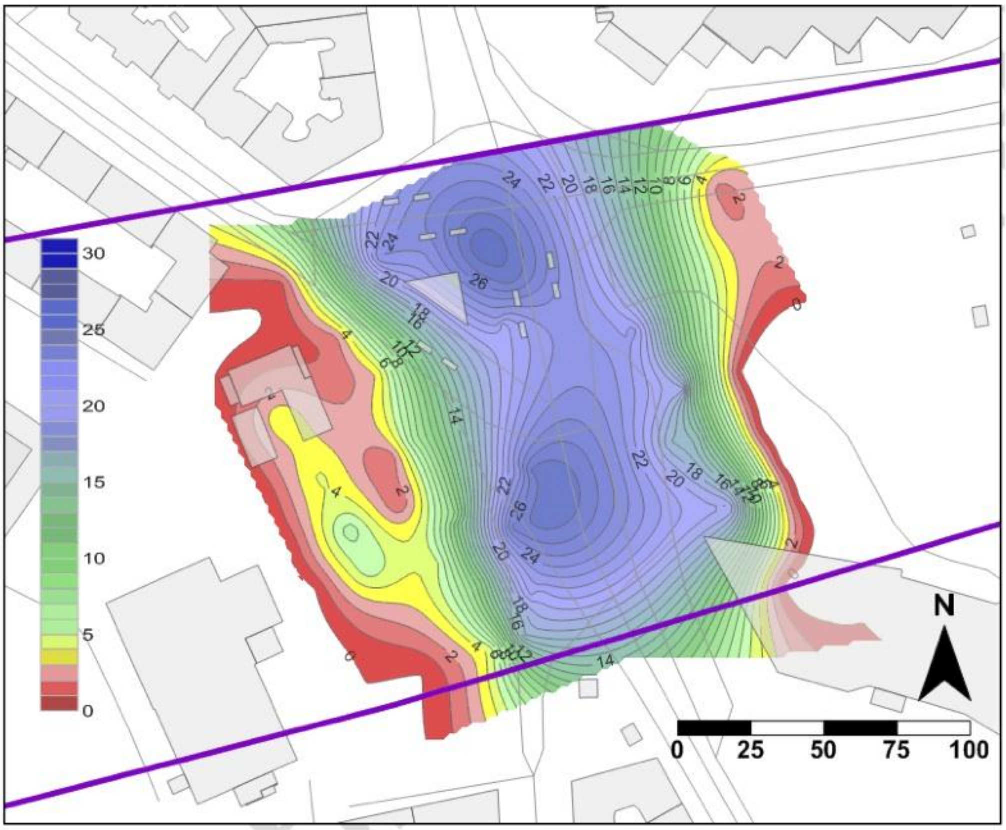

Figure 6 Soil depth at Korsvägen, scale in meters. The corridor where the tunnel will be situated is marked with purple lines (SWECO, 2013a)

There is in some places an upper groundwater zone in the fill on top of the clay. Where the thickness of this layer is less than 2 meters there is probably no water. Some friction material has also been found inside the clay, which may constitute a middle zone, but the thickness and range of this is quite uncertain and probably limited in its extension.

The lower ground water zone in the friction material is characterized as fine sand to sand on top of glacial till. The thickness of this zone varies between approximately 1-10 meters, see Figure 7.

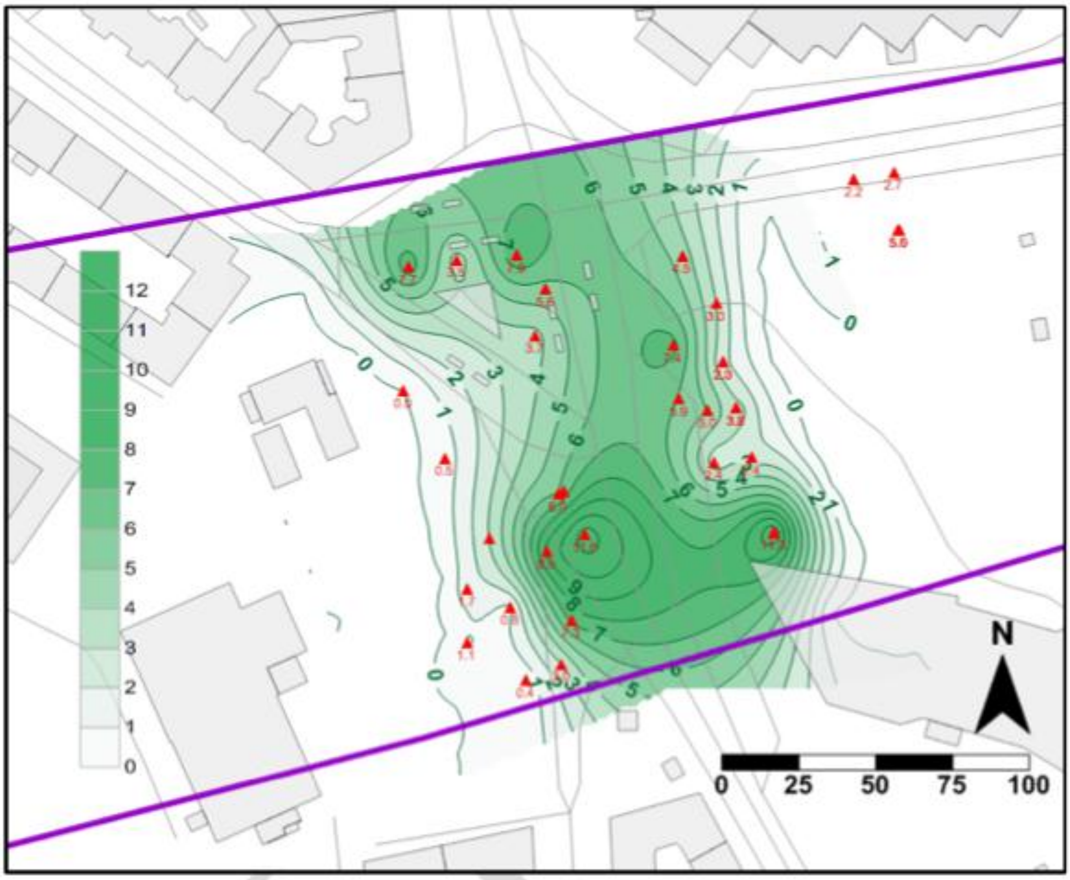

Figure 7 The thickness of the lower ground water zone at Korsvägen, scale in meters. (SWECO, 2013a)

5 Methods for measuring hydraulic conductivity

There are several different methods to determine hydraulic conductivity. Firstly, indirect methods based on grain size distribution will be presented and then field methods and laboratory methods will be shortly described. The three indirect methods presented below are some of the most commonly used. Hazen and Gustafson depend only on grain size distribution while Kozeny-Carman takes other factors into consideration.

When looking at the scale of these tests, slug tests test the permeability of the soil layer directly adjacent to the filter part of the ground water pipe. The grain size analyses gives a value of the hydraulic conductivity for a specific borehole at a certain depth and pumping tests gives values for a larger area. The hydraulic conductivity evaluated from the pumping tests is thus an average of different conductivities in the soil. This is especially true in a heterogeneous soil, where parts of the area can have very deviating values. To get an average value for a larger area, several grain size analyses and/or slug tests needs to be done. This needs to be taken into consideration when evaluating grain size distributions, so that the results are interpreted in the context of the larger area.

5.1 Indirect methods

Indirect methods have been developed by empirically, where a large number of samples have been studied to determine the coefficients used in the equations. The grain size of the particles in the grain distribution curve that corresponds to the passing mass amount 60%, 40% is determined d_{60}, d_{40} and so on (Larsson, 2008). When using grain size distributions, d_{10} and d_{60} are the most commonly used.

5.1.1 Hazen

In 1893, Hazen published his formula for estimating hydraulic conductivity:

$$K = C_H \cdot d_{10}^2 \qquad 5.1.$$

K = *Hydraulic conductivity*	[m/s]
C_H = *Empirical constant, in this thesis set to 0.01157*	[-]
d_{10} = *The particle size for which 10% of the material is finer*	[mm]

This formula was developed for designing sand filters for water purification but is very commonly used to estimate the permeability of soil.

5.1.2 Gustafson

Gustafson introduced a way to calculate hydraulic conductivity from grain size analyses that is often used in Sweden today. The formula was calculated by using a large number of samples where results from grain size analyses were compared with results from pumping tests (Andersson, et al., 1984). The hydraulic conductivity is calculated as follows:

$$K = E(C_U) \cdot \left(\frac{d_{10}}{1000}\right)^2 \qquad 5.2.$$

The uniformity coefficient C_U is defined as the ratio between d_{60} and d_{10}, see equation 5.3 (Larsson, 2008). A one-graded soil has a steep grain size curve and a low uniformity coefficient, and a more multi-graded soil has a high uniformity coefficient. A soil with a uniformity coefficient of 15 or higher is usually classified as a till.

$$C_U = \frac{D_{60}}{D_{10}} \qquad 5.3.$$

The function $E(C_U)$ is expressed through the following connections:

$$E(C_U) = 10{,}2 \cdot 10^6 \cdot \frac{E^3}{1+E} \cdot \frac{1}{g(C_U)^2} \qquad 5.4.$$

$$E = 0{,}8 \cdot \frac{1}{2 \cdot ln(C_U)} - \frac{1}{{C_U}^2 - 1} \qquad 5.5.$$

$$g(C_U) = \frac{1{,}3}{\log_{10} C_U} \cdot \frac{{C_U}^2 - 1}{{C_U}^{1{,}8}} \qquad 5.6.$$

5.1.3 Kozeny-Carman

The Kozeny-Carman equation was proposed by Kozeny in 1927 and modified by Carman in 1937 and 1956. It is a semi-empirical, semi-theoretic formula, and will be explained a bit more in detail below (Carrier, 2003).

$$K = \frac{\gamma}{\mu} \cdot \frac{n^3}{k_0 \left(\frac{L_e}{L}\right)^2 (1-n)^2 S_0^2} \qquad 5.7.$$

K = Hydraulic conductivity	[m/s]
γ =Specific weight	[N/m^3]
μ = Viscosity	[(Ns)/m^2]
n = Porosity	[-]
k_0 = Constant	[]
L_e = Average length of capillaries	[m]
L = Length of test piece	[m]
S_0 = Specific grain surface of solids	[m]

The $(L_e/L)^2$ term is usually called the tortuosity factor, T (Åhlén, 1993). This refers to the ratio between the paths that the liquid follows in a porous media, L_e, compared to a straight path, L. L_e is thus greater than L, and can be approximated with $\sqrt{2} \times L$. This means that the tortuosity factor can be set to 2. The constant k_0 has empirically been approximated to 2.5.

The Kozeny-Carman equation is based on the assumption that the flow in porous rock is equivalent to the flow in channels that are not inter-connected (Carman, 1956). The pore space is assumed to be equivalent to several parallel capillaries with a common hydraulic radius. The shape factor is a representative of the average shape of a pore cross-section, and is based on the hydraulic radius, m. When looking at a channel with liquid flowing through, the hydraulic radius is defined as the ratio of the channel's cross-sectional area to the wetted perimeter (that is, the part of the channel where the flow comes in contact with solid walls). For a pipe of uniform cross-section, this can be defined as

$$m = \frac{A}{P} \qquad 5.8.$$

m = hydraulic radius	[-]
A_C = cross-sectional area of channel	[m^2]
P = wetted perimeter	[m^2]

This relationship can be used when looking at flow in a porous media. Using the porosity, *n*, a random-packed bed can be regarded as a single pipe with a complicated cross-section, which gives

$$m = \frac{n}{S} \qquad 5.9.$$

m = hydraulic radius	[-]
n =*Porosity*	[-]
S = Particle surface for unit volume of the porous media	[-]

S is the particle surface for unit volume of the porous media. The specific surface S_0, relates to the particle surface as

$$S = S_0(1 - n) \qquad 5.10.$$

S = Particle surface for unit volume of the porous media	[-]
S_0 = *Specific grain surface of solids*	[-]
n =Porosity	[-]

In a porous media, the specific surface is the surface of the grains that comes into contact with the fluid.

The specific surface S_0 can be described in terms of effective grain size, d_{50}, and geometric standard deviation, σ, for spherical normally distributed grains. The derivation of this can be seen in detail in the study by Åhlén (1993). This means that the Kozeny-Carman equation can now be described using void ratio, effective grain size and geometric standard deviation in phi units, see equation 5.11. This version of the Kozeny-Carman equation was developed by Bengt Åhlén and is the version used in this thesis (Åhlén, Not yet published).

$$K = \frac{{d_{50}}^2}{180} \cdot \frac{\varepsilon^3}{1+\varepsilon} \cdot \mathrm{e}^{-0{,}48\cdot\sigma^2 - 0{,}9\cdot\sigma} \cdot \frac{\gamma}{\mu} \cdot 1000 \qquad 5.11.$$

K = Hydraulic conductivity	[m/s]
d_{50} = *The particle size for which 50% of the material is finer*	[mm]
ε = Void ratio	[-]
e = *Euler's number, mathematical constant*	[-]
σ = *Geometric standard deviation*	[mm]
γ =Specific weight (For water set to 9.81)	[N/m^3]
μ = Viscosity (For water at 20°C set to 0.001)	[(Ns)/m^2]

The geometric standard deviation is calculated by

$$\sigma = \left(\frac{\ln\left(1/_{d_{10}}\right)}{\ln 2} - \frac{\ln\left(1/_{d_{60}}\right)}{\ln 2} \right) \Big/ 1{,}53 \qquad 5.12.$$

σ = *Geometric standard deviation* [mm]

d_{10} = *The particle size for which 10% of the material is finer* [mm]

d_{60} = *The particle size for which 60% of the material is finer* [mm]

5.2 Hydraulic tests

In the field, hydraulic conductivity as well as other soil properties can be determined by several methods. The advantage of these methods is that the soil is less disturbed than in a laboratory and therefore may provide more accurate measurements.

5.2.1 Pumping test

A way to determine hydraulic conductivity by in-situ methods is through aquifer tests. A short-term pumping test is often performed, where water is pumped with a steady state for at least a day. Several observation wells nearby are studied to see the how the water levels changes by the pumping, and thus can a model of the aquifer be made. By using formulas like the Theis well equation, which is used for two-dimensional radial flow in a confined aquifer, different parameters such as transmissivity and specific storage coefficient can be determined (Knutsson & Morfeldt, 2002). The Cooper-Jacob method is simpler than the Theis equation and uses semi-logarithmic graph paper instead of logarithmic. Under ideal conditions the drawdown data can thus be plotted along a straight line instead of a curve. (Moore)

5.2.2 Slug test

Slug tests are another way to estimate flow parameters of aquifers (Fakhry & LaMoreaux, 2004). It is quicker and simpler than a pumping test as it does not require any observation wells. By removal or addition of water rapidly, the difference in hydraulic head or pressure is measured and evaluated. There are type curves and solutions that can be used for analysing slug tests. It was originally developed for unconfined aquifers, but was modified to be used for confined or stratified aquifers if certain conditions are fulfilled.

The Cooper-Bredehoeft-Papadopulous method is one method used for aquifers with confined conditions, and is used in the project studied in this thesis (Moore, 2012).

5.3 Laboratory methods

To evaluate hydraulic conductivity with laboratory methods, the constant head method or the falling head method can be used (Larsson, 2008). When the constant head method is used, water is moved through a soil under a constant head condition. The volume of water passing through the sample is measured and a hydraulic conductivity can be calculated. When the falling head method is used, the soil sample is saturated to a certain head and water then flows through the material without maintaining a constant head.

5.4 Porosity

Åberg (1992a & 1992b) studied the porosity function in the Kozeny-Carman equation. By studying the solid volume of grains of the granular material and the fraction of the solid volume that passes through a specific grain size, he set up integrals to describe grain size distribution. The void ratio and thus the porosity can then be calculated on the basis of the grain size distribution. These integrals will not be explained in this thesis, but is based on the effective grain size and the geometric standard deviation. For a thorough explanation, see the paper by Åberg (1992a & 1992b). This gives the parameters A_0 and B_0 by the following equations:

$$A_0 = \frac{2^{d_{50}}}{2 \cdot \pi} \cdot (3{,}0523 - 1{,}1549\sigma + 0{,}6497\sigma^2 - 0{,}1521\sigma^3 + 0{,}0281\sigma^4) \quad 5.13.$$

$$B_0 = 2^{d_{50}} \cdot 2^{\sigma^2 \ln 2/2} \quad 5.14.$$

The geometric is mean used to calculate the effective grain size d_{50}:

$$\mu_G = \frac{\ln\left(1/d_{60}\right)}{\ln 2} + 0{,}25 \cdot \sigma \quad 5.15.$$

μ_G = *Geometric mean* [mm]

d_{60} = *The particle size for which 60% of the material is finer* [mm]

σ = *Geometric standard deviation* [mm]

Effective grain size d_{50}:

$$d_{50} = \frac{1}{2^{\mu}} \cdot 0{,}001 \quad 5.16.$$

d_{50} = *The particle size for which 60% of the material is finer* [mm]

μ = *Geometric mean* [mm]

The void ratio is a function of the constant c, A_0, B_0 and degree of compaction d:

$$\varepsilon = 2c\frac{A_0}{B_0} + 2d \quad 5.17.$$

ε = *Void ratio*

c = *Constant, in this thesis set to 0.73*

d = *degree of compaction*

The constant d depends on the degree of compaction, and is determined by Proctor compaction. d varies between 0.18 and 0, for very loose to very compact packing. The different values can be seen in Table 1.

Table 1 Classification of degree of compaction

Value of d	No. of blows	Classification
0.18	-	Very loose
0.045	3	Loose
0.03	6	Medium
0.015	12	Compact
0	25	Very compact

The porosity is then calculated with the equation:

$$n = \frac{\varepsilon}{1+\varepsilon} \quad 5.18.$$

6 Methodology laboratory work

Laboratory work has been done to calculate hydraulic conductivity in several ways. The grain size analysis has been used to calculate a hydraulic conductivity by the use of the Hazen equation and the Gustafson equation. It is also used as part of the shape factor in the Kozeny-Carman equation. The compact density, bulk density, water content and colon test have all been used to determine the porosity, which is an important part of the Kozeny-Carman equation. The permeameter test has been used to calculate the hydraulic conductivity experimentally.

6.1 Grain size analysis

The grain size analysis is done through sieving. Several sieves with mesh sizes ranging from 20 mm to 0.063 mm are used. The soil material is first dried in an oven at 105° C to remove water content, weighed, and then washed in a fine-grained sieve to remove material smaller than 0.063 mm. The material is then dried and weighed to calculate the amount that has been washed away. The material is then sieved. The amount of material on each sieve is weighed and the percentage of the entire material that is passing through each sieve can be entered into a grain size diagram. The soil type is determined by noting how much of the material that contains of sand, gravel, silt or clay.

When reviewing the grain size diagrams, some things can be noted by observing the curve. A multi-graded material like a glacial till, containing all different grain sizes, is usually normally distributed and the curve has a slight inclination. In contrast, a more one-graded material has a much steeper inclination.

If the soil material contains a high amount of fine material that passes through the smallest 0.063 mm sieve, a sedimentary analysis is done to determine the fine soil distribution.

To determine the soil type, the amount of gravel, sand and fine material is determined, in percentages, and by entering these percentages into a nomogram the soil type can be determined, see Figure 8 (Larsson, 2008).

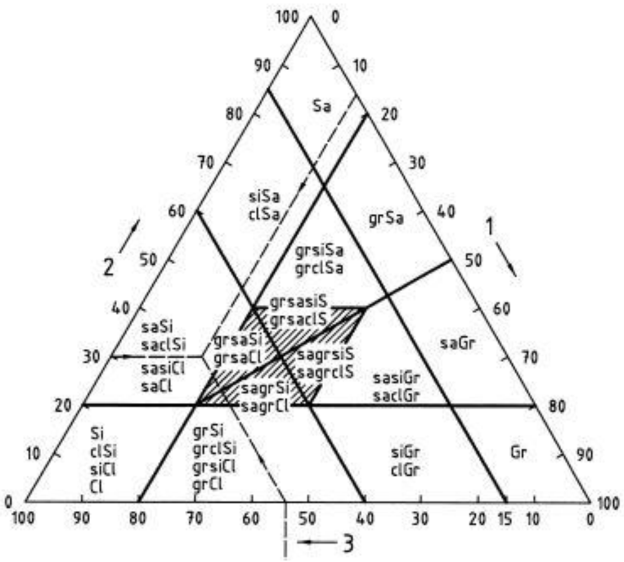

Figure 8 Nomogram for the classification of mineral soil after grain size distribution (Larsson 2008)

The percentage of gravel is placed in the side marked 1, the percentage of sand in the side marked 2, and the fine material in the side marked 3. This nomogram does not determine if the fine material is silt or clay, as a sedimentary analysis is necessary to determine the fine material.

6.2 Permeameter test

To evaluate hydraulic conductivity with laboratory methods, the constant head method or the falling head method can be used. When the constant head method is used, water is moved through a soil under a constant head condition. The volume of water passing through the sample is measured and a hydraulic conductivity can be calculated. When the falling head method is used, the soil sample is saturated to a certain head and water then flows through the water without maintaining a constant head (Fagerström & Wiesel, 1972).

For these laboratory tests, the constant head method has been used. When measuring hydraulic conductivity with the constant head method, a permeameter is used. The packed and saturated soil material is placed inside a container. The time it takes for a certain volume of water to move through the material is measured and thus the flow can be calculated in cm^3/s. The water pillar is measured to calculate the pressure. This, along with the dimensions of the container is used to calculate the hydraulic conductivity with the use of equation 6.1.

$$K = \frac{V \cdot l}{A_s \cdot t \cdot h} \cdot 10^{-2} \qquad 6.1.$$

K = Hydraulic conductivity	[m/s]
V = Volume of water flowing through the sample	[cm^3]
l = Length of sample	[cm]
A_s = Cross sectional area of sample	[cm^2]
t = Time of water flowing through the sample	[s]
h = Height of water pillar	[cm]

6.3 Compact density

To determine the compact density of a soil sample, a pycnometer test can be used (Sällfors, 1993). The volume of the pycnometer is determined as well as the weight. The pycnometer is filled with a liquid (water) of known density and weighed. A soil sample, which has been dried to 105°C and then grinded, is put into the pycnometer, which is weighed. The pycnometer is then filled with water and weighed. Both the water used and the saturated soil sample has been de-aered to remove all possible air bubbles. The volume of the water can now be calculated. The difference between the volume of the pycnometer and the volume of the water gives the volume of the soil sample. The compact density is thus calculated by equation 6.2.

$$\rho_s = \frac{m_{soil}}{V_{soil}} = \frac{m_{soil}}{V_{py} - V_w} \qquad 6.2.$$

ρ_s = *Compact density of soil sample*	[g/cm^3]
m_{soil} = *Weight of soil sample*	[g]
V_{soil} = *Volume of soil sample*	[cm^3]
V_{py} = *Volume of pycnometer*	[cm^3]
V_w = *Volume of water*	[cm^3]

6.4 Bulk density

To determine the bulk density of the sample, Archimedes principle is used (Pusch, 1973). The saturated soil sample is placed in a container. The container has previously been weighed empty and filled with mineral turpentine. The container with the soil sample is weighed in air and filled with mineral turpentine, and the bulk density can then be calculated by equation 6.3:

$$\rho = \frac{m_3 - m_1}{m_3 - m_4 - m_1 + m_2} \cdot \rho_1 \qquad 6.3.$$

ρ = *Bulk density of soil sample*	[g/cm^3]
ρ_1 = *Density of mineral turpentine*	[g/cm^3]
m_1 = *Weight of empty container*	[g]
m_2 = *Weight of container and mineral turpentine*	[g]
m_3 = *Weight of soil sample*	[g]
m_4 = *Weight of soil sample and mineral turpentine*	[g]

The mineral turpentine is used since it does not penetrate the saturated soil sample and will evaporate when the soil sample is taken out of the liquid.

6.5 Porosity

The measurements to calculate the porosity has been done in two different ways, depending on the methods used for the soil sampling. The porosity of the samples from Korsvägen has been calculated by using specific gravity and water content and the porosity of the samples from Skansen Lejonet has been calculated by colon tests.

6.5.1 Porosity measurements on Skansen Lejonet samples

Since the samples from Skansen Lejonet was taken with a sampling method that did not preserve the original water content, a method that compares the relationship between masses instead of between densities have been used, equation 6.6, as the other method requires water content to calculate the porosity (see equation 6.4) (Fransson & Nordén, 1996). The sample is packed up to a mark in a cylinder, which has been weighed empty and filled with de-aered water to the mark. The material is weighed and saturated with de-aered water and the total mass is weighed. By using the following equation, the porosity can then be measured, see equation 6.4:

$$n = \frac{m_8 - m_7}{m_6 - m_5} \cdot 100 \qquad 6.4.$$

n = Porosity	[-]
m_5 = Mass of cylinder	[g]
m_6 = Mass of water up to mark and cylinder	[g]
m_7 = Mass of soil up to mark and cylinder	[g]
m_8 = Mass of water and soil up to mark and cylinder	[g]

6.5.2 Porosity measurements on Korsvägen samples

To determine the porosity, water content, compact density and bulk density has been used as seen in equation 6.5 (Larsson, 2008):

$$n = \left(1 - \frac{\rho}{\rho_s(w+1)}\right) \qquad 6.5.$$

n = Porosity	[-]
ρ = Bulk density of soil sample	[g/cm^3]
ρ_s = Compact density of soil sample	[g/cm^3]
w = Water content	[%]

The bulk density and compact density is determined as described in chapter 6.3 and 6.4. The water content is determined by weighing a soil sample before and after it has been dried for 24 hours in 105°C (Larsson, 2008), see equation 6.6:

$$w = {}^{m_w}/_{m_s} \cdot 100 \qquad 6.6.$$

w = *Water content*	[%]
m_w = *Mass of water*	[g]
m_s = *Mass of soil*	[g]

7 Execution and observations

7.1 Soil sampling

For the tests executed in this thesis, three different methods have been used to collect samples. The sampling was performed on March 25-26, 2013.

7.1.1 Skansen Lejonet

At Skansen Lejonet, five boreholes were made, OC4008, OC4009, OC4010, OC4011 and OC4012, see Figure 9. Both the previous and current boreholes can be seen in Figure 10.

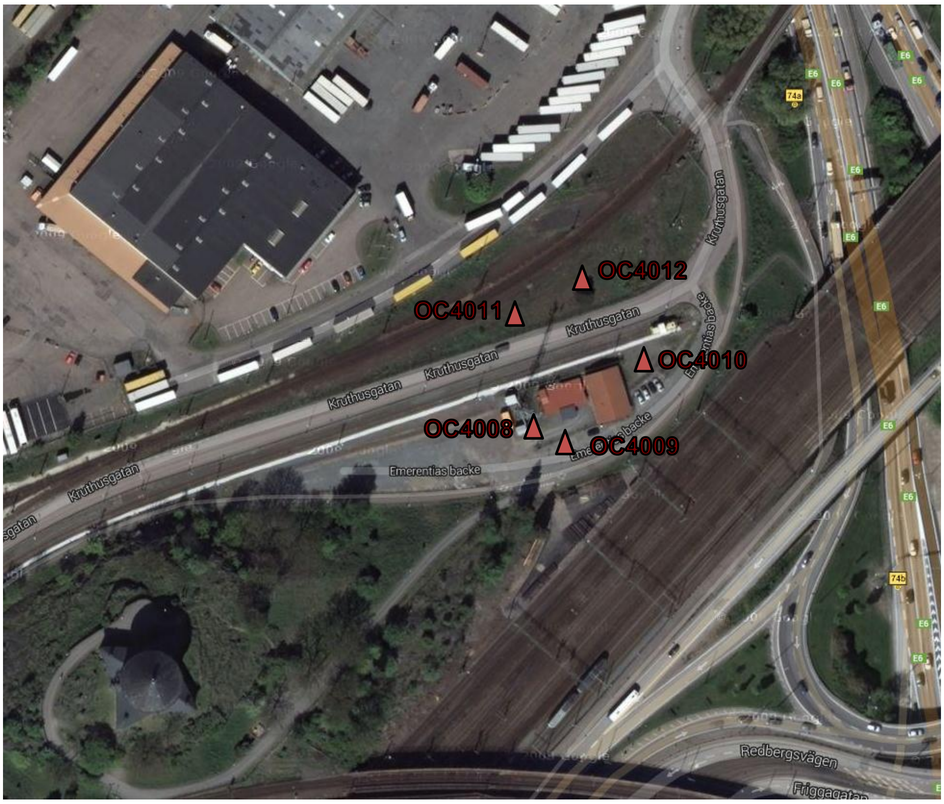

Figure 9 Map over Skansen Lejonet with boreholes marked in red (Google Maps, 2013b). Modified.

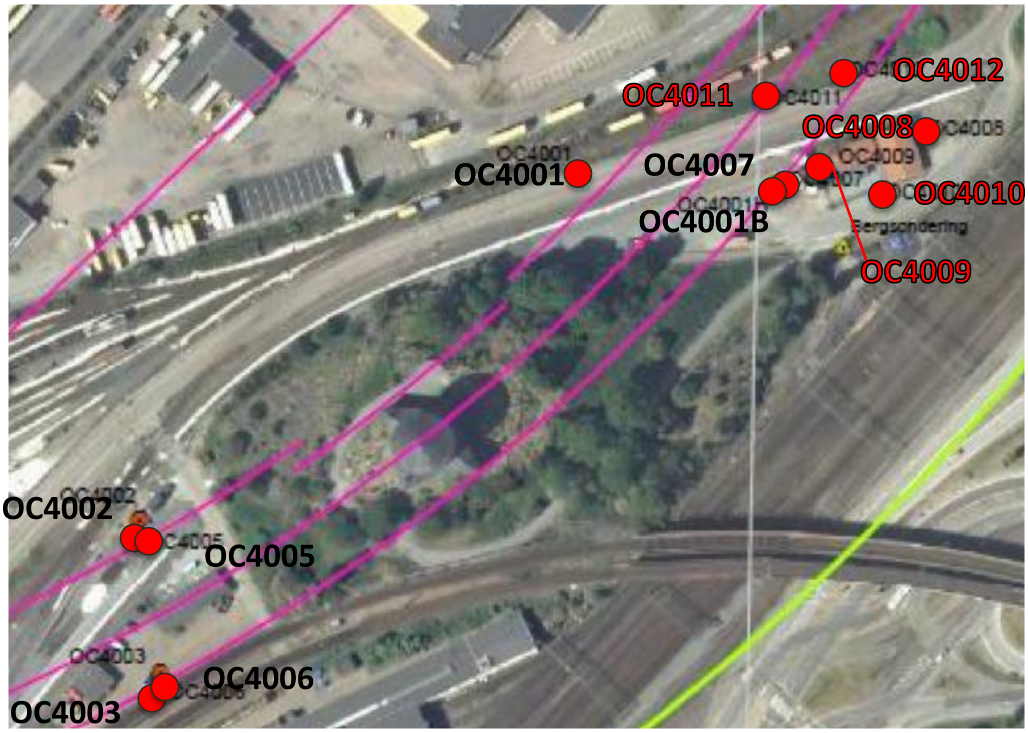

Figure 10 The boreholes at Skansen Lejonet, with the mountain block in the center of the picture. The previous boreholes are marked in black and the current in red (SWECO, 2013c).

At Skansen Lejonet, the soil material was flushed up with compressed air and water, see Figure 11. The tip of the drill were perforated with oval holes approximately 20x40 millimetres, see Figure 12. This sample method provides more disturbed samples than when using a moraine sampler. As the material is flushed with water, the original water content of the soil cannot be calculated.

Figure 11 The hammer drill used at Skansen Lejonet

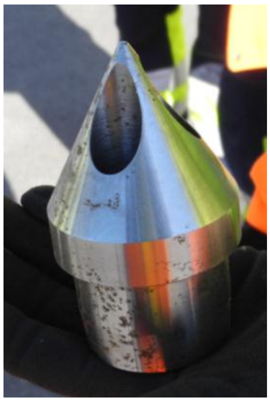

Figure 12 The tip of the drill used at Skansen Lejonet

At the same time, WSP took samples from the same boreholes, which are the ones with the same borehole id-number mentioned in chapter 8.3. However, for the tests executed in this thesis, care was taken to collect samples that were as complete as possible and included all of the finer material. To achieve this, the material that was flushed up was collected in fibre cloth. This explains the differences in the different results from the same boreholes.

When drilling at Skansen Lejonet, the sand layer under the clay was found to be small, not more than one or a couple of meters. There was a high content of fine sand and silt and a smaller content of gravel and coarse sand. The small content of gravel probably means that in this case, this method of sampling did not miss the coarser material.

7.1.2 Korsvägen

At Korsvägen, samples were collected at two boreholes, KK5038 and KK5040, see Figure 13. When comparing the test results from this sampling to previous sampling, the borehole closest to KK5038 is KK4012, only a few meters away. The borehole closest to KK5040 is KK4003 approximately 15 meters away and KK4014, 20 meters distance from KK5040 and 20 meters distance from KK5038.

Originally, a moraine sampler was going to be used in the sampling, but it broke down during sampling, and only the first sample (KK5038-1) at borehole KK5038 were collected with this sampler. The moraine sampler has an inner diameter of 42 mm and collects samples similar to a piston sampler, in order to achieve as undisturbed samples as possible. After the moraine sampler broke down, a barrel sampler was used to collect the rest of the samples. The barrel sampler has an inner diameter of 30 mm.

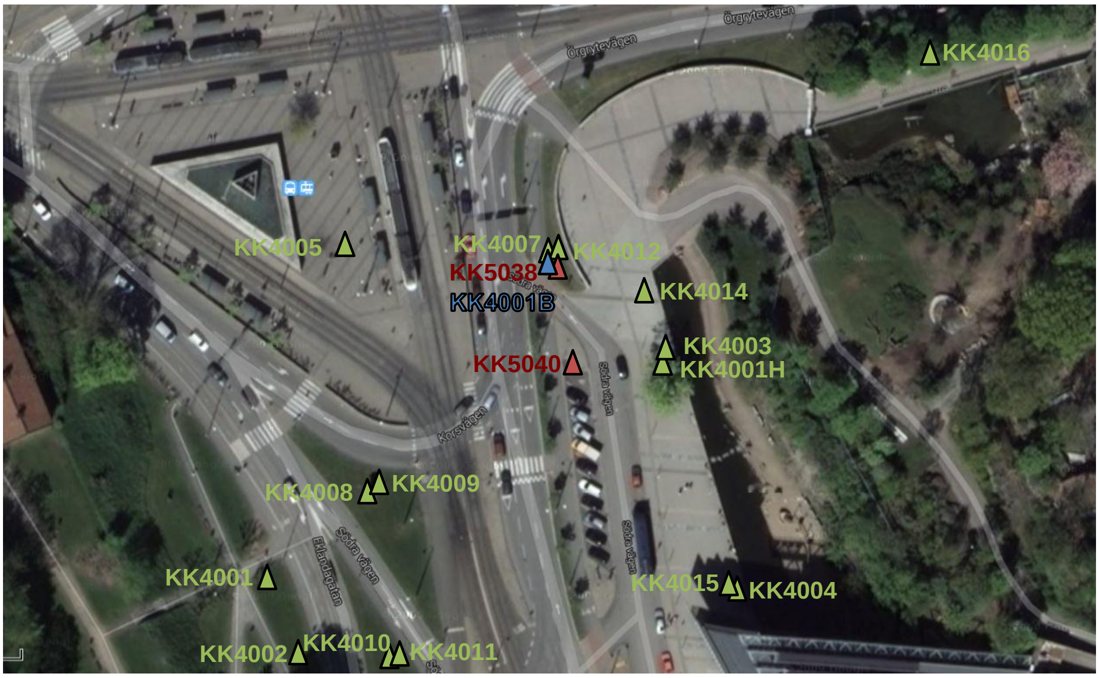

Figure 13 Map showing the boreholes at Korsvägen. Current sampling is marked in red and previous sampling in green. The pumping well is marked in blue (Google Maps, 2013a) (Modified).

The samples were to various degrees rather heterogenous, with all sorts of grain sizes from clay to gravel. It is worth noting that in several of the samples, gravel larger than 8 millimetres were found, the largest stone as big as 23 millimetres.

7.2 Previous sampling

Previously, soil samples have been retrieved from the boreholes to perform grain size analyses. Hydraulic tests such as slug tests, pumping tests and measurements of the recharge have also been performed.

7.2.1 Soil sampling for grain size analyses

The soil samples used in this thesis have been compared to previous grain size analyses taken in nearby boreholes. The boreholes are mostly 2 inch-pipes, and in a few cases hammer boreholes into bedrock with 4.5 inch-pipes. The previous soil samples used for grain size analyses were taken with perforated pipes. These pipes are perforated with holes spanning 8 millimetres in diameter, see Figure 15. The soil enters the pipe through these holes. A hose with compressed air or water is used to blow out the soil material, which is collected in a vessel, and the wanted amount of material is taken from the vessel, see Figure 14. Using this method means that coarser fractions than 8 millimetres of the soil material are not part of the sample. The finest fractions are also removed during sampling. Depending on if the material is relatively single-graded or multi-graded this may lead to the grain size analysis being skewed. A single-graded sand may very well give good results, as the majority of the material is captured by this sample methodology, but a more multi-graded soil may give misleading results if the coarser and finer fractions that are being left out by this type of sampling makes up a larger part of the material.

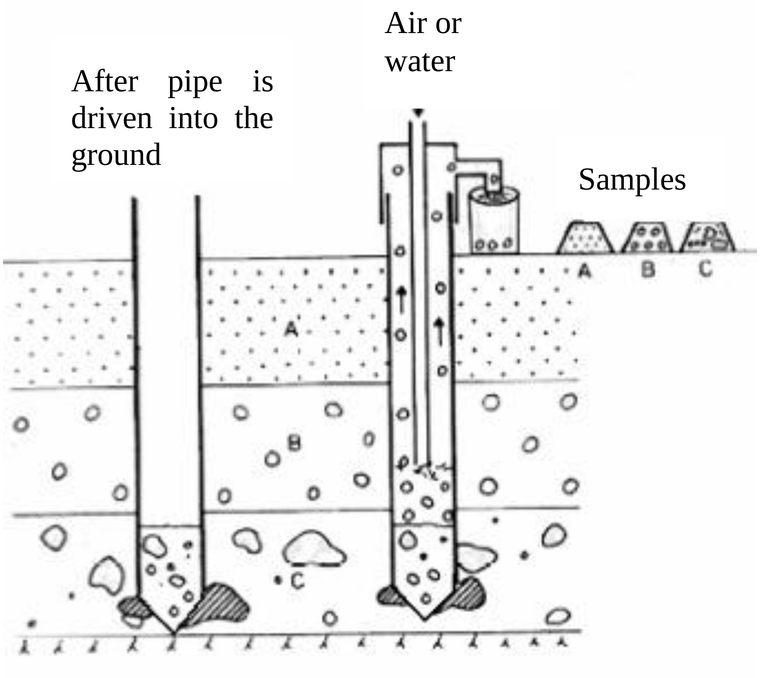

Figure 14 Principal sketch of the sampling method used in previous sampling (Gustavsson, 2005)

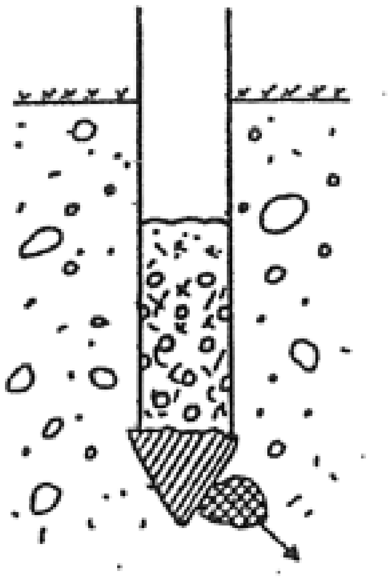

Figure 15 Drawing of a perforated pipe (Andersson, et al., 1984)

7.2.2 Slug tests

As a complement to the grain size analyses, hydraulic tests have also been done, both at Skansen Lejonet and at Korsvägen. Four tests were performed at Skansen Lejonet and fourteen tests were performed at Korsvägen in the 2 inch-pipes. A certain volume of water was added to the pipes, and the change in pressure at the ground water Table was measured both manually during the first 10 minutes, and with a pressure transmitter. The slug tests were evaluated with the Cooper-Bredehoeft-Papadopulos method.

7.2.3 Pumping tests

When performing the pumping tests, a general assessment was made for which observation wells can be influenced during the interference tests. The properties of the pumping well and the aquifers are evaluated and the boundary conditions are determined to create a model of the aquifer. The response from the observation wells are then studied and evaluated. The pumping tests were performed with wells with adapted filter widths. The observation wells are drilled down to the glacial till on top of the bedrock so that the filter part of the wells is placed into the conductive friction material. Just as with the boreholes, there are 8 mm holes perforated across the mantel area. The inside diameter of the casing tubes are approximately 52 mm and the diameter of the filter is approximately 50 mm. The Cooper-Jacob method was used to evaluate the results (SWECO, 2013b).

The pumping test at Skansen Lejonet was performed in April 2013 in the well OC4001B (see Figure 10). At the beginning of the test there was heavy rainfall that affected the response in four of the observation wells. The measurements from these wells were consequently not used in the analysis. Five observation wells in the lower aquifer to the northwest responded to the pumping, while the well in the upper aquifer to the west did not respond. The results showed that the aquifer probably was limited in a longitudinal extent, confined to a few 100 meters.

At Korsvägen, a pumping test was performed in January 2013 in the well KK4001B (see Figure 13). Six of the observation wells around Korsvägen and south responded to the pumping. An observation well north-northwest of the area does also show a response but the observation well to the north does not show a clear recharge. To the east, towards Liseberg, none of the four observation wells showed any response, however a pumping test performed in 2005 indicated some hydraulic contact, which cannot be disregarded.

7.3 Laboratory work

The laboratory work was performed between April and June of 2013 in the geotechnical and hydrogeological laboratory at Chalmers University of Technology. Due to the differences in sampling method, mainly that the sampling at Skansen Lejonet did not preserve the original water content, different laboratory tests were performed on the samples. The permeameter test requires samples to be at least a volume of one litre. Four samples were large enough to perform this test, see description in chapter 6.2. The samples were packed to simulate in-situ conditions. During the test, the flow was measured until it had reached a steady state, and several values in a row were the same within a margin of ±1%. The test setup can be seen in Figure 16.

Figure 16 From left to right, permeameter test, pycnometer with soil and water, pycnometer with soil and mineral turpentine

All samples were sieved to perform a grain size analysis, see description in chapter 6.1. Many of the samples from Korsvägen had a large amount of fine material, but these samples were prematurely destroyed before a sedimentation analysis could be done.

The porosity measurements were done in two different ways, described in chapter 6.5. The methods used for samples were the water content cannot be determined requires the samples to be of a certain volume, which is why experimental porosity values are missing for some of the samples from Skansen Lejonet. This method is also more likely to have uncertainties since it is less precise. The porosity values from Korsvägen are therefore probably more reliable than the values from Skansen Lejonet. For the Korsvägen samples, pycnometers were used to determine compact and bulk density, see Figure 16.

7.4 Calculations of hydraulic conductivity

The three different empirical methods that are described in chapter 3 have all been used to calculate the hydraulic conductivity. Gustafson and Hazen both depend on grain size, more particularly the parameters d_{60} and d_{10} and the relationship between these. In the cases where d_{10} were smaller than 0,063 millimetres the values have been extrapolated with a log-normal distribution using the Excel add-on @risk.

The Kozeny-Carman method also uses d_{60} and d_{10}, but in addition to this, porosity is also used.

8 Results

The results from the porosity calculations and the hydraulic conductivity calculations are presented below. The results from previous sampling are also presented in this chapter.

8.1 Porosity

The porosities have been calculated experimentally in two different ways depending on the origin of the samples (see chapter 6.5 for description). The porosity measurements on the samples from Korsvägen is likely to have less uncertainties than the samples from Skansen Lejonet, where the measurements are less exact and the samples are more disturbed than the Korsvägen samples. The porosity has not been calculated experimentally for three of the Skansen Lejonet samples due to the insufficiently small sample size in these cases.

The porosity has also been calculated from grain size analysis, as described in chapter 5.4. In this thesis, no Proctor compaction has been done and the optimal water content is thus not determined. The degree of compaction is therefore not determined. However, the porosities for different d-values have been calculated and compared to the experimentally obtained porosities. The porosities from Skansen Lejonet can be seen in Table 2. The degree of compaction was chosen depending on the soil type and the experimentally obtained porosity. As it is not likely that different levels of the same borehole have different degrees of compaction, a degree of compaction where the porosity calculated from this correspond best to the experimentally obtained porosity on average for the borehole have been chosen. Table 2 and 3 shows the different porosities based on a span of compaction degrees. The chosen porosity is marked in grey and is the one used to calculate hydraulic conductivity with the Kozeny-Carman equation, K_{KC1}.

Table 2 The porosities from Korsvägen depending on degree of compaction, as well as experimentally calculated. The porosity used in the calculations is marked in grey. The uniformity coefficient, Cu, is also presented.

Skansen Lejonet	V. loose	Loose	Medium	Com-pact	V. compact	Exp	Soil type	C_u
OC4008-1	0.31	0.16	0.14	0.11	0.09	0.28	Gravelly sand	23.8
OC4008-2	0.36	0.23	0.21	0.19	0.17		Gravelly sand	9.8
OC4008-3	0.34	0.19	0.17	0.15	0.13		Gravelly sand	15.0
OC4009-1	0.45	0.36	0.34	0.33	0.32	0.34	Sand	2.6
OC4009-2	0.43	0.33	0.32	0.30	0.29	0.33	Sand	3.4
OC4010	0.44	0.34	0.33	0.32	0.30	0.34	Sand	3.0
OC4011-1	0.46	0.37	0.36	0.35	0.33		Sand	2.3
OC4011-2	0.45	0.35	0.33	0.32	0.31	0.34	Sand	2.9
OC4012	0.45	0.35	0.34	0.33	0.31	0.34	Sand	2.7

For the porosities from Skansen Lejonet the theoretical porosities closest to the experimentally varies from Very Loose to Medium.

When comparing the experimental values from Korsvägen with the closest corresponding theoretical value, the degree of compaction varies a lot. The chosen degree of compaction for the porosities is Compact, however the porosity at KK5040-1 is so different from the experimentally obtained one that Loose is chosen instead. This borehole level is in this case seen as an anomaly.

Table 3 The porosities from Korsvägen depending on degree of compaction, as well as experimentally calculated. The porosity used in the calculations is marked in grey.The uniformity coefficient, Cu, is also presented.

Korsvägen Borehole	V. loose	Loose	Medium	Compact	V. compact	Exp.	Soil type	C_u
KK5040-1	0.30	0.14	0.12	0.10	0.07	0.20	Gravelly sand	31.1
KK5040-2	0.41	0.30	0.29	0.27	0.26	0.27	Gravelly silty sand	4.5
KK5040-3	0.40	0.29	0.27	0.26	0.24	0.19	Sandy silt/clay	5.2
KK5038-1	0.42	0.31	0.29	0.28	0.26	0.27	Clayey silty sand	4.2
KK5038-2	0.33	0.18	0.16	0.14	0.11	0.18	Clayey silty sand	17.5

Two factors can be seen that influences the porosity, soil type and uniformity coefficient. When calculating the theoretical porosity, the uniformity coefficient influences the value quite a lot. A multi-graded soil gives a low porosity as smaller grains fits into the voids left by larger grains. For soil with a high content of fine material, the material is probably more compacted whereas for coarser material the packing is looser. This influences what grade in the compaction index the porosity will lie in. A graph of how the different porosities vary can be seen in appendix 4. The impact of the degree of compaction for the hydraulic conductivity can be seen in appendix 3.

8.2 Hydraulic conductivity

The hydraulic conductivity has been calculated with four different methods, a short description of these can be seen in Table 4. There are two different calculations based on the Kozeny-Carman method, as the porosity is calculated in two different ways, see chapter 6.5.

Table 4 The different methods used to calculate the hydraulic conductivity, K.

Name	**Abbreviation**	**Parameters**
Hazen	K_H	Grain size, empirical constant
Gustafson	K_G	Grain size, uniformity coefficient
Kozeny-Carman	K_{KC1}	Grain size, shape factor, tortuosity, theoretical porosity
Kozeny-Carman	K_{KC2}	Grain size, shape factor, tortuosity, experimental porosity
Permeameter	K_{exp}	Flow

The hydraulic conductivity results are shown in Table 5. The permeameter test has only been performed on four samples, and only three of these gave a result. The Kozeny-Carman hydraulic conductivity calculated from experimental porosity, K_{KC2}, have not been calculated in three cases due to the lack of porosity calculations in these cases. To show the difference between the results based on Gustafson and the results based on Kozeny-Carman, the ratio, K_G/K_{KC1}, between these two methods are also shown.

Table 5 Hydraulic conductivity measurements from four different methods.

Borehole	K_H	K_G	K_{KC1}	K_{KC2}	K_{exp}	K_G/K_{KC1}	Soil type
Skansen Lejonet	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]		
OC4008-1	4.6E-05	2.2E-05	2.7E-06	1.6E-06	2.4E-07	8.20	Gravelly sand
OC4008-2	8.8E-05	7.3E-05	3.4E-05		-	12.65	Gravelly sand
OC4008-3	1.2E-04	7.5E-05	1.9E-05		-	31.09	Gravelly sand
OC4009-1	2.0E-04	2.8E-04	1.3E-04	1.2E-04	-	2.17	Sand
OC4009-2	2.0E-04	2.7E-04	9.2E-05	1.1E-04	-	2.44	Sand
OC4010	9.4E-05	1.3E-04	5.3E-05	5.9E-05	No flow	2.13	Sand
OC4011-1	5.7E-05	8.3E-05	4.4E-05		5.3E-06	1.88	Sand
OC4011-2	5.0E-05	7.2E-05	3.0E-05	3.2E-05	-	2.05	Sand
OC4012	4.9E-05	7.0E-05	3.2E-05	3.1E-05	1.6E-06	2.20	Sand
Korsvägen							
KK5040-1	2.9E-05	1.3E-05	8.30E-08	2.3E-07	-	203.00	Gravelly sand
KK5040-2	1.9E-05	2.3E-05	4.4E-06	4.3E-06	-	5.24	Gravelly silty sand
KK5040-3	2.4E-06	1.9E-06	6.0E-08	8.0E-08	-	8.73	Sandy silt/clay
KK5038-1	1.6E-05	1.9E-05	3.0E-06	3.7E-06	-	5.98	Clayey silty sand
KK5038-2	4.6E-06	2.7E-06	2.4E-08	2.7E-07	-	45.17	Clayey silty sand

It is clear that Gustafson and Hazen gives the highest values, sometimes with a difference of several orders of magnitude between the highest and the lowest values. The lowest values are the ones experimentally calculated from permeameter tests, K_{exp}, and the Kozeny-Carman equation with porosities calculated from grain size, K_{KC1}.

Skansen Lejonet shows higher hydraulic conductivity than Korsvägen. The values at Skansen Lejonet spans between 10^{-4} and 10^{-7} m/s and at Korsvägen between 10^{-5} and

10^{-8} m/s. The grain size curves for Skansen Lejonet can be seen in appendix 1, and the grain size curves for Korsvägen in appendix 2. In appendix 2, some values have been extrapolated with a log-normal distribution.

8.3 Previous sampling – grain size analysis

The results from previous samplings are shown in Tables 6 and 7 (SWECO, 2013a) (SWECO, 2013c). The previous analyses have used the Gustafson equation, K_G, to calculate hydraulic conductivity. To compare the different results, the hydraulic conductivity has now also been calculated with the Hazen equation, K_H, and the Kozeny-Carman equation, K_{KC1}. The porosities used for the Kozeny-Carman equation are empirically calculated from grain size. The degree of compaction has been chosen depending on soil type, with the values from current sampling as model. This might make the Kozeny-Carman results somewhat uncertain. The uniformity coefficient, C_U, is also shown. The boreholes at Skansen Lejonet that are the same as the ones tested in this thesis are marked with italic letters in Table 6.

Table 6 Hydraulic conductivity from boreholes at Skansen Lejonet calculated with three different methods, and the uniformity coefficient C_U.

Borehole Skansen Lejonet	Level [m]	K_H [m/s]	K_G [m/s]	K_{KC1} [m/s]	C_U [-]
OC4001H	7-8	8.2E-03	1.1E-02	3.7E-03	3.1
OC4001H	8-9	5.1E-04	6.6E-04	1.8E-04	4.0
OC4001H	9-10	1.3E-03	1.3E-03	1.2E-04	6.7
OC4001H	10-11	1.0E-03	1.3E-03	2.3E-04	4.7
OC4001H	11-12	1.7E-03	2.3E-03	6.5E-04	3.4
OC4001	18-19	5.3E-05	7.7E-05	3.5E-05	2.6
OC4001	19-19.3	6.9E-05	1.0E-04	5.2E-05	2.3
OC4002	14-15	4.6E-05	6.5E-05	2.6E-05	3.0
OC4002	15-16	1.4E-04	2.0E-04	7.9E-05	3.0
OC4002	16-17	4.7E-05	6.1E-05	1.3E-05	4.2
OC4002	17-18	1.4E-04	1.4E-04	1.7E-05	6.8
OC4002	18-19	4.6E-05	5.4E-05	1.1E-05	5.1
OC4003	12-13	2.9E-05	4.0E-05	1.6E-05	3.4
OC4003	13-14	7.4E-05	1.1E-04	5.2E-05	2.5
OC4005	1-2	2.9E-03	3.2E-03	3.5E-03	1.0
OC4006	0-2.7				
OC4007	7-8	7.4E-05	1.1E-04	4.7E-05	2.8
OC4007	8-9	7.2E-04	1.0E-03	3.7E-04	3.2
OC4007	9-10	1.2E-03	1.6E-03	5.5E-04	3.4
OC4008	16.0-17.0	3.5E-03	4.9E-03	1.5E-03	3.2
OC4008	15.0-16.0	1.9E-05	5.9E-06	1.9E-09	45.8
OC4008	15.5-16.5	8.2E-05	7.8E-05	7.3E-06	7.7
OC4009	8-9	2.0E-04	2.9E-04	1.2E-04	2.8
OC4009	9-10	3.3E-04	4.2E-04	1.1E-04	4.2
OC4010	11.6-12.6	6.3E-05	9.2E-05	4.3E-05	2.6
OC4011	13.1-14.1	5.0E-05	7.2E-05	3.0E-05	2.9
OC4012	13.4-14.4	7.6E-05	1.1E-04	5.1E-05	2.6

Just as in previous results, Hazen and Gustafson show fairly similar results where Kozeny-Carman gives lower hydraulic conductivity than the other two. The hydraulic conductivity at this location is rather high, with maximum values in orders of 10^{-2} and 10^{-3} m/s and ranging down to around 10^{-5} or 10^{-6} m/s in the case of K_{KC1}.

In Table 7, the results from Korsvägen can be seen. At Korsvägen, some of the d_{10}-values are too small to have been determined from grain size analysis and was instead extrapolated. This makes the results more uncertain. The samples were d_{10} is extrapolated is marked with an asterisk in Table 7.

Table 7 Hydraulic conductivity from boreholes at Korsvägen calculated with three different methods, and the uniformity coefficient C_U.

Borehole Korsvägen	Level [m]	K_H [m/s]	K_G [m/s]	K_{KC1} [m/s]	C_U [-]
KK4001	10-11	1.9E-09	3.2E-10	1.9E-15	125
KK4002*	10-11	4.6E-06	1.6E-06	8.7E-10	40
KK4003	9-10	2.9E-05	3.9E-05	1.2E-05	3.6
KK4003	10-11	2.9E-05	4.2E-05	2.0E-05	2.2
KK4003	11-12	7.4E-05	9.0E-05	1.9E-05	4.75
KK4004	13-14	1.4E-04	1.6E-04	2.5E-05	5.7
KK4004	14-15	9.4E-05	1.2E-04	2.8E-05	4.4
KK4004	15-16	9.4E-05	8.9E-05	8.3E-06	7.8
KK4004	16-17	1.4E-04	1.7E-04	3.9E-05	4.6
KK4004	17-18	1.2E-04	1.4E-04	3.2E-05	4.6
KK4004	18-19	1.2E-04	1.4E-04	3.2E-05	4.6
KK4004	19-20	2.9E-05	3.1E-05	3.4E-06	6.2
KK4005	12-13	1.4E-04	1.4E-04	1.4E-05	7.5
KK4005	13-14	7.4E-05	6.1E-05	3.3E-06	10.1
KK4005*	19-20	1.0E-05	1.5E-05	5.8E-06	2.7
KK4005	21-22	4.2E-05	5.9E-05	2.5E-05	2.8
KK4005	22-23	4.2E-05	5.8E-05	2.2E-05	3.2
KK4007*	9-10	4.6E-06	2.9E-06	3.7E-08	15.5
KK4008	20-21	9.4E-05	1.3E-04	5.0E-05	3.1
KK4008	21-22	5.7E-05	8.2E-05	3.9E-05	2.6
KK4010*	17-18	1.9E-05	2.6E-05	7.8E-06	3.3
KK4011*	1-1,6	4.6E-06	1.6E-06	8.7E-10	40
KK4012	17-18	5.7E-05	8.1E-05	3.4E-05	2.9
KK4012	20-21	7.4E-05	7.0E-05	6.4E-06	7.9
KK4014	5-6	2.9E-05	2.3E-05	1.0E-06	11
KK4014	10-11	2.9E-05	4.2E-05	1.7E-05	2.6
KK4014	11-12	4.2E-05	5.3E-05	1.3E-05	4.3
KK4015	7-8	4.2E-05	5.7E-05	1.9E-05	3.5
KK4015*	9-10	1.9E-05	2.7E-05	1.1E-05	2.5
KK4015	10-11	5.7E-05	8.2E-05	4.1E-05	2.4
KK4016	4.5-5.5	4.2E-05	4.9E-05	1.1E-05	5.2
KK4016	6-7	2.3E-04	2.8E-04	6.6E-05	4.5
KK4016*	7-8	4.6E-06	2.5E-06	1.5E-08	20
KK4016	8-9	2.9E-05	2.7E-05	1.8E-06	8
KK4001H	11-13	2.0E-04	6.5E-05	1.3E-07	43.1

The results from Korsvägen indicate that the Kozeny-Carman equation gives a lower hydraulic conductivity, just as in previous results. It is worth noting that the results differ the most when the uniformity coefficient is high. This is especially the case in borehole KK4001, where the uniformity coefficient is as high as 125 and the hydraulic conductivity differ with five and six orders of magnitude respectively between Gustafson/Hazen and Kozeny-Carman. Even though this value seems to be an anomaly (the soil from this borehole is classified as sandy silty clay), the results from the next borehole, KK4002, shows a difference between Gustafson/Hazen and Kozeny-Carman of four orders of magnitude, and a uniformity coefficient of 40. The hydraulic conductivity is generally lower at Korsvägen than at Skansen Lejonet, with most values around 10^{-5} m/s and ranging down a few orders of magnitude. The uniformity coefficient is generally quite small and indicating of a one-graded soil, but in several cases the uniformity coefficient is higher and indicating of a more till-like soil.

8.4 Hydraulic tests

As well as grain size analyses, some hydraulic tests have been made at both locations.

8.4.1 Slug tests

At Skansen Lejonet, slug tests were performed in four of the boreholes (SWECO, 2013c). The slug tests were evaluated with the Cooper-Bredehoeft-Papadapulos method and the recovery measurements with the Cooper-Jacob method. The results are presented in Table 8, along with the hydraulic conductivity with Gustafson, K_G, and Kozeny-Carman, K_{KC1}, method from the grain size analysis for comparison.

Table 8 Hydraulic conductivity evaluated from slug tests at Skansen Lejonet, compared to hydraulic conductivity calculated from grain size analysis.

Borehole Skansen	Filter level [m]	K_{slug} [m/s]	K_G [m/s]	K_{KC1} [m/s]
OC4001	18.3-19.3	-	7.7E-05	3.5E-05
OC4002	18-19	2.50E-06	5.4E-05	1.1E-05
OC4003	13.1-14.1	1.30E-08	1.1E-04	5.2E-05
OC4005	2-3	-	3.2E-03	3.5E-03

In two of the four boreholes, the filters were clogged and no results were achieved. For the two boreholes where results were achieved, K_{slug} in OC4002 were slightly lower than both K_G and K_{KC1}. In borehole OC4003, K_{slug} were significantly lower than both K_G and K_{KC1}.

At Korsvägen, slug tests were performed in 14 of the boreholes and measurements of the recovery of the ground water Table was made in the three percussion boreholes (SWECO, 2013a). The results are presented in Table 9, similar to Table 8. In some of the boreholes, no grain size analysis has been done and K_G and K_{KC1} are left blank.

Table 9 Hydraulic conductivity evaluated from slug test at Korsvägen, compared to hydraulic conductivity calculated from grain size analysis.

Borehole Korsvägen	Filter level [m]	K_{slug} [m/s]	K_G [m/s]	K_{KC1} [m/s]
KK4001	10.5-11.5	4.7E-09	3.2E-10	1.9E-15
KK4002	9.75-10.75	3.6E-10	1.6E-06	8.7E-10
KK4003	11.2-12.2	3.0E-05	9.0E-05	1.9E-05
KK4004	18.9-19.9	6.8E-10	3.1E-05	3.4E-06
KK4005	21.7-22.7	6.3E-10	5.8E-05	2.2E-05
KK4006	12.2-13.2	3.2E-07	-	-
KK4007	9-10	4.4E-07	2.9E-06	3.7E-08
KK4009	20-21	1.9E-05	-	-
KK4010	19.3-20.3	-	2.6E-05	7.8E-06
KK4011	0.5-1.5	1.9E-05	1.6E-06	8.7E-10
KK4013	17-18	1.2E-04	-	-
KK4014	11.3-12.3	1.8E-05	5.3E-05	1.3E-05
KK4015	10-11	1.3E-05	8.2E-05	4.1E-05
KK4016	8.5-9.5	8.3E-07	2.7E-05	1.8E-06

8.4.2 Pumping tests

The analysis from the pumping test at Skansen Lejonet shows that a model with a 30-meter wide channel can explain the response at the first 50 minutes, where the flow is linear. The drawdown rate is then lowered which is interpreted as leakage from the friction material surrounding the channel. The analysis shows that the channel probably represents a limited aquifer in a longitudinal extent, confined to a few 100 meters.

The result of the pumping tests shows that the lower aquifer is probably closed. The transmissivity for the channel is rather high, $1.2*10^{-3}$ m^2/s. Outside the channel the transmissivity is estimated to approximately $3*10^{-6}$ – $3*10^{-5}$ m^2/s. There are large uncertainties when estimating the height of the ground water zone, but a rough estimation based on sounding is a depth of 1 meter. The hydraulic conductivity inside the channel is then $1.2*10^{-3}$ m/s, and the hydraulic conductivity outside is between $3*10^{-6} – 3*10^{-5}$ m/s.

The pumping test at Korsvägen showed a large influence area, probably several hundreds of meters (SWECO, 2013b). The tests showed a probable connection between the lower and middle ground water zone. Probably, the lower zone is also hydraulically connected to the upper zone and the bedrock aquifer. The transmissivity was calculated to be between $0.9 – 2 *10^{-4}$ m^2/s. As the height of the ground water zone was approximated to 6 meters, the hydraulic conductivity then becomes between $1.5 – 3.3 *10^{-5}$ m/s.

8.5 Statistical analysis

A statistical analysis has been performed to compare the different methods for measuring hydraulic conductivity. The hypothesis is that the methods for measuring hydraulic conductivity, Kozeny-Carman, Hazen and Gustafson, are significantly different from each other, and that the results do not differ because of random differences in the samples. This has been tested with an ANOVA single factor analysis, see appendix 5. The analysis shows that with 97.8% certainty, the methods are significantly different. This means that the Kozeny-Carman equation will give a different result than Gustafson. However, the Hazen and Gustafson methods are not significantly different from each other.

9 Evaluation of results

The four different methods for estimating hydraulic conductivity used in this thesis, Kozeny-Carman, Hazen, Gustafson and experimental, provides different values with some clear trends. To illustrate the differences between the methods, the results from the current sampling have been plotted in a column chart. As the difference in magnitude is the most interesting to see, the y-scale is logarithmic and reversed. This means that the lowest conductivities have the highest bars in these charts, and vice versa.

The results from Skansen Lejonet are presented in Figure 17.

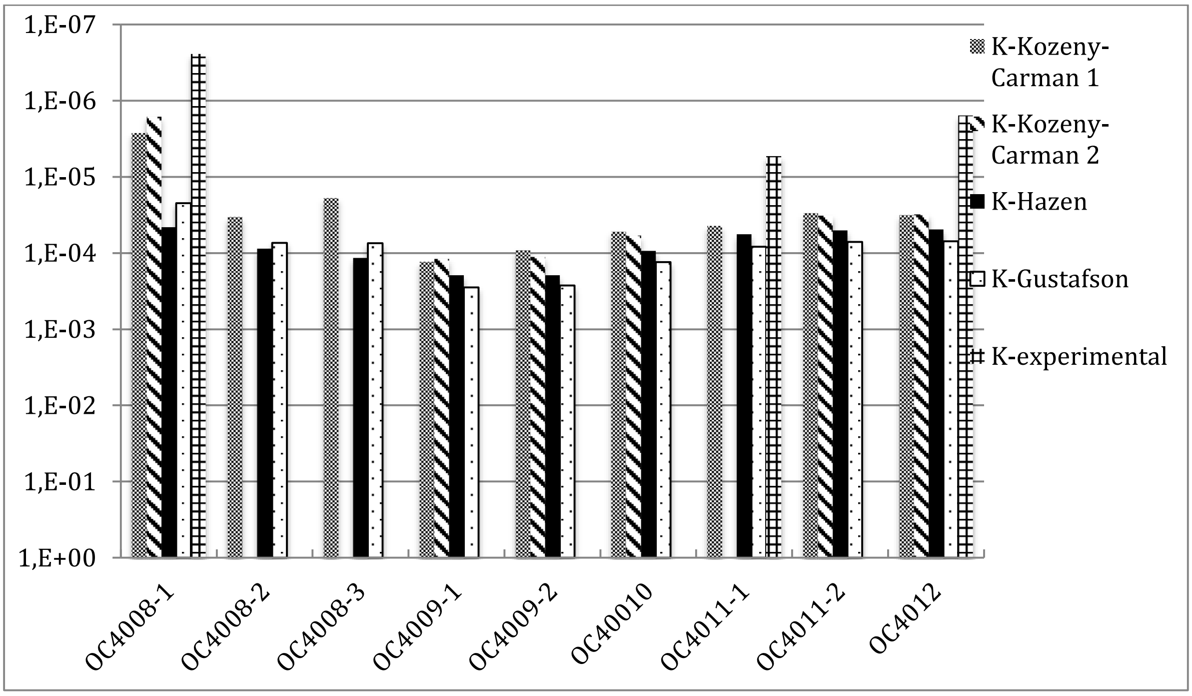

Figure 17 Comparison of the results from Skansen Lejonet of the hydraulic conductivity with different methods. The highest bars show the lowest conductivities.

The soil at Skansen Lejonet is generally more one-graded, which can be seen in these results. The exceptions for this are partly in borehole OC4008 and partly in the permeameter results. The Kozeny-Carman equation gives up to one and a half order of magnitude difference in this borehole, which differ from the other boreholes, were the results are almost similar.

The results from Korsvägen are presented in Figure 18.

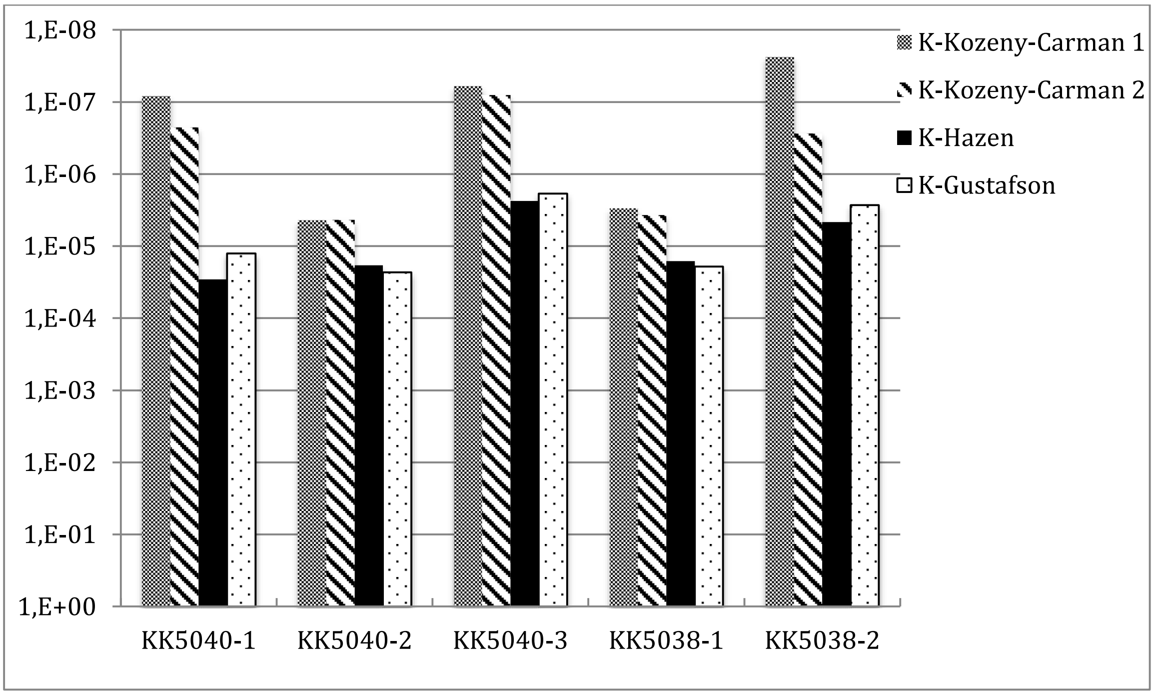

Figure 18 Comparison of the results from Korsvägen of the hydraulic conductivity with different methods. The highest bars show the lowest conductivities

The results at Korsvägen show some differences between the different methods. Hazen and Gustafson are consistently fairly similar, which also corresponds to the statistical analysis that showed no significant differences between the methods. They are also consistently higher than Kozeny-Carman. The more multi-graded soil at Korsvägen is evident as the results from Korsvägen show the largest differences between calculation methods, despite using the same sampling method. The differences vary between one up to almost three orders of magnitude. A discussion of the permeameter result will follow.

9.1 The effect of porosity on Kozeny-Carman results

When comparing the two different Kozeny-Carman results, K_{KC1} are sometimes lower than K_{KC2}. K_{KC1} is the hydraulic conductivity when using the theoretically calculated porosities and K_{KC2} is the hydraulic conductivity when using the experimentally obtained porosities. This difference is especially clear when the uniformity coefficient is high. As can be seen in Table 7, chapter 8.3, there are some high C_U-values that lead to a difference between the two methods of many orders of magnitude. The most extreme case is in borehole KK4001 where the uniformity coefficient is 125. However, the soil from this borehole is classified as sandy silty clay, and the value can be viewed as an anomaly. Even without this extreme value, there are results from Korsvägen with uniformity coefficients up to 40, which leads to a difference of four orders of magnitude between Kozeny-Carman and Gustafson, from 10^{-10} to 10^{-6} at for example borehole KK4002 and KK4011. The hydraulic conductivity is thus almost ten thousand times higher when using K_G than K_{KC}, obviously one of these values is not realistic. An important thing to take into consideration is that some of the D_{10}-values at Korsvägen are extrapolated and thus uncertain.

When using the theoretically calculated porosities, two parameters seem to influence the value. The degree of compaction depends a lot on the soil type, for example a clayey soil is more compacted than a granular soil. Obviously this also influences the porosity, as the voids between grains are smaller if the grains are smaller and vice versa. In this thesis, the degree of compaction has not been the focus, but in retrospect, this is something that could have been worth studying a lot more. When calculating the porosities theoretically for the previous sampling, a rough estimation of the degree of compaction from the soil type has been done. The comparison between experimentally calculated porosities and the theoretically calculated ones from current sampling has been used as a model to determine the degree of compaction from the soil type. For example, in the borehole KK5040-2 the experimental value was 0.27. This corresponds to the value when the degree of compaction is “Compact” (12 blows with the Proctor compaction). As can be seen in Table 10, the values fits better in some cases than in other, but a rough estimation can be made.

Table 10 Example of different porosities based on various degree of compaction and experimental values. The values marked in grey are the porosities that best correspond to the experimental values.

Korsvägen	V. loose	Loose	Medium	Compact	V. compact	Exp.
KK5040-2	0.41	0.30	0.29	0.27	0.26	0.27
KK5040-3	0.40	0.29	0.27	0.26	0.24	0.19

There are however only a few samples which makes the comparison somewhat uncertain and arbitrary. Using experimentally calculated porosities as a key to study how the soil type determines the degree of compaction would be most interesting, and could if done thoroughly lead to a simplification when using the Kozeny-Carman equation to calculate hydraulic conductivity.

As Vienken and Dietrich (2011) showed, the method to calculate porosity must be chosen carefully as this may skew the results. The conclusion from Frings et al. (2011) that there are no unique relationships between grain size and porosity means that it might be difficult to use the Kozeny-Carman equation without performing more laboratory tests to determine the porosity, at least when investigating a more multi-graded soil such as glacial till. However, the authors that have studied porosities in the articles mentioned above have not used degree of compaction as a factor. The correlation between experimentally obtained porosities and theoretically calculated porosities seem to be higher when using this method. There might of course be uncertainties in the experimentally calculated porosities if the in-situ conditions were disturbed during sampling and laboratory work, which might render very different results than the actual in-situ porosity.

9.2 Permeameter test

In the few cases were a permeameter were used to obtain an experimentally calculated hydraulic conductivity, K_{exp}, these results are among the lowest in the tests. At

OC4008-1, K_{exp} were as low as approximately 10^{-7}, K_H and K_G 10^{-5}, while K_{KC1} and K_{KC2} was 10^{-6}. At OC4011-1, K_H, K_G and K_{KC1} were all at 10^{-5} (K_G at $8.3 \cdot 10^{-5}$ approaching 10^{-4}) while K_{exp} where a bit lower at 10^{-6}. At OC4012, the experimental results were also the lowest at $10^{-6,}$ while the other four results were a bit higher at 10^{-5}. What is most remarkable is that at OC4010, despite the four methods based on grain size giving results in the 10^{-4}-10^{-5} regions, there was so much fine material that there was no flow at all in the permeameter. An uncertainty with these results is the fact that there was not enough material to perform a standard Proctor-compaction. The question is if the condition in the permeameter could be translated to in-situ conditions, and if not, how much this affects the result. There does not seem to be any support in the literature that hydraulic conductivity estimated from permeameter tests gives lower values than other methods.

9.3 Comparison between previous and current sampling at Skansen Lejonet

The sampling for the two different grain size analyses was taken at the same time from the same borehole. The location of the boreholes can be seen in Figure 19. Skansen Lejonet can be seen in the southwest corner of the Figure. From the outcrop, the bedrock is quite steep and the soil depth increases rather rapidly.

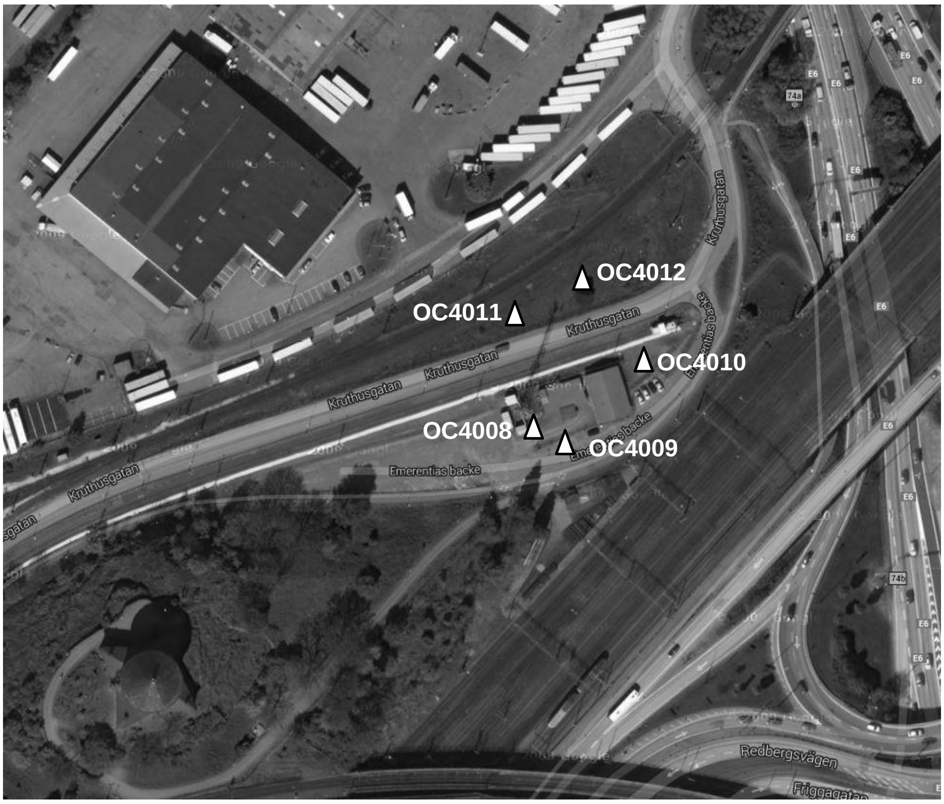

Figure 19 Map of the boreholes at Skansen Lejonet (Google Maps, 2013b). Modified.

The results can be seen in Table 11. The previous and current sampling from the same borehole is arranged between each other, with previous sampling marked with grey cells. The results are arranged to facilitate easy comparison between the results where the same method have been used.

Table 11 Comparison between previous and recent sampling at Skansen Lejonet, ordered by borehole. Grey cells show previous sampling and white current.

OC4008		**OC4008-1**	**OC4008-2**	**OC4008-**	**OC4008**	**OC4008**	**OC4008**
Level	[m]	15.5-16	16-16.5	16.5-	15.0-16.0	15.5-16.5	16.0-
K_G	[m/s]	2.2E-05	7.3E-05	7.5E-05	5.9E-06	7.8E-05	4.9E-03
K_{KC1}	[m/s]	2.70E-06	3.4E-05	1.9E-05	1.9E-09	7.3E-06	1.5E-03
K_{KC2}	[m/s]	1.6E-06					
K_{EXP}	[m/s]	2.4E-07					
OC4009		**OC4009-1**	**OC4009-2**	**OC4009**	**OC4009**		
Level	[m]	8-9	9-10	8-9	9-10		
K_G	[m/s]	2.8E-04	2.7E-04	2.9E-04	4.2E-04		
K_{KC1}	[m/s]	1.30E-04	9.2E-05	1.2E-04	1.1E-04		
K_{KC2}	[m/s]	1.2E-04	1.1E-04				
OC4010		**OC4010**	**OC4010**				
Level	[m]	11.6-12	11.6-12.6				
K_G	[m/s]	1.3E-04	9.2E-05				
K_{KC1}	[m/s]	5.3E-05	4.3E-05				
K_{KC2}	[m/s]	5.9E-05					
OC4011		**OC4011-1**	**OC4011-2**	**OC4011**			
Level	[m]	13-14	13.1-14.1	13.1-			
K_G	[m/s]	8.3E-05	7.2E-05	7.2E-05			
K_{KC1}	[m/s]	4.40E-05	3.0E-05	3.0E-05			
K_{KC2}	[m/s]		3.2E-05				
K_{EXP}	[m/s]	5.3E-06					
OC4012		**OC4012**	**OC4012**				
Level	[m]	14.1-14.4	13.4-14.4				
K_G	[m/s]	7.0E-05	1.1E-04				
K_{KC1}	[m/s]	3.20E-05	5.1E-05				
K_{KC2}	[m/s]	3.1E-05					
K_{EXP}	[m/s]	1.6E-06					

The results show that the results between the different samplings are very small, except for the borehole OC4008. Despite the fact that the two samplings were done at the same time and with the same material, the results from the grain size analysis differed a lot between the two samplings, which is quite inexplicable. For the rest of the boreholes, the differences between the results are so small that the conclusion can be drawn that the original sampling gives accurate and reliable results when the soil is as one-graded as it is at Skansen Lejonet. The material lacks both very fine fractions as well as very coarse fractions, and makes it ideal for the kind of testing were only the middle fractions is sampled. Even though a barrel sampler was not used at Skansen Lejonet, as would have been preferred, the results seem likely to have been the same even with a more undisturbed and complete type of sampler.

9.4 Comparison between previous and current sampling at Korsvägen

When comparing previous and current sampling at Korsvägen, the boreholes closest to the current boreholes KK5038 and KK5040 have been studied. The boreholes KK4007 and KK4012 are very close to KK5038. The borehole closest to KK5040 is KK4003, at a distance of approximately 15 meters (see Figure 20 for map).

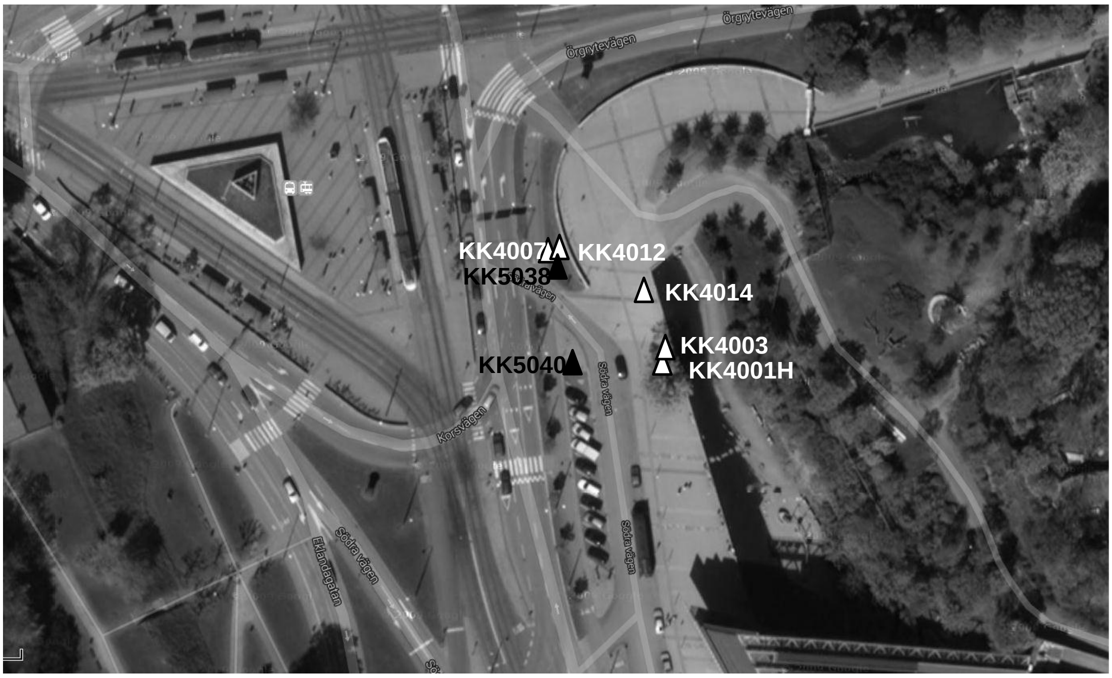

Figure 20. Map over Korsvägen. The two boreholes from current sampling are marked in black, and the four boreholes from previous sampling closest to the current are marked in white. For a coloured map, see Figure 13 in chapter 7.1.2 (Google Maps, 2013c)

The difference in depth between these two boreholes does however make the comparison less direct. Borehole KK4014 is situated between KK5038 and KK5040, and is also studied in this comparison. As can be seen in Table 12, the values are generally around 10^{-6}-10^{-5} for both previous and current sampling.

Table 12 Comparison between previous and recent sampling at Skansen Lejonet. Grey cells show previous sampling and white current.

Borehole	KK5038-1	KK5038-2	KK4007	KK4012	KK4012
Level	18.6-19.2	20.1-20.6	9-10	17-18	20-21
K_G	1.9E-05	2.7E-06	2.9E-06	8.1E-05	7.0E-05
K_{KC1}	3.0E-06	2.4E-08	3.7E-08	3.4E-05	3.4E-05
K_{KC2}	3.7E-06	2.7E-07			

The comparison between borehole KK5038 and KK4007 and KK4012 show values in approximately the same region between results calculated with the same method. K_G is as previously highest with values from 10^{-5} to 10^{-6}. K_{KC1} and K_{KC2} vary more, from 10^{-5} to 10^{-8}. The current sampling show somewhat lower results than the previous sampling.

Table 13 Comparison between previous and recent sampling at Korsvägen. Grey cells show previous sampling and white current.

Bore-hole	KK5040-1	KK5040-2	KK5040-3	KK4014	KK4014	KK4014	KK4003	KK4003	KK4003
Level	15.7-16.1	16.4-16.8	17.0-17.4	5-6	10-11	11-12	9-10	10-11	11-12
K_G	1.3E-05	2.3E-05	1.9E-06	2.3E-05	4.2E-05	5.3E-05	3.9E-05	4.2E-05	9.0E-05
K_{KC1}	8.3E-08	4.4E-06	6.0E-08	1.0E-06	1.7E-05	1.3E-05	1.2E-05	2.0E-05	1.9E-05
K_{KC2}	2.3E-07	4.3E-06	8.0E-08						

When comparing borehole KK5040 with KK4014 and KK4003, the trend from the previous comparison continues. There are larger differences between the results based on Kozeny-Carman than between the results based on Gustafson, which is not unexpected as the Kozeny-Carman equation puts larger weight on uniformity coefficients than Gustafson. As the sampling at Korsvägen are so scattered, it is difficult to compare the many results from previous sampling with the few results from current sampling. If more sampling had been performed, so that each borehole from previous sampling would correspond to a borehole from current sampling, the comparison would have been more relevant and accurate. As the soil at Korsvägen is quite heterogeneous, especially compared to Skansen Lejonet, a more complete comparison would have been preferred as the results are now difficult to put into a more overall picture.

9.5 Comparison between grain size analysis and hydraulic tests at Skansen Lejonet

Generally, the slug tests indicate a lower hydraulic conductivity than the grain size analysis. With only two slug test results from Skansen Lejonet, confident conclusions can't be drawn, however when comparing slug test with K_{KC1}, these results are more similar than the slug test results and Hazen/Gustafson. When performing the analysis of the previous sampling, the conclusion seemed to be that the slug tests were unreliable and that the higher hydraulic conductivity indicated by grain size analysis were more realistic (SWECO, 2013c). In this analysis that studies more methods of measuring hydraulic conductivity, there are several factors that point to a lower hydraulic conductivity than what Gustafson implies. Studying the Kozeny-Carman results along with slug tests and experimentally calculated hydraulic conductivity, there is a possibility that the chosen method (Gustafson) along with the sampling methodology that filters out the finer material overestimates the hydraulic conductivity.

The pumping test showed different results as a highly transmissive channel was found, with a lower transmissivity outside the channel. When looking outside the channel, the hydraulic conductivity from the pumping tests seems to correspond best to the hydraulic conductivity based on the Kozeny-Carman equation.

9.6 Comparison between grain size analysis and hydraulic tests at Korsvägen

At Korsvägen, a lot more slug tests have been performed. In many of the boreholes there appears to be a correlation between K_{slug}, K_G and K_{KC1}, and in the cases where K_{slug} is much lower, the previous analysis interprets this as unreliable values due to sand-filled pipes (SWECO, 2013a). In one case, at borehole KK4007, K_{slug} is $4.4 \cdot 10^{-7}$, K_G $2.9 \cdot 10^{-6}$ and K_{KC1} $3.7 \cdot 10^{-8}$. The analysis for this slug test states “The interpretation is uncertain; it can be significantly more conductive”. However, when comparing this to K_{KC1} and not only to K_G, the low conductivity does not seem unreasonable.

It is important to remember that the pumping test gives an overall judgement of the hydraulic conductivity over an entire area, whereas grain size analyses represent the specific hydraulic conductivity of a certain borehole. This means that all of the grain size analyses need to be studied together, to show the trends and the probable overall conductivity. When comparing the results from the pumping test, with hydraulic conductivities between $1.5 - 3.3 * 10^{-5}$ m/s, with grain size analyses, these values seem to correspond to the lower values calculated with the Gustafson methods, and to the higher values calculated with the Kozeny-Carman methods. The interpretation is then that Gustafson may overestimate the hydraulic conductivity somewhat, while Kozeny-Carman may underestimate the hydraulic conductivity.

9.7 Uncertainties

Several uncertainties exist within the results of this thesis, chiefly the small amount of samples compared to the more extensive previous sampling. As the environment is quite heterogeneous, this leads to individual differences between boreholes, in some cases even if the boreholes are close to each other. This makes it difficult to determine trends and draw conclusions on the accuracy of the results.

Using two different sampling methods at the different locations was not optimal, and in retrospect, using a barrel sampler or moraine sampler at both Korsvägen and Skansen Lejonet would have been preferable as this gives more undisturbed samples. The flushed samples were not only more disturbed, but also could not be used for the more exact way of measuring porosity as the information about the in-situ water content was lost. There are also some uncertainties about the fine material of these samples, if it is part of the friction material or if it is flushed up from the clay layer.

The samples taken in this thesis were also small, which resulted in some difficulties when performing the laboratory work, the largest of these were that a Proctor compaction was impossible to perform, as this requires much larger sample amounts (several kilograms). Some porosity measurements were also difficult to perform when the samples were very small.

9.8 Consequences of selecting method

As can be seen in Figure 17 (Chap 9 Skansen Lejonet), in the cases in this study where there is a poorly graded soil, this does not lead to large differences in hydraulic conductivity between the different methods used. However, when the uniformity coefficient is large, as can be seen in Figure 18, the differences can be up to several orders of magnitudes. The consequences of this are that the estimated inflow of water can differ by several tens of litres per minute. This should be taken into careful consideration when selecting which method to use to calculate the hydraulic conductivity. A high hydraulic conductivity gives a flatter drawdown profile than a lower hydraulic conductivity and thus larger drawdowns far away from the disturbance. This means that using the higher values minimizes the risks for unwanted effects, but expensive actions may be carried out unnecessary. In each project, the risk of unwanted effects must be weighed against the cost for the preventive actions. If a method such as Gustafson is chosen because it is easy to use and inexpensive, but overestimates the hydraulic conductivities which lead to increased costs in the implementation stage, there is a case to be made that examining the hydraulic conductivity more closely through more laboratory tests is worthwhile.

As there can be large consequences if the hydraulic conductivity is underestimated a safety factor could be useful to have, that increases the calculated hydraulic conductivity. One could argue that if Gustafson overestimates the hydraulic conductivity, this safety factor is already built in. An experienced hydrogeologist is probably aware of this and interprets the results with this in mind.

Comparing how different sample methods affect results of the grain size analysis is another question that is central to this thesis, but this does not seem to have been a prioritised subject for researchers.

The hydrogeological surroundings are important to study when the sampling method is selected. Using perforated pipes that has a limited range of what material is collected can give an accurate result when the soil is one-graded, as seems to be the case at Skansen Lejonet. The sampling there does not seem to have missed any coarser material as there was a very low gravel content in the soil. At Korsvägen there seems to be a more multi-graded soil which is confirmed by the high uniformity coefficient in many cases. Extrapolating the values of fine material instead of performing a sedimentary analysis leads to further uncertainties in the results, which has been done for several of the previous samples at Korsvägen. The current samples that were collected with barrel samplers also showed an amount of coarse material which is missed by the 8mm sampling. All this points to the conclusion that a more thorough investigation might be necessary, with a more undisturbed sampling and more laboratory tests to ensure that the hydraulic conductivity is estimated more accurately. If so, the measures taken based on these values will be more fitted to the actual hydrogeological environment.

10 Conclusions

- The Kozeny-Carman equation gives lower hydraulic conductivity than Gustafson. The differences between the methods are statistically significant.
- The porosity and how to determine it accurately in laboratory conditions is of great importance to accurately predict the hydraulic conductivity when using the Kozeny-Carman equation.
- There are doubts if the porosity is possible to estimate from grain-size analyses alone, or if other analyses must be performed to accurately determine the porosity.
- The most important parameter besides the grain size to determine porosity seems to be degree of compaction. The connection between degree of compaction and soil type should be studied more.
- The sampling method used should be selected with the hydrogeological environment in mind. A sampling method that only collects the middle part of a grain size distribution is not appropriate to use in a multi-graded soil due to the amount of fine and coarse material.
- The slug tests together with the K_{KC} indicate that the Gustafson equation might overestimate the hydraulic conductivity at these locations.

From this study the following recommendations are given:

- To be more certain of the conclusions in this thesis, more samples should be taken – corresponding to the boreholes where the more incomplete sampling has been performed – with the same sampling method (preferably a barrel sampler).
- The packing of the soil sampling has not been considered. If further investigations were to be made, Proctor compaction should be used to ensure that the samples are packed to simulate in-situ conditions as closely as possible, and also to investigate the effect of packing on hydraulic conductivity and porosity.
- The importance of the degree of compaction to theoretically calculate porosity, and further the hydraulic conductivity through the Kozeny-Carman equation have only been studied very briefly in this thesis. For future studies, studying how the degree of compaction influences the porosity as well as the connection between soil type and degree of compaction could be an interesting subject. To increase the understanding of these connections could be very important to facilitate the use of the Kozeny-Carman equation. This might increase its use in Swedish projects, and by extension improve the accuracy when determining hydraulic conductivity.
- In this thesis, the focus has been on undisturbed samples, using a moraine sampler to provide as undisturbed samples as possible. However, the moraine sampler (or barrel sampler) limits the size of the sample. As a Proctor compaction requires much larger sample sizes, an assessment of the importance of undisturbed samples compared to a focus on the degree of compaction should be made. In a study focusing on degree of compaction, the desire to get undisturbed samples might need to be abandoned and digging a test pit might be preferable instead of using a barrel sampler. In this thesis this

would probably not have been possibly due to the location of the test sites in an urban and sensitive environment.

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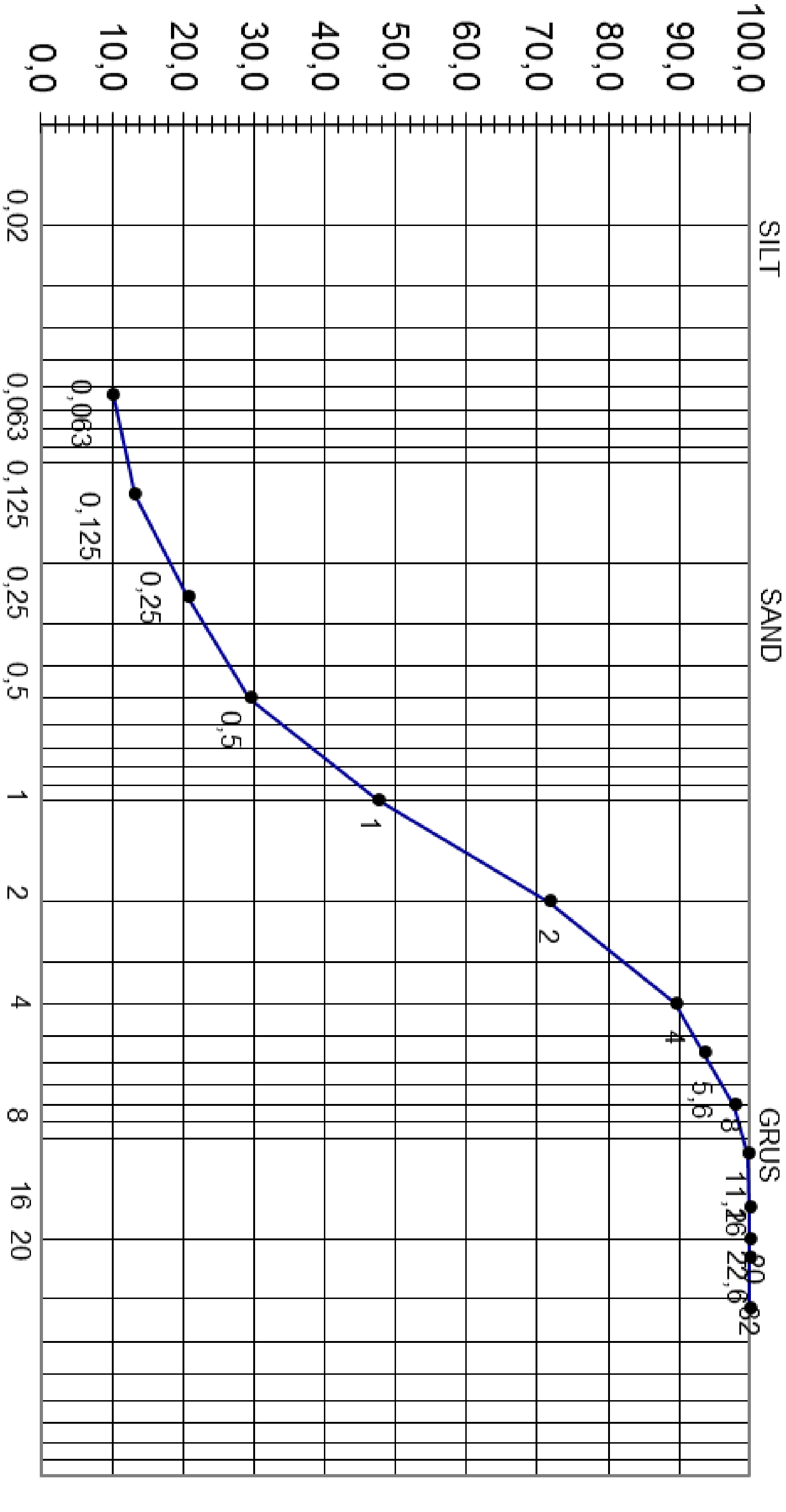
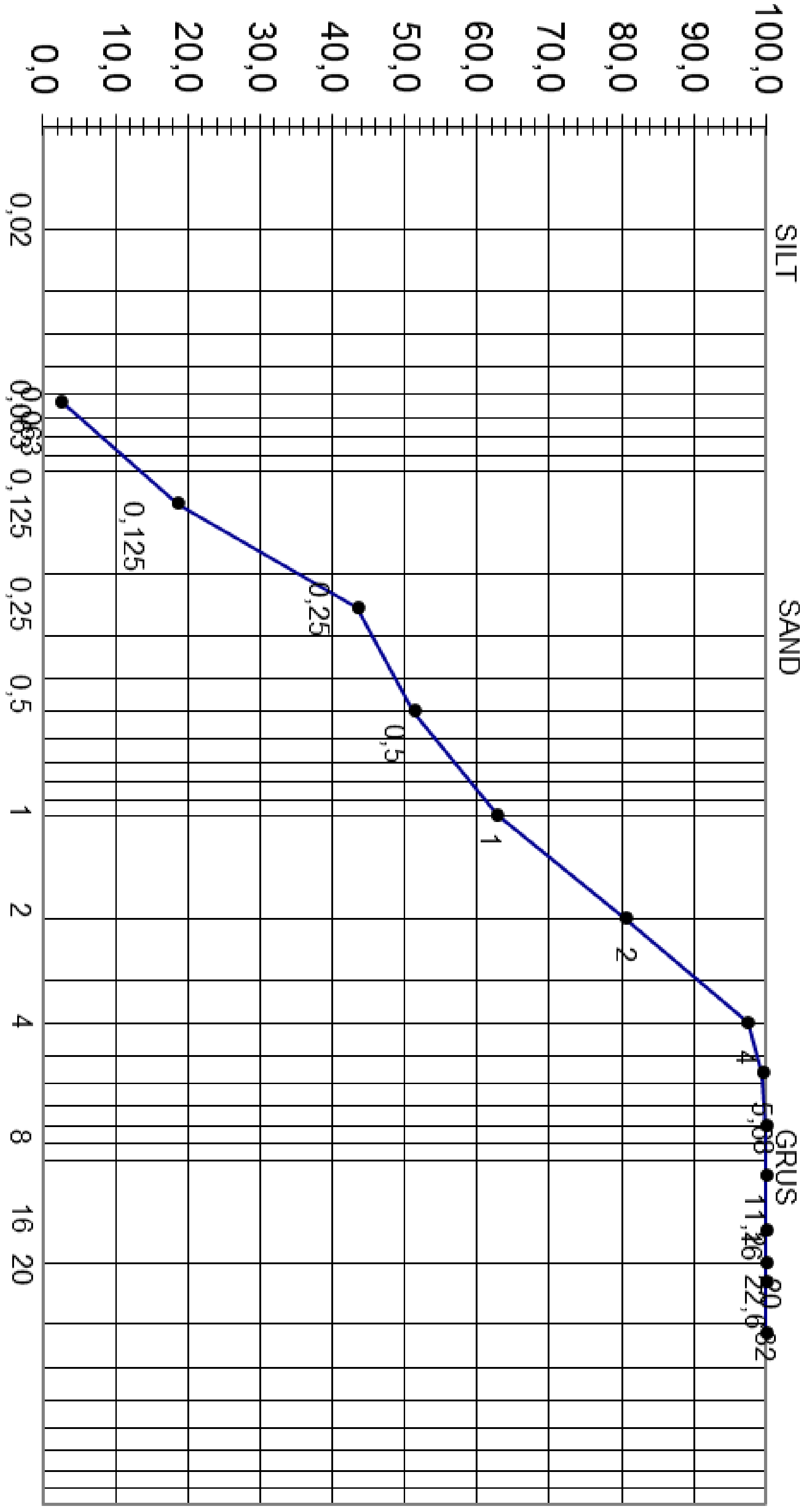
Appendix 1. Skansen Lejonet

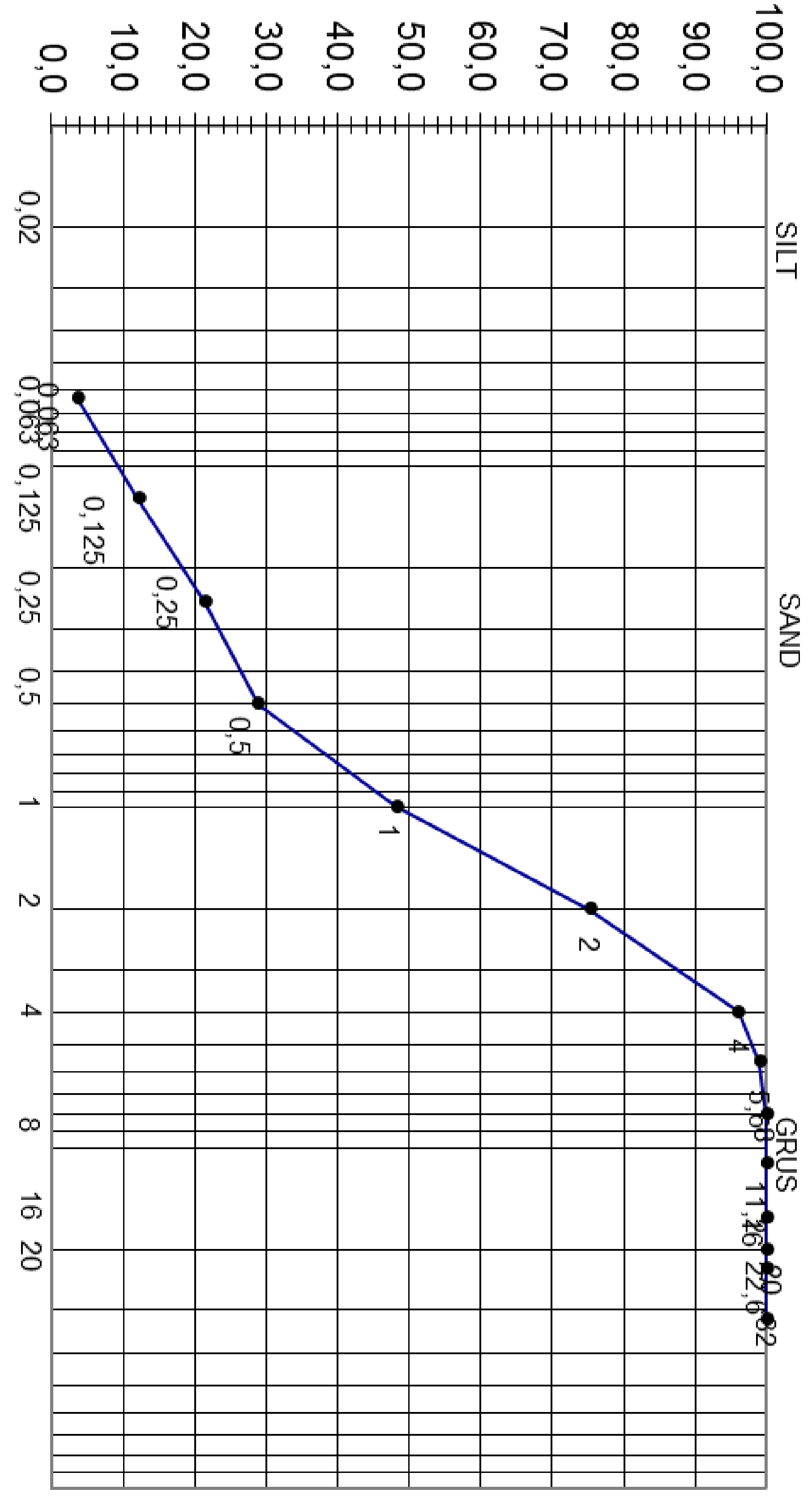
Borehole OC4008 Level 1



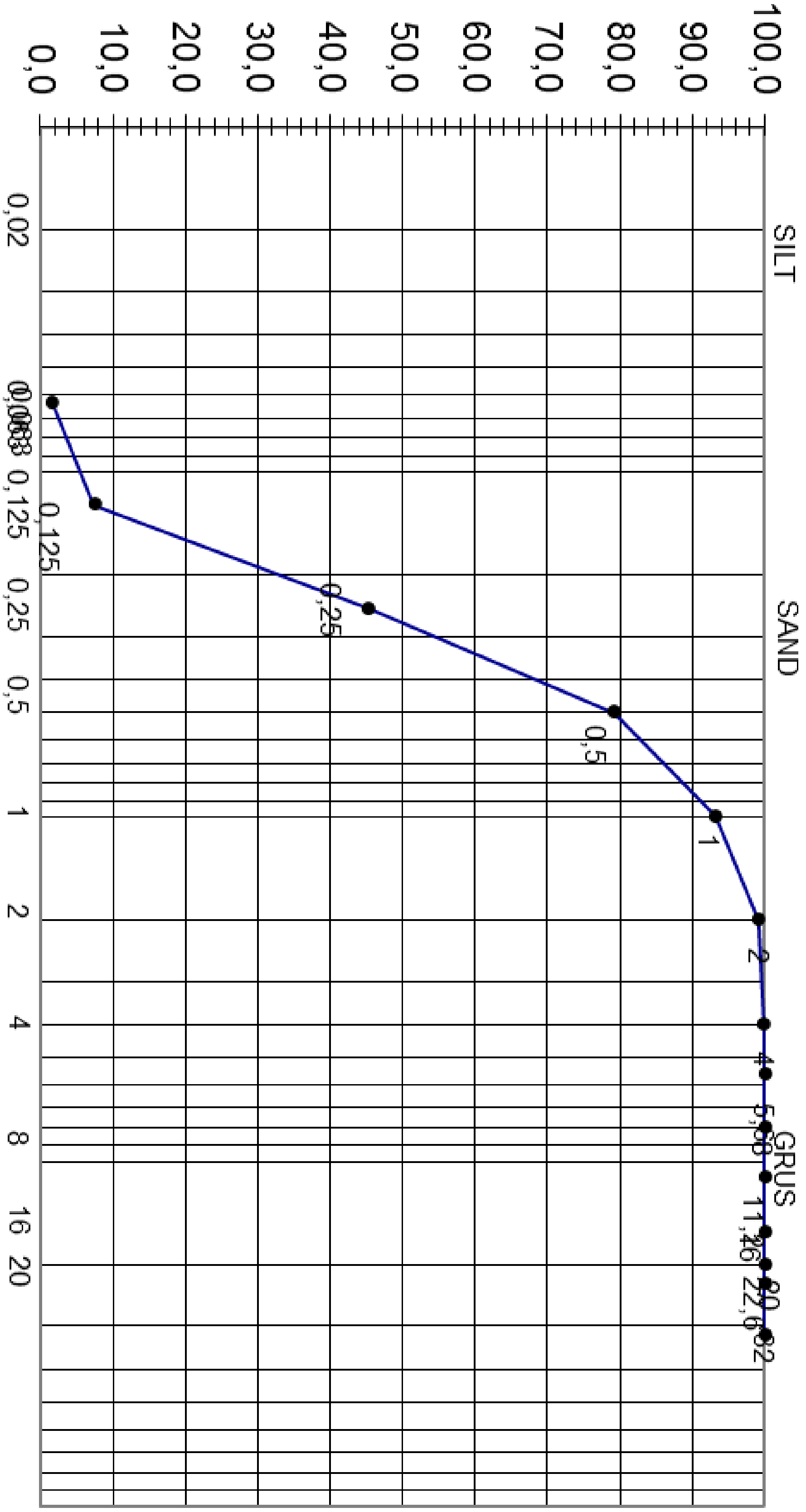
Borehole OC4008 Level 2



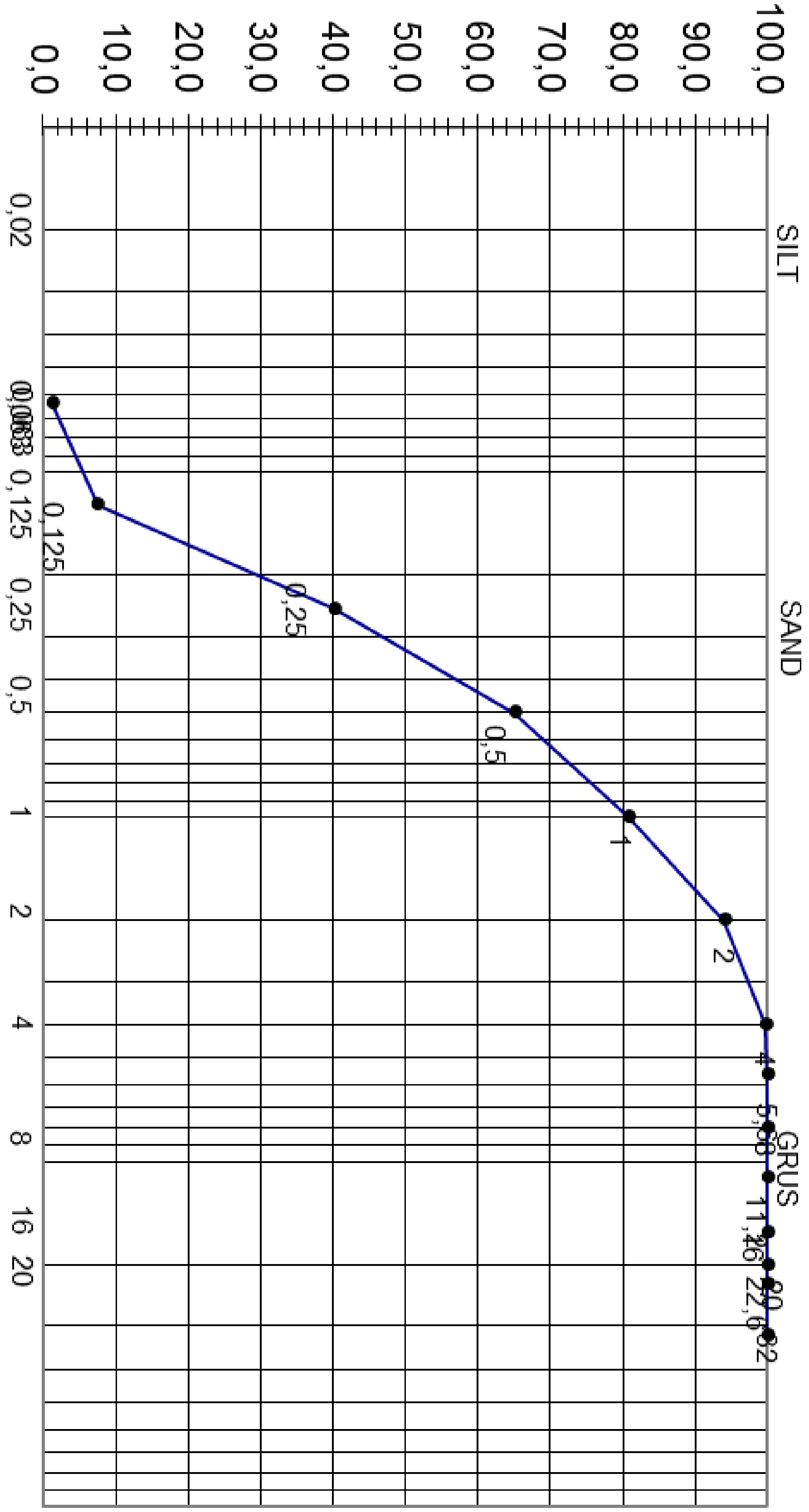
Borehole OC4008 Level 3



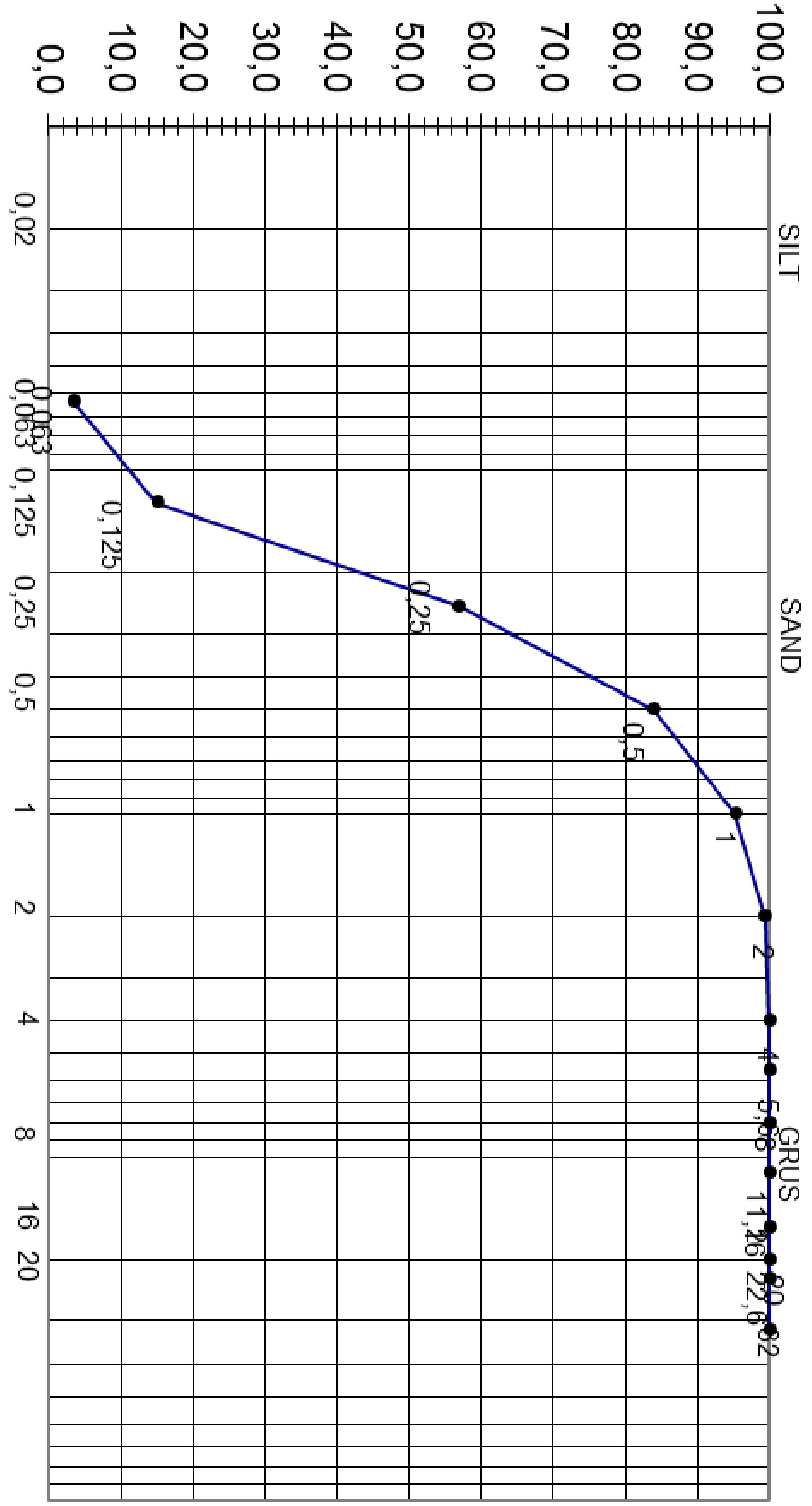
Borehole OC4009 Level 1



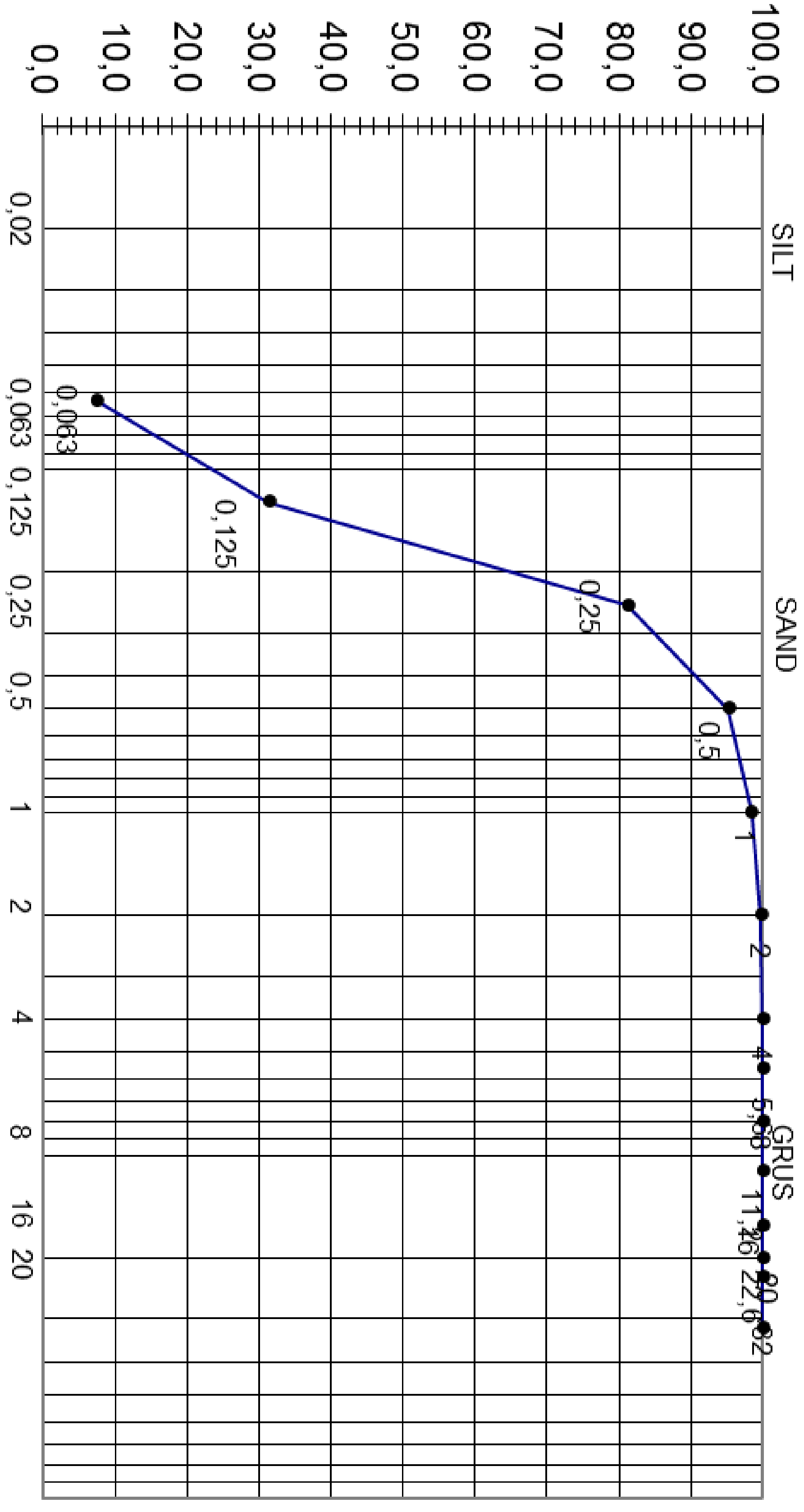
Borehole OC4009 Level 2



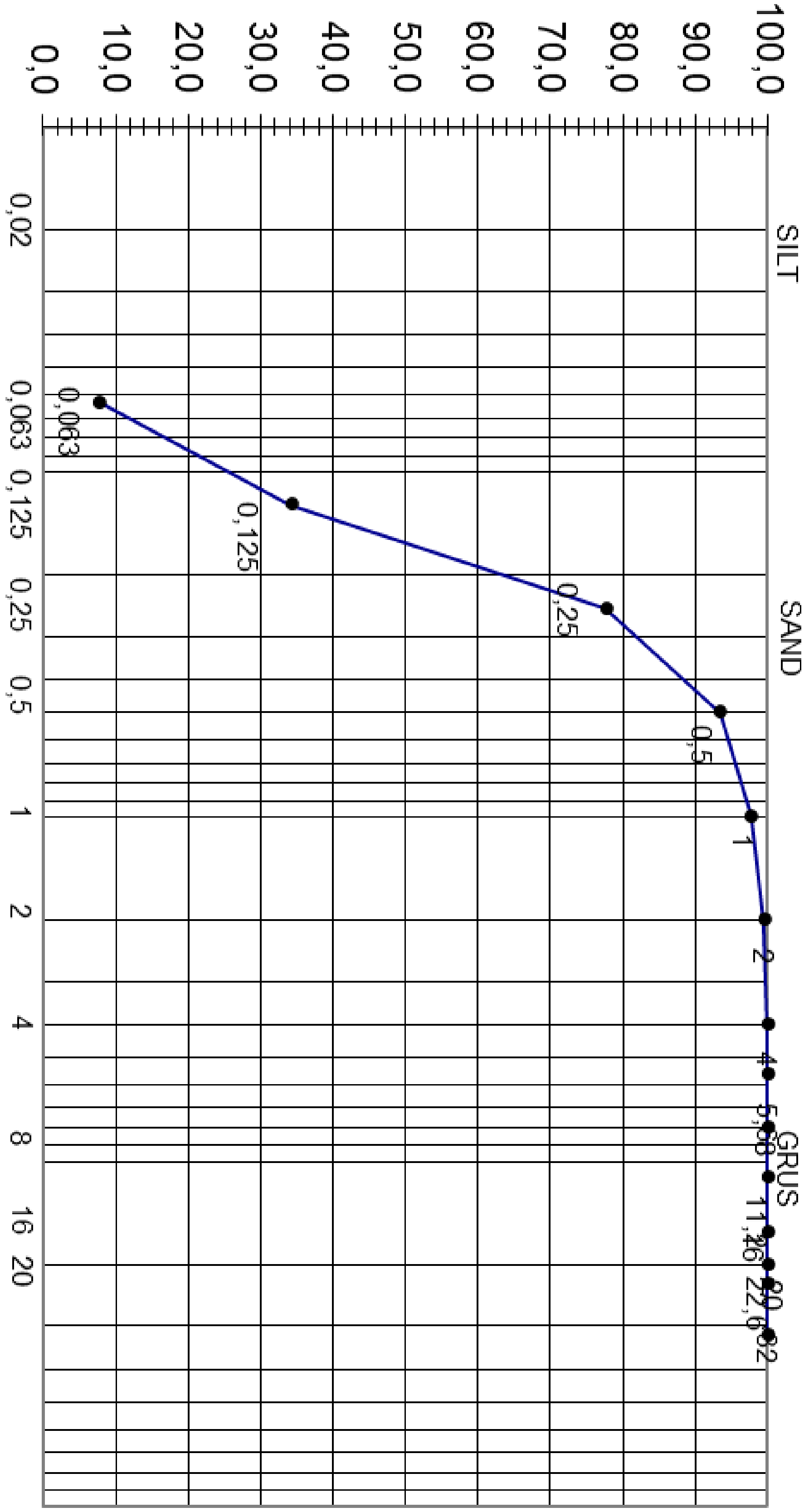
Borehole OC4010 Level 1



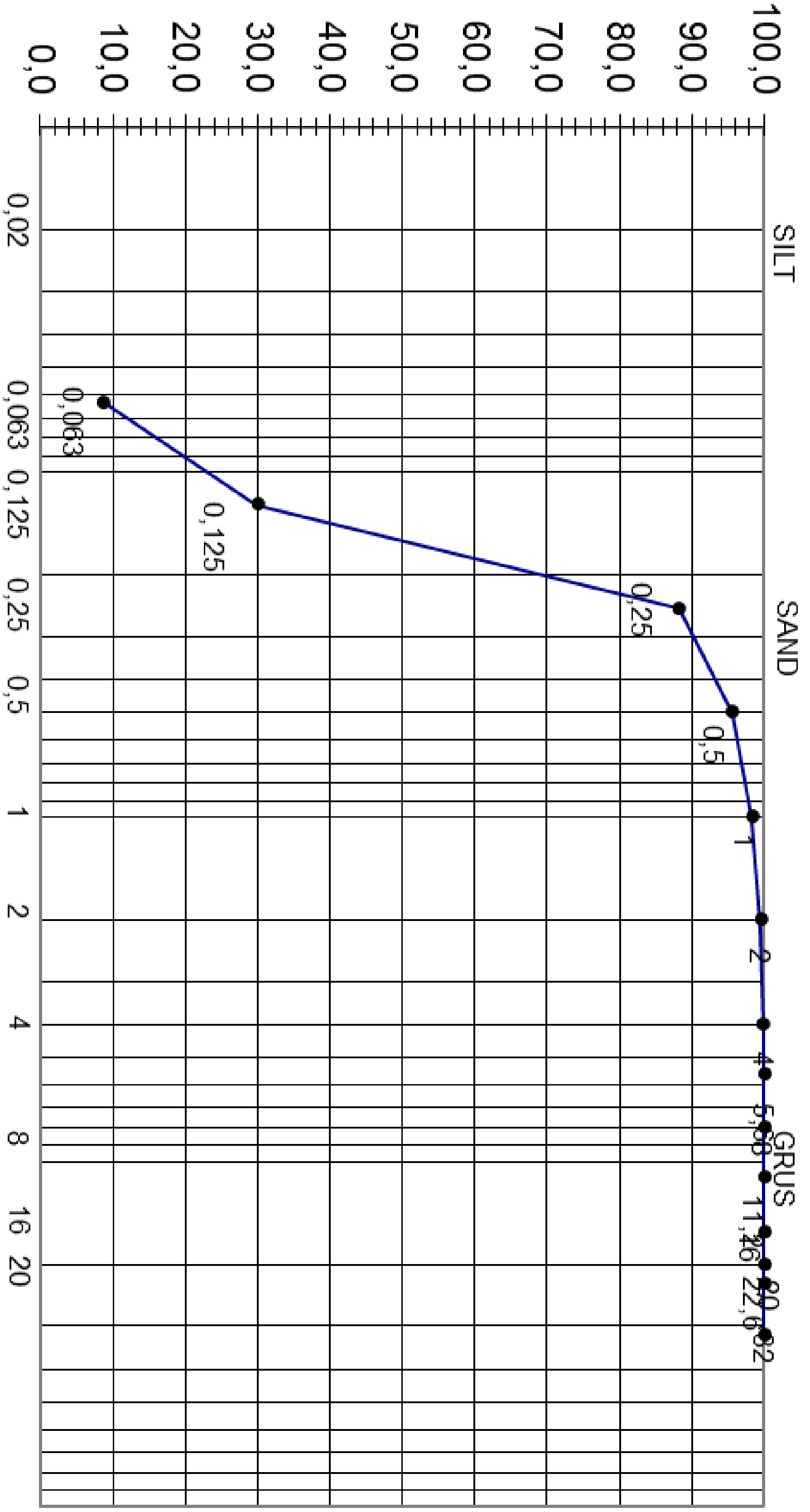
Borehole OC4011 Level 1



Borehole OC4011 Level 2

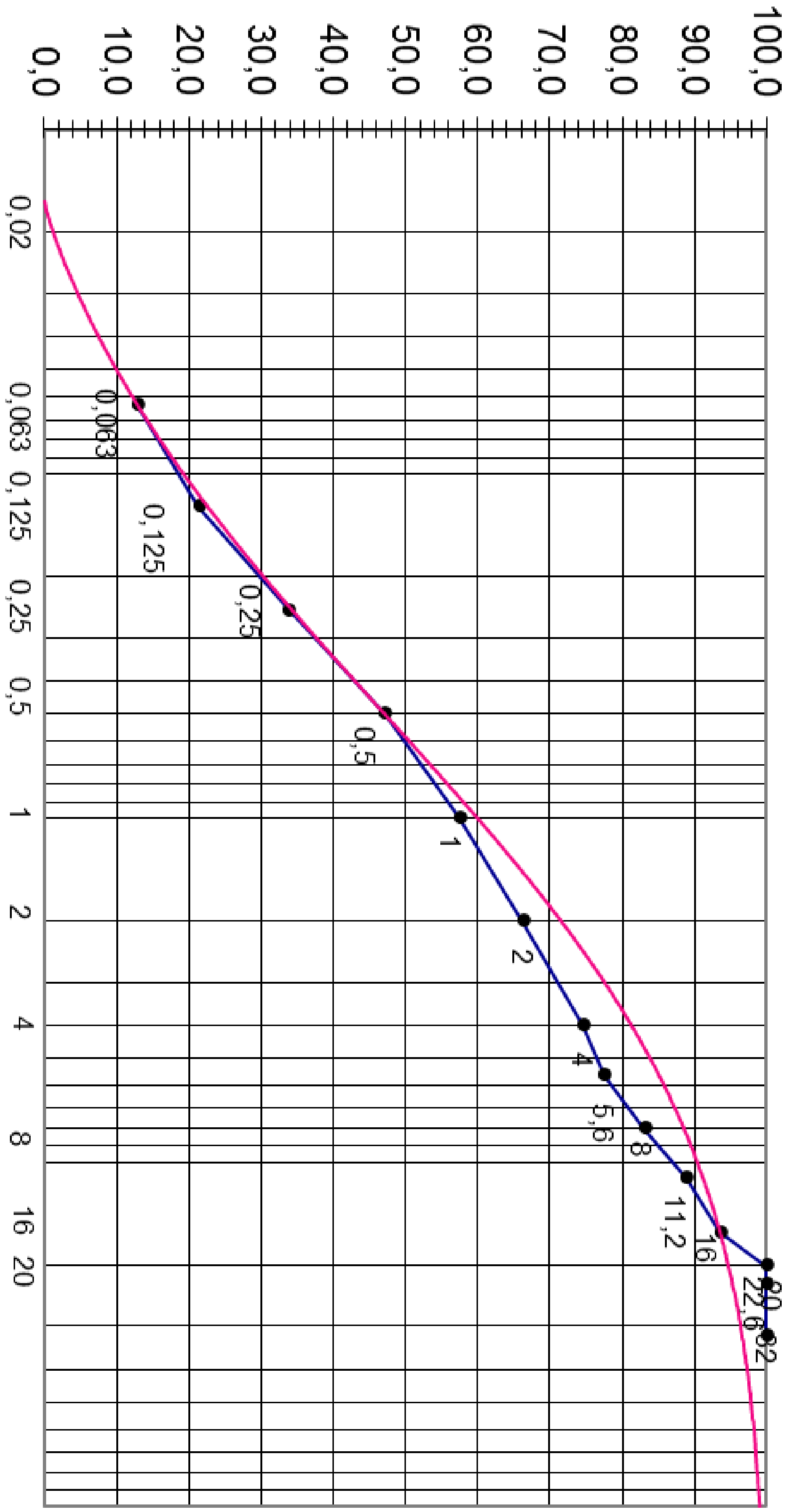


Borehole OC4012 Level 1

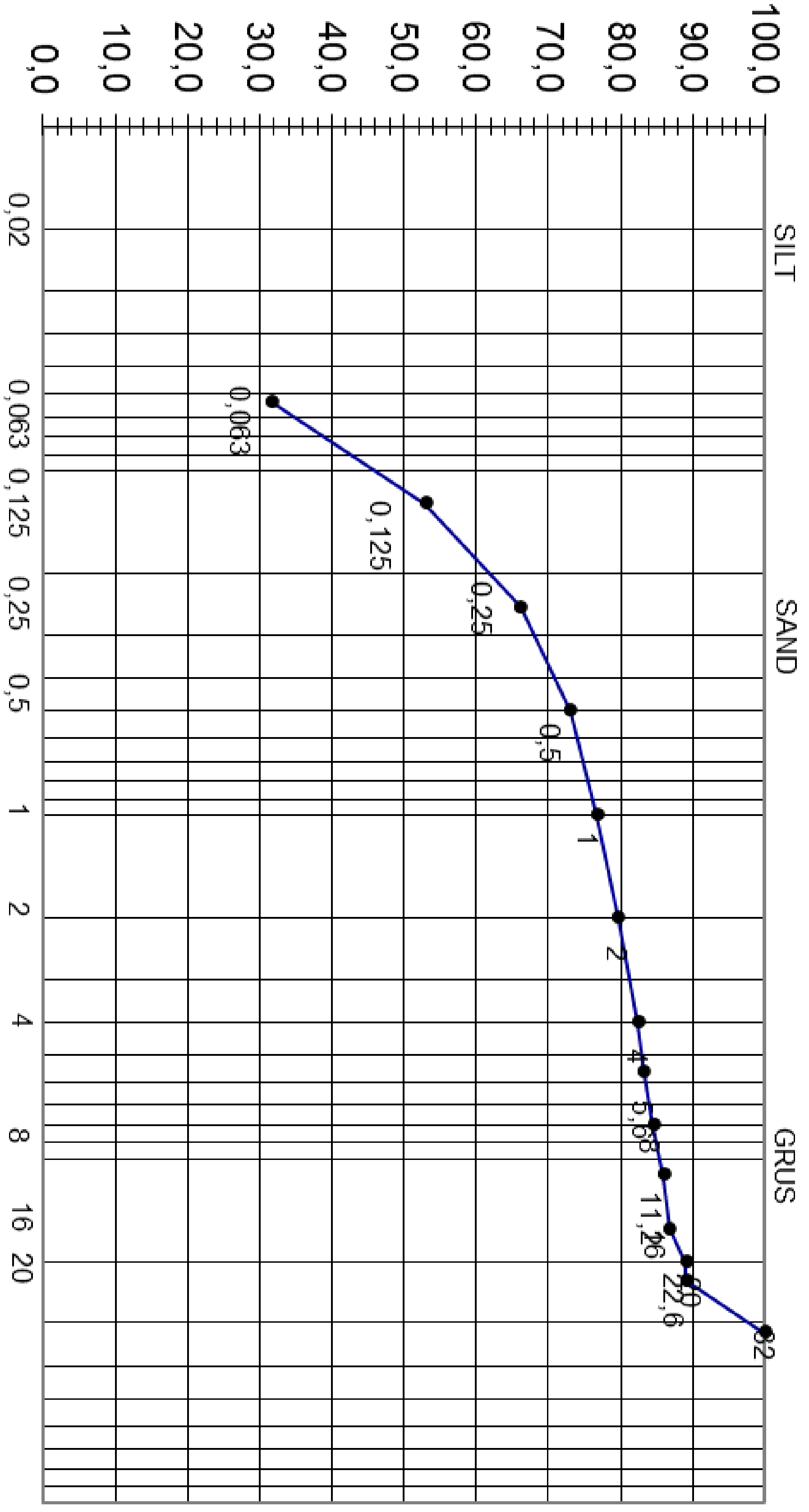


Appendix 2. Korsvägen

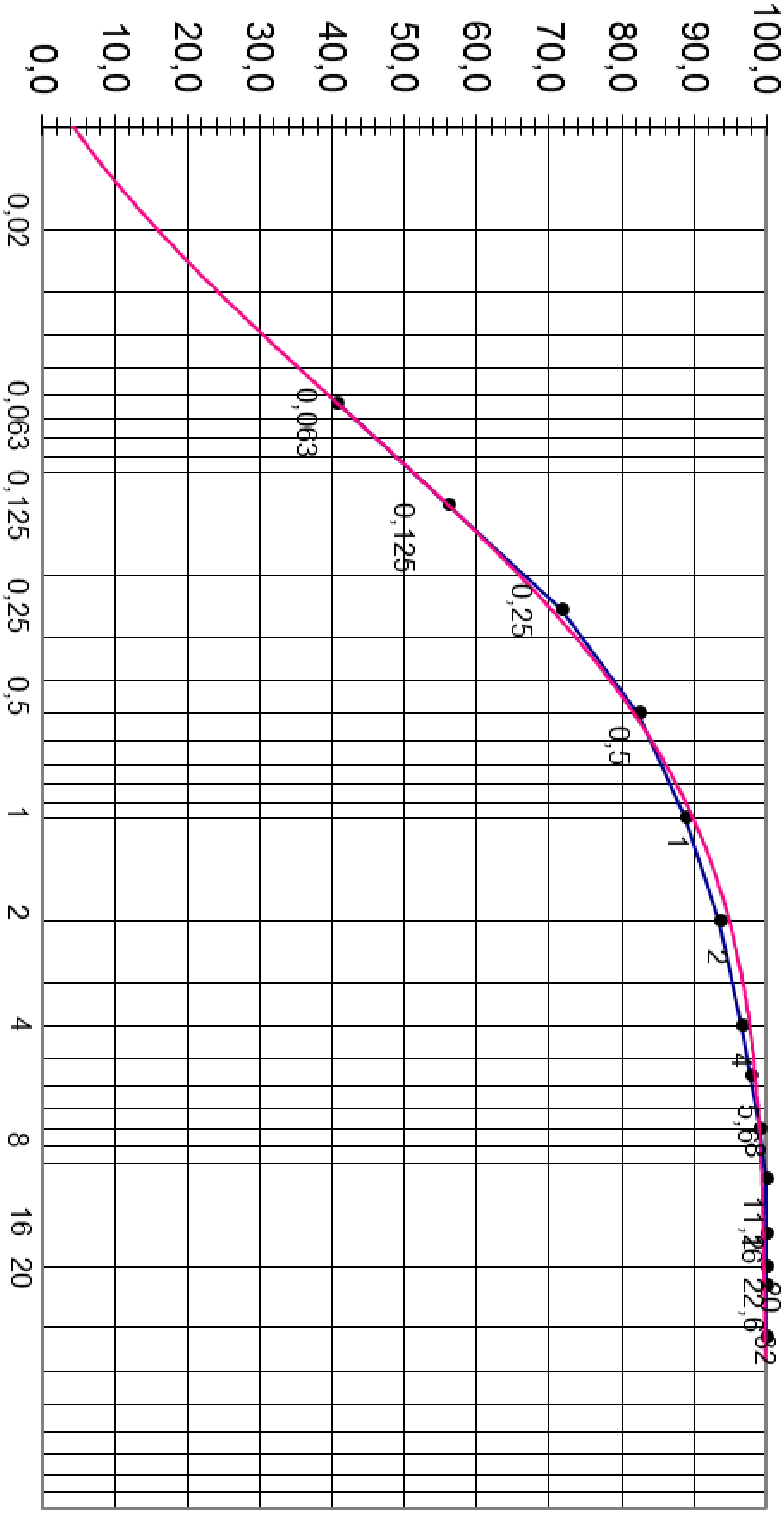
Borehole KK5040 Level 1



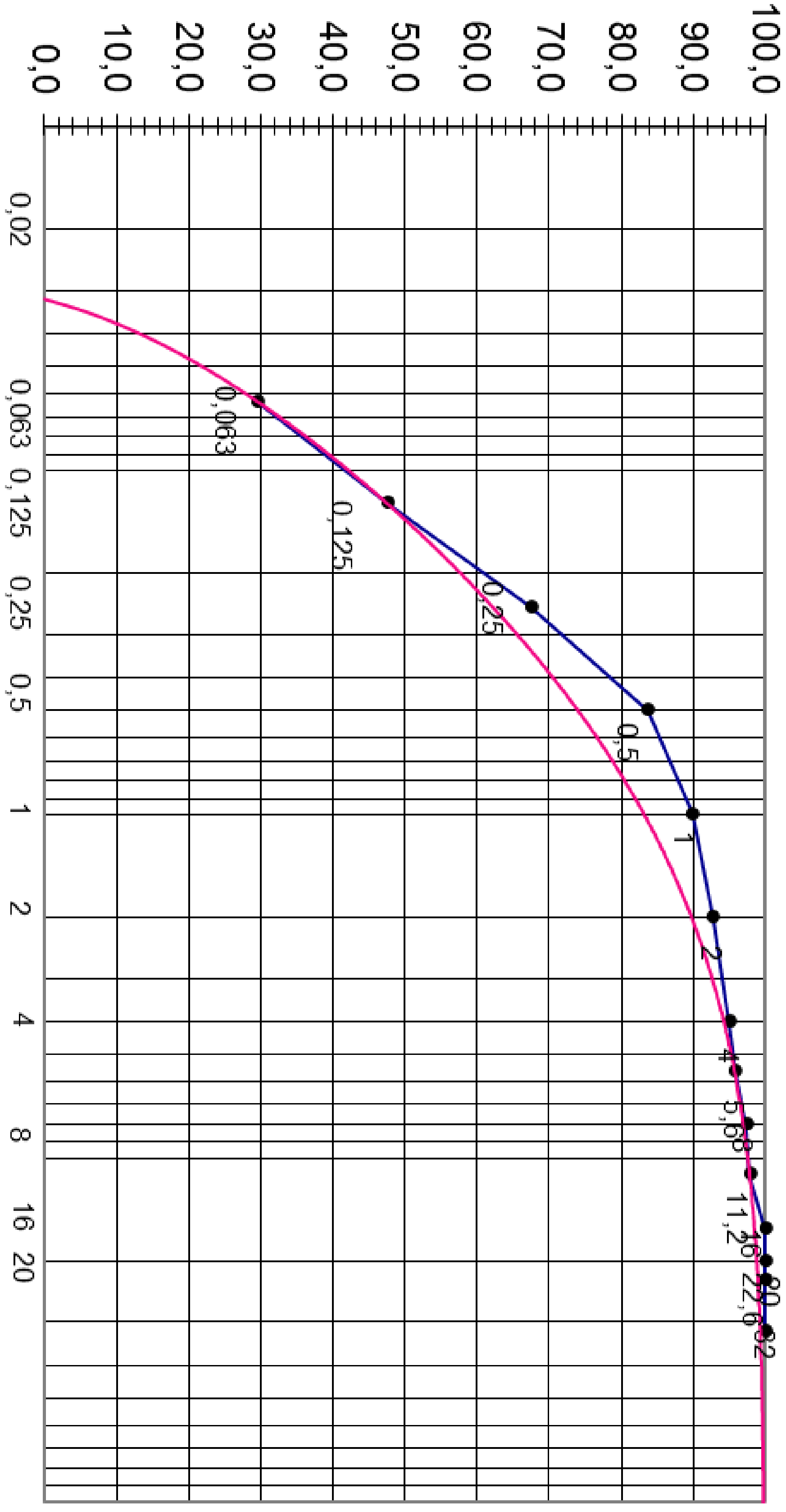
Borehole KK5040 Level 2



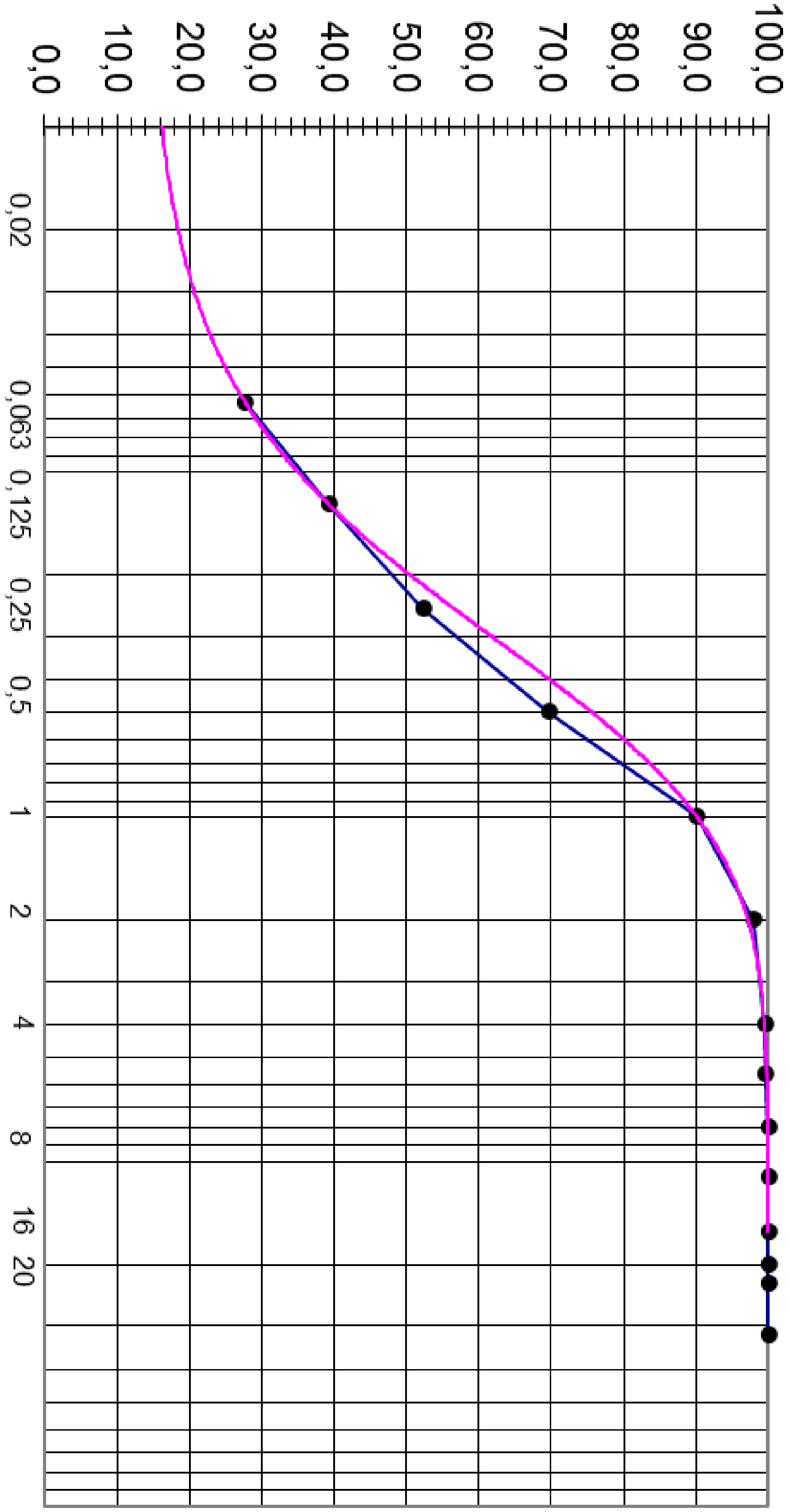
Borehole KK5040 Level 3



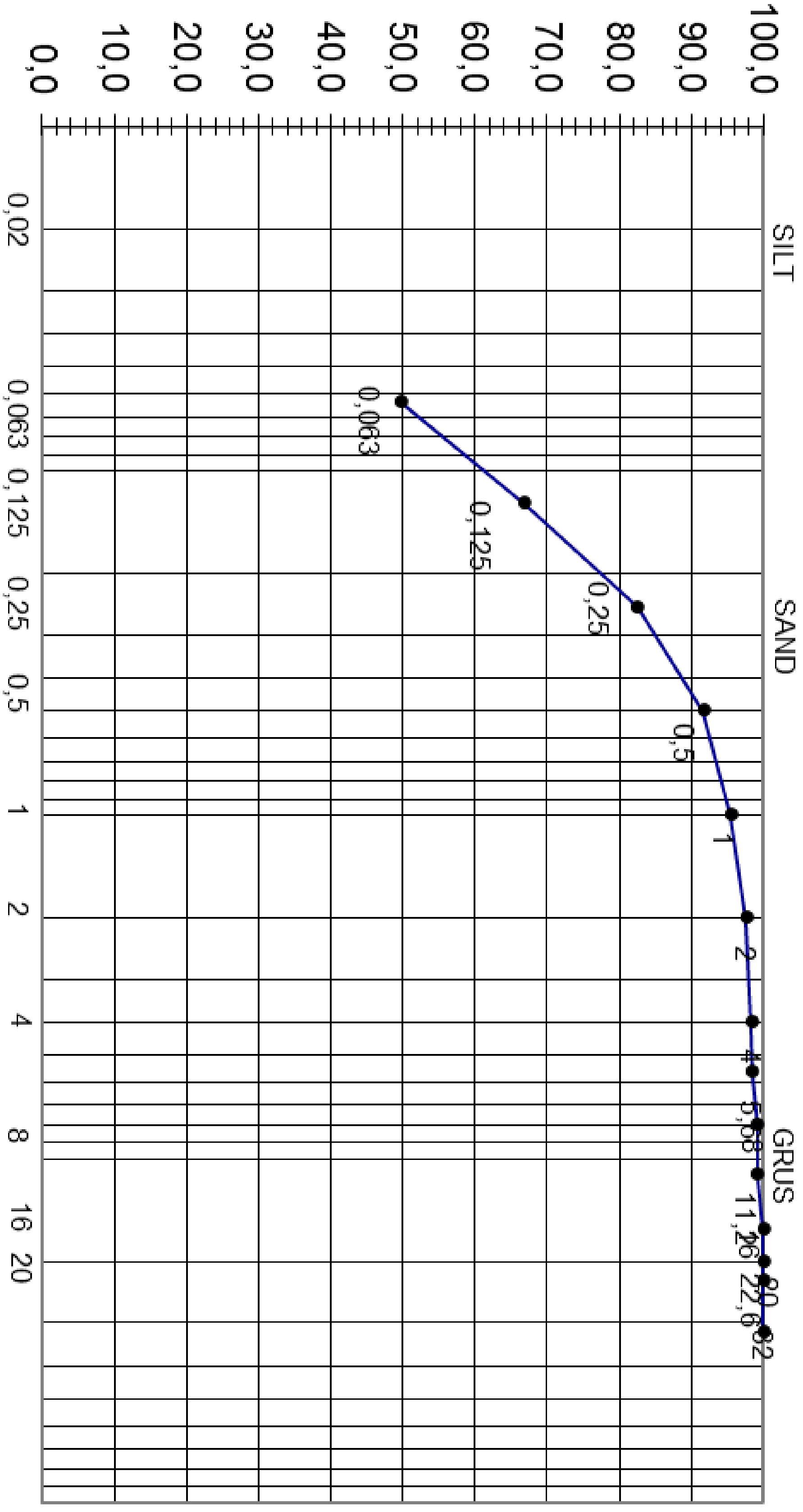
Borehole KK5038 Level 1



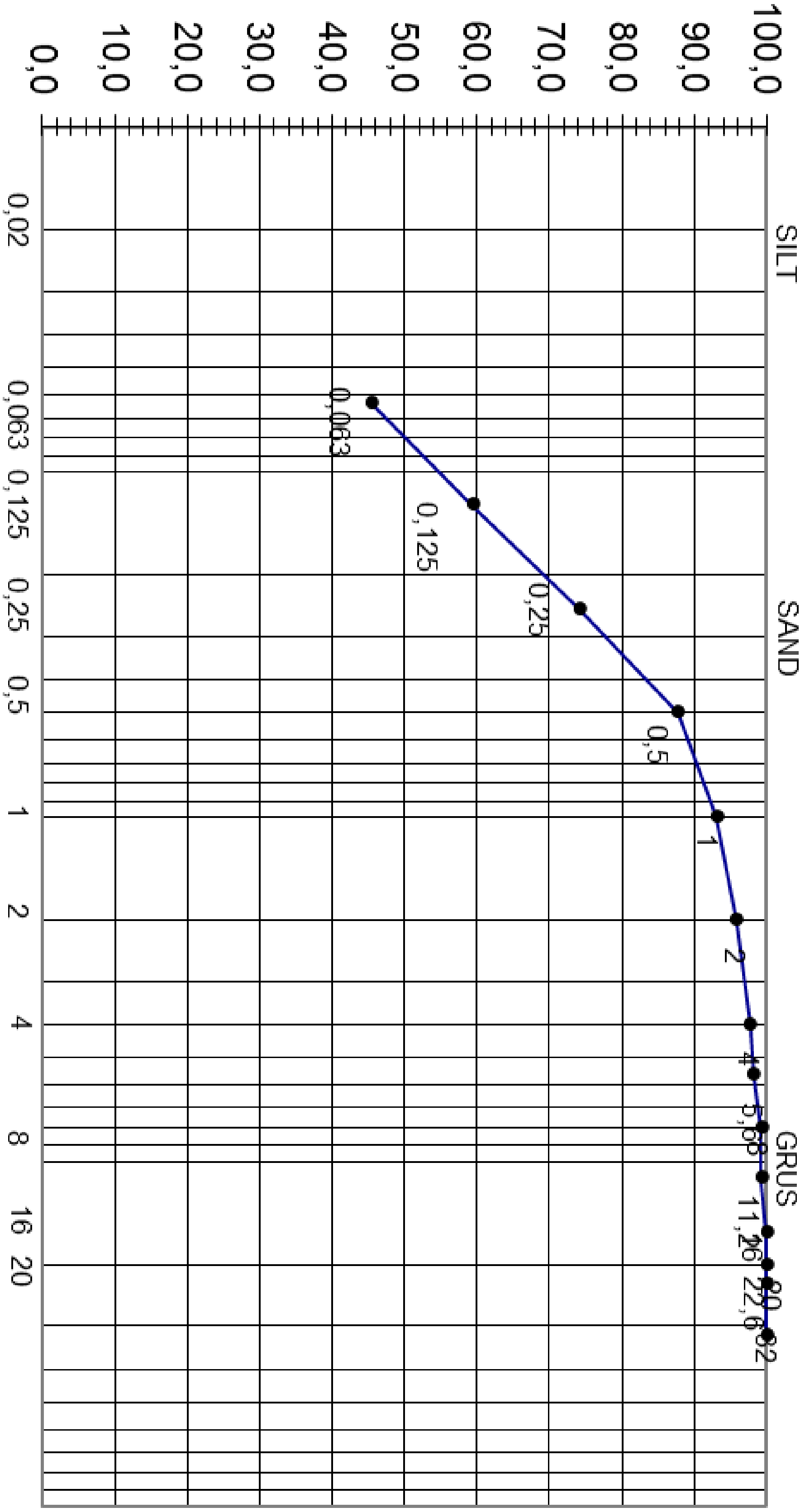
Borehole KK5038 Level 2



Borehole KK5038 Level 3

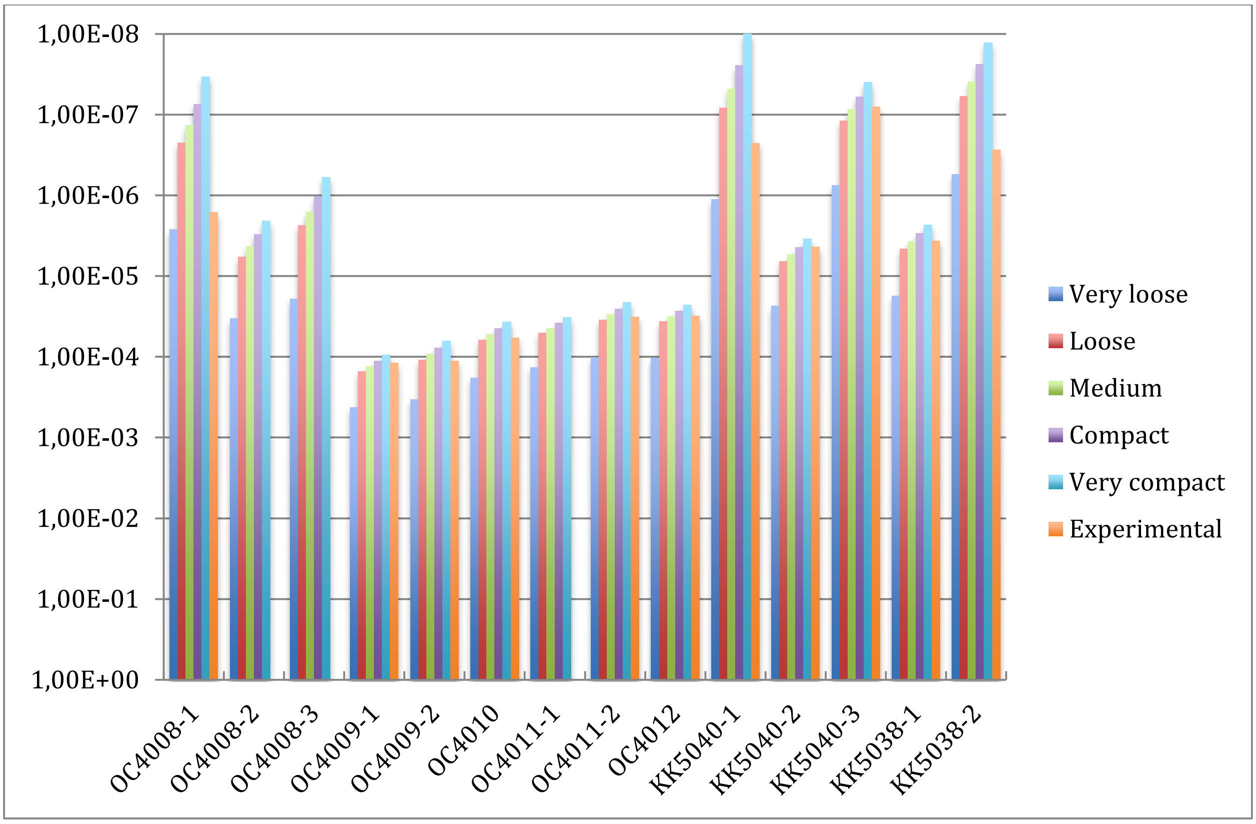


Borehole KK5038 Level 4

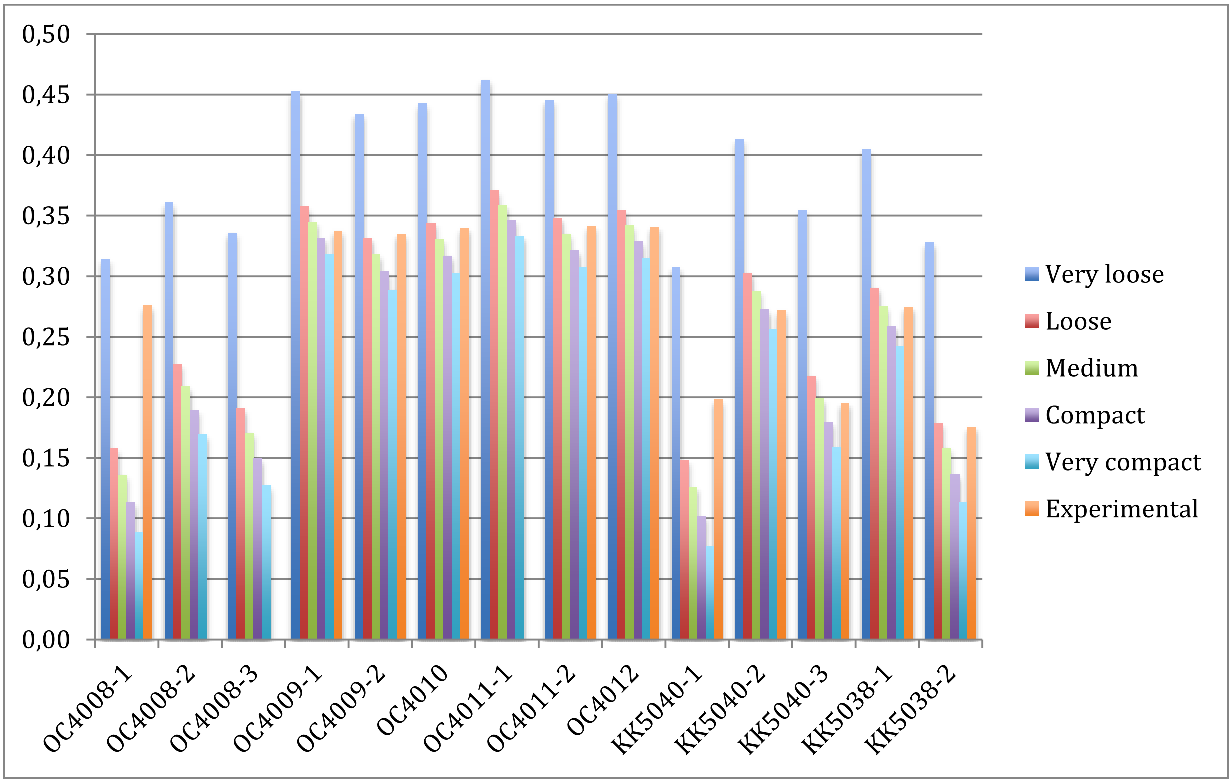


Appendix 3. Variation of hydraulic conductivity based on degree of compaction

	Very Loose	Loose	Medium	Compact	Very Compact	
Borehole	K_{KC1}	K_{KC2}	K_{KC3}	K_{KC4}	K_{KC5}	K_{KCexp}
Skansen						
OC4008-1	2,66E-06	2,25E-07	1,37E-07	7,43E-08	3,41E-08	1,62E-06
OC4008-2	3,37E-05	5,77E-06	4,28E-06	3,05E-06	2,07E-06	-
OC4008-3	1,91E-05	2,35E-06	1,60E-06	1,02E-06	5,99E-07	-
OC4009-1	4,24E-04	1,52E-04	1,31E-04	1,12E-04	9,49E-05	1,20E-04
OC4009-2	3,40E-04	1,09E-04	9,22E-05	7,71E-05	6,36E-05	1,13E-04
OC4010	1,82E-04	6,16E-05	5,26E-05	4,45E-05	3,72E-05	5,87E-05
OC4011-1	1,34E-04	5,07E-05	4,42E-05	3,82E-05	3,27E-05	-
OC4011-2	1,01E-04	3,49E-05	2,99E-05	2,54E-05	2,13E-05	3,23E-05
OC4012	1,04E-04	3,67E-05	3,16E-05	2,70E-05	2,28E-05	3,11E-05
Korsvägen						
KK5040-1	1,13E-06	8,30E-08	4,82E-08	2,45E-08	1,01E-08	2,25E-07
KK5040-2	2,35E-05	6,55E-06	5,39E-06	4,37E-06	3,48E-06	4,34E-06
KK5040-3	7,51E-07	1,19E-07	8,65E-08	6,03E-08	3,97E-08	8,04E-08
KK5038-1	1,76E-05	4,59E-06	3,73E-06	2,98E-06	2,33E-06	3,70E-06
KK5038-2	5,46E-07	5,95E-08	3,91E-08	2,38E-08	1,30E-08	2,74E-07


1,00E-08
1,00E-07
1,00E-06
1,00E-05
1,00E-04
1,00E-03
1,00E-02
1,00E-01
1,00E+00
OC4008-1
OC4008-2
OC4008-3
OC4009-1
OC4009-2
OC4010
OC4011-1
OC4011-2
OC4012
KK5040-1
KK5040-2
KK5040-3
KK5038-1
KK5038-2
Very loose
Loose
Medium
Compact
Very compact
Experimental

Appendix 4. Graph of different porosities based on degree of compaction and experimental porosity



Appendix 5. ANOVA single factor analysis

	Input data for ANOVA analysis			
Skansen Lejonet	**K_{KC1}**	**K_{KC2}**	**K_H**	**K_G**
OC4007-1	2,7E-06	1,6E-06	4,6E-05	2,2E-05
OC4007-2	3,4E-05		8,8E-05	7,3E-05
OC4007-3	1,9E-05		1,2E-04	7,5E-05
OC4008-1	1,3E-04	1,2E-04	2,0E-04	2,8E-04
OC4008-2	9,2E-05	1,1E-04	2,0E-04	2,7E-04
OC4009	5,3E-05	5,9E-05	9,4E-05	1,3E-04
OC4010-1	4,4E-05		5,7E-05	8,3E-05
OC4010-2	3,0E-05	3,2E-05	5,0E-05	7,2E-05
OC4012	3,2E-05	3,1E-05	4,9E-05	7,0E-05
Korsvägen				
KK5040-1	8,30E-08	2,3E-07	2,9E-05	1,3E-05
KK5040-2	4,4E-06	4,3E-06	1,9E-05	2,3E-05
KK5040-3	6,0E-08	8,0E-08	2,4E-06	1,9E-06
KK5038-1	3,0E-06	3,7E-06	1,6E-05	1,9E-05
KK5038-2	2,4E-08	2,7E-07	4,6E-06	2,7E-06

Skansen Lejonet	Logarithmic values			
OC4007-1	-5,5751184	-5,7895068	-4,3379855	-4,6548364
OC4007-2	-4,4723701		-4,0576281	-4,1346459
OC4007-3	-4,7189666		-3,9366666	-4,1271295
OC4008-1	-3,8827287	-3,9207195	-3,7087799	-3,5494819
OC4008-2	-4,0352691	-3,9467833	-3,7087799	-3,5716491
OC4009	-4,2790143	-4,2313392	-4,0281816	-3,8785834
OC4010-1	-4,3545777		-4,2464706	-4,0827968
OC4010-2	-4,5243288	-4,4910903	-4,2975788	-4,1445408
OC4012	-4,5003129	-4,5070089	-4,3108399	-4,1531684
Korsvägen				
KK5040-1	-7,0809219	-6,6478103	-4,5387266	-4,9000584
KK5040-2	-5,3595186	-5,3627886	-4,7325467	-4,6372888
KK5040-3	-7,2196827	-7,0945944	-5,6259946	-5,7298486
KK5038-1	-5,5257837	-5,4321346	-4,7909234	-4,7179252
KK5038-2	-7,623423	-6,5616697	-5,3346066	-5,5670284

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	14	-73,152	-5,22514	1,547315
Column 2	11	-57,9854	-5,2714	1,303981
Column 3	14	-61,6557	-4,40398	0,317735
Column 4	14	-61,849	-4,41778	0,434731

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9,214695	3	3,071565	3,505294	0,022073	2,793949
Within Groups	42,93697	49	0,876265			
Total	52,15166	52				