CHALMERS
UNIVERSITY OF TECHNOLOGY

Thermal classification of cable route

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ANDREAS LILLIESTIERNA
JOHAN UTAS

Department of Civil and Environmental Engineering
Division of GeoEngineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Master's Thesis 2015:40

MASTER'S THESIS 2015:40

Thermal classification of cable route

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ANDREAS LILLIESTIERNA

JOHAN UTAS

Department of Civil and Environmental Engineering

Division of GeoEngineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2015

Thermal classification of cable route

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ANDREAS LILLIESTIERNA

JOHAN UTAS

Examensarbete 2015:40/ Institutionen för bygg och miljöteknik

Chalmers tekniska högskola 2015

Department of Civil and Environmental Engineering
Division of GeoEngineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Warning sign at Lagan.

Department of Civil and Environmental Engineering Göteborg, Sweden, 2015

Thermal classification of cable route
Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering
ANDREAS LILLIESTIERNA
JOHAN UTAS
Department of Civil and Environmental Engineering
Division of GeoEngineering
Chalmers University of Technology

Abstract

In this study a strategy for thermal soil classification for high voltage direct current projects with buried cable is evaluated. The cable route of the South West Link project is investigated in order to find potential hotspots where the soil's thermal resistivity (the inverse of thermal conductivity) is high since the temperature of the cable is critical. If the designed maximum temperature is exceeded it shortens the life length of the cable and the warranty is no longer valid. The cable will also loose effect at high temperatures.

Based on geological data and information on installed cable types a stretch with potential hotspots is found south of Ljungby where a field study is conducted. Potential hotspots are where the thinner cable type is located in dry soil which is classified as thermal soil class B in this study. These results show that coarse grained soils with low water content have low thermal conductivity. Soil samples classified as both coarse and dry have in average 40 % lower thermal conductivity compared to the mean of all samples. The field measurements of thermal conductivity resulted in an average of 1.21 W/(m·K) where the 5th percentile is 0.66 W/(m·K) and the 1st percentile is 0.43 W/(m·K).

The proposed strategy for thermal soil classification is developed from the original strategy based on experiences from the investigation of the South West Link project. In this proposed strategy it is recommended to start with a pre-study of geological maps and data of groundwater table, soil type and thermal conductivity. In areas with potential hotspots where shallow groundwater table can be expected it is recommended to install piezometers in an early stage for accurate estimations of the groundwater variations. The areas with coarse soil types in combination with deep groundwater table are then investigated further at site. In this investigation a soil sampler is used every 20th metre or when changes in soil type can be expected. Measurements of thermal conductivity are made where low values are expected based on the samples from the soil sampler and visual inspection of the terrain. It is recommended that these measurements take place during the designing period in the beginning of the autumn at a depth of 50 cm, deeper if the first soil layer is not penetrated.

The design phase shall contain thermal calculations based on the design values of the construction. A numerical model is set up in a simulation software based on the design values in order to simulate cable temperature. Due to variations of thermal conductivity at a small scale in the soil and the difficulties to predict the conductivity it is recommended to use the observational method during HVDC projects. The observational method includes instructions of alternative actions based on different scenarios.

During the construction phase it is recommended that a geological expert attends when there are uncertainties about which of the scenarios is occurring. The construction is then built according to instruction formed in the design phase for the current scenario.

Termisk klassificering av mark vid högspänningsledning
Examensarbete inom masterprogrammet Infrastructure and Environmental Engineering
ANDREAS LILLIESTIERNA
JOHAN UTAS
Institutionen för bygg- och miljöteknik
Avdelningen för GeoEngineering
Chalmers tekniska högskola

Sammanfattning

I denna studie är en strategi för termisk klassificering av högspänningsledningsprojekt för likström med nedgrävd kabel utvärderad. Sydvästlänkens kabelsträcka är undersökt för att hitta potentiella kritiska områden där jordens termiska resistivitet (inversen av termisk konduktivitet) är hög då det är problematiskt med höga kabeltemperaturer. Om den dimensionerade maximala temperaturen överstigs förkortas kabelns livslängd och garantin gäller ej längre. Kabeln tappar även effekt vid höga temperaturer.

Baserat på geologisk data och ritningar från projekteringen har ett potentiellt kritiskt område hittats söder om Ljungby där ett fältarbete har genomförts. De potentiellt kritiska områdena är där den mindre dimensionen på kabel, kallad Normalkabel, ligger i torr jord vilken är klassad som termisk jordtyp B i denna studie. Resultaten visar att de grovkorniga jordarterna med låg vattenhalt har låg termisk konduktivitet. Jordprover klassade som både grova och torra har i snitt 40 % lägre termisk konduktivitet jämfört med medel för alla jordprover. Fältmätningen av termiska konduktiviteten resulterade i ett snitt på 1.21 W/(m·K) där femte percentilen är 0.66 W/(m·K) och första percentilen är 0.43 W/(m·K).

Den föreslagna strategin för termisk klassificering är utvecklad från den ursprungliga strategin baserat på undersökningen av Sydvästlänken. I denna föreslagna strategi är det rekommenderat att börja med en förstudie där geologiska kartor och information om grundvattennivå, jordtyp och termisk konduktivitet studeras. I potentiellt kritiska områden där låg grundvattennivå förväntas rekommenderas installering av grundvattenrör i ett tidigt skede för noggrann beräkning av grundvattenvariationerna. Områden med grova jordtyper i kombination med djup grundvattennivå undersöks ytterligare på plats. I denna undersökning används ett jordspjut var tjugonde meter eller där en jordartsförändring kan förväntas. Mätningar av den termiska konduktiviteten görs där låga värden förväntas baserat på proverna från jordspjutet och okulär besiktning av terrängen. Det rekommenderas att dessa mätningar görs under den dimensionerande perioden i början på hösten på ett djup av 50 cm eller djupare om jordmånen ej är genomträngd.

Projekteringsfasen ska innehålla termiska beräkningar baserat på konstruktionens dimensionerande värden. En numerisk modell görs i ett simuleringsprogram baserat på dessa värden för att simulera kabeltemperaturen. På grund av variationerna av termisk konduktivitet i liten skala och svårigheterna att förutsäga konduktiviteten rekommenderas observationsmetoden i högspänningsledningsprojekt. Observationsmetoden innefattar instruktioner om alternativa åtgärder baserat på olika scenarier.

Under konstruktionsfasen rekommenderas att en geolog närvarar då det finns en osäkerhet om vilket scenario som råder. Konstruktionen byggs sedan enligt den instruktion som utformades under projekteringsfasen för det rådande scenariot.

Contents

Preface

This Master Thesis is written at the department of *Civil and Environmental Engineering*, division of *GeoEngineering* at *Chalmers*. The thesis is a part of the development project *Strategy for Thermal design of high voltage underground cables* which was proposed by Vectura and Chalmers and ordered by state-owned *Svenska kraftnät* (Swedish National Grid for Electricity). In charge of the development project is Ph. D. Jan Sundberg and it is divided in three integrated parts;

- Evaluation of thermal transfer processes and back-fill material around buried high voltage power cables
- Feedback of experience from Sydvästlänken (The South West Link)
- Strategy for the prediction of thermal properties and optimisation of the design of cable routing

Examiner for the thesis is Prof. Lars. O Ericsson while the role of supervisors for the project is axled by Msc. Peter Lidén, and Jan Sundberg. Peter, Jan and Lars are also part of the reference group working with the development project. The full list of the reference group is as follows;

- Valentinas Dubickas, *Svenska kraftnät*
- Lars. O. Ericsson, *Chalmers*
- Håkan Garin, *GeoVerkstan*
- Gunnar Gehlin, *Svenska kraftnät*
- Peter Lidén, *Chalmers*
- Jan Sundberg, *Chalmers*
- Erik Thunberg, *Energiforsk*

We would like to express our endless gratitude towards our supervisors Jan Sundberg and Peter Lidén. Without their support and expertise in the field this project would not have been possible. A special thanks to Peter Hedborg for his unconditional willingness to help us in the laboratory. We also enjoyed the stay at the hostel in Södra Ljunga and the hospitality of the owners. The access to the cable route given by the landowners were greatly appreciated. Additionally we are thankful to Vectura, GeoVerkstan and Tyréns for providing us with vital data. Finally a big thanks to Svenska kraftnät for offering us the opportunity to work with this project.

Notations

AC – Alternate Current

DC – Direct Current

Gw – Groundwater

HVAC – High Voltage Alternate Current

HVDC – High Voltage Direct Current

IEG – Implementation Commission of European Geotechnical Standards

kV – Kilovolt

mH_2O – Pressure head, metre water column

MW – Megawatt

SGI – Swedish Geotechnical Institute

SGU – Geological Survey of Sweden

SMHI – Swedish Meteorological and Hydrological Institute

1 Introduction

1.1 Background

Construction of high voltage underground cables on land is a fairly new phenomenon in Sweden as the high voltage grid network consists almost exclusively of HVAC overhead power lines. HVDC on the other hand has been the standard for long distance submarine connections for the past couple of decades. Only short distances where the underwater cable reach shore have previously been dug down. Therefore there is no standardised method for thermal classification of buried cable in large HVDC projects.

The South West Link, which this project has been focused on, was the first of its kind in Sweden and the longest in the world (Svenska kraftnät, 2014) with 190 km of underground 400 kV HVDC cable. Two other HVDC projects are presented alongside the South West Link in chapter 2.

It is known that one of the factors affecting the design of the cables is the thermal conductivity of the surrounding soil. With low conductivity follows low cooling of the cables. This brings multiple side effects that are not desirable.

A big challenge when installing buried cable is to prevent the cable from exceeding the designed maximum temperature. The cable needs to be naturally cooled in the ground since a too heated cable will lose effect, the warranty of the cable will not be valid and it shortens the lifetime of the cable. In order to meet this requirement it is important to have advantageous thermal soil properties with high thermal conductivity. The cable trench cross-section in Figure 1 shows the area with thermal sand and the surrounding original soil.

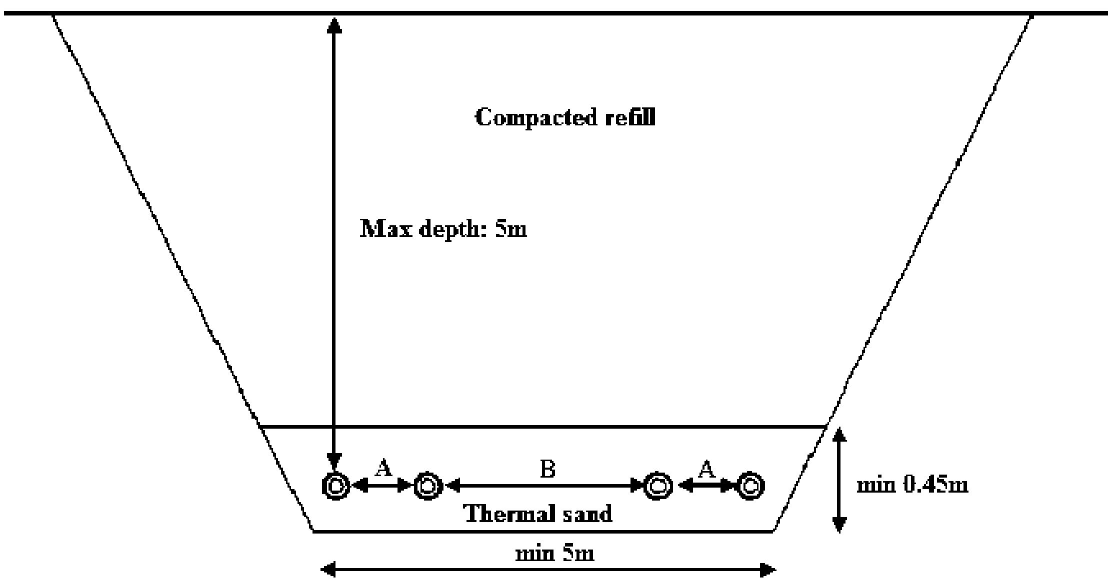


Figure 1. Cable trench example, translated image (Sundberg, 2012)

The thermal soil properties depend mainly on water content, density and types of minerals (Sundberg, 2012). Also the grain size distribution and the compaction ability are of great significance. Besides the geological properties also the hydrological properties such as the groundwater level affect the heat transfer. The impact of thermal conductivity in soil for underground cables is further explained in chapter 3.

Thermal runaway is a phenomena that can occur in cables when the temperature increases, leading to low internal conductivity, which in turn leads to additional temperature rise. This can happen due to overloading where the electrical effect exceeds the designed value (James & Su, 2008). It can also be caused by too low thermal conductivity in the surrounding soil which has to be taken into account when designing buried HVDC cables. The thermal runaway can lead to thermal breakdown where the heat causes decomposition of the material in the cable and a system failure occurs (Reddy & Ramu, 2007).

1.2 Aim

The goal of the project is to evaluate critical parameters regarding low conductivity in soil during HVDC projects with buried cable. Grain size distribution and gravimetric water content are examples of parameters being evaluated. A proposed method for evaluation and classification of thermal characteristics in soil is tested and further developed. The proposed method in its completeness can be seen in Appendix 1.

The results is shared with Svenska kraftnät and includes in their development project Strategy for Thermal design of high voltage underground cables.

1.3 Scope of work

This project has been made in the following steps:

- Literature study
- Pre-study of the South West link
- Field work
- Laboratory work
- Analysis of the results
- Evaluation of the method

A literature study was performed continuously throughout the project to learn about thermal effects on underground high voltage power cables, methods for measuring and classification of thermal properties.

The geological conditions on a regional scale were assessed using the online library of maps from Geological Survey of Sweden and Swedish University of Agricultural Sciences. Together with existing data from the South West Link, a suitable part of the stretch with potential hotspots was chosen for a more in-depth investigation.

The next step was to perform in-situ investigation by walking the selected stretch with a soil sampler, examining the soil type, and documenting the findings. During this walk, observations of local geological variations, as well as potential indications of the groundwater table from watercourses, were noted. Where it is available, existing piezometers for groundwater monitoring has be used.

In addition to the existing data, complementary investigations of thermal conductivity were carried out on chosen locations. This includes excavation of the ground in order to measure thermal conductivity and obtain soil samples for laboratory analysis.

The stretch, excavations and other sights of importance has been logged using ArcGIS to produce accurate and appealing maps of the project.

The data has been analysed for its geological, hydrogeological and thermal properties with the purpose of evaluating and enhancing an existing method for thermal classification. The results and consequent alterations of the strategy for thermal classification of cable in natural ground conditions is included in Chalmers development project for Svenska kraftnät named Strategy for Thermal design of high voltage underground cables.

1.4 Limitations

Geographically this project is limited to the area around the underground cable connecting Värnamo and Hurva. Effectively this gives a length of 190 km underground cable that is considered when selecting a stretch which may contain potential hotspots. The amount of input data for the analysis is restricted by the size of the previous studies and the extent of additional measurements. During the field study some areas of the stretch were unreachable for various practical reasons.

A typical cable trench looks similar to the one presented in Figure 1. This project has been focused on the natural soil around the cable trench, not the thermal sand located directly around the cables. The refill material is generally the original natural material of the dug trench, however material might have been transported from other places as well to even out possible deficits or surpluses.

2 Underground HVDC projects

This chapter provides information on some HVDC projects in northern Europe. Aside from the South West Link, there are numerous other similar projects around the globe. In this subchapter three projects is presented, the recently finished South West Link, the planned project The Gotland Connection and the existing Estlink.

2.1 The South West Link - SydVästlänken

The South West Link is a high voltage cable route project between Hurva and Hallsberg (Svenska kraftnät, 2014). This project was planned by the board of Svenska kraftnät in 2005 in order to improve the transmission capacity of the Swedish national grid for electricity. It is also a way of increasing the operational reliability of the power net system and contributes to reduce the difference in electricity cost for different areas.

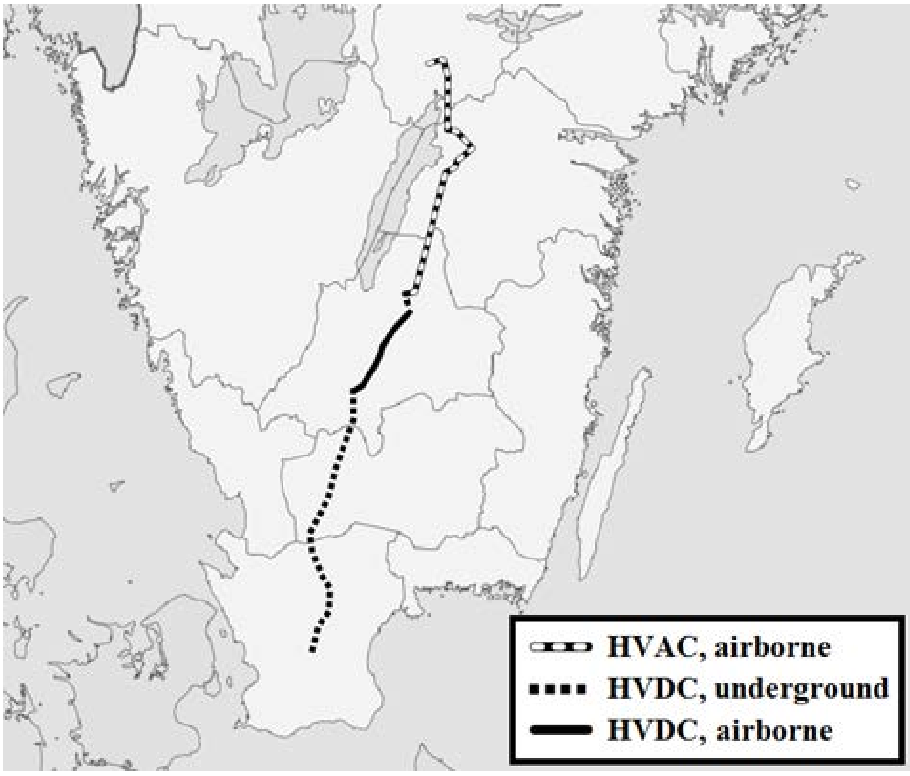


Figure 2. Map displaying the cable route of the South West Link.

The northern part of the cable route between Hallsberg and Barkeryd consists of an alternate current link above ground, which is illustrated in Figure 2. This stretch is 180 km and has a voltage of 400 kV with a transmission capacity of about 1200 MW. From Barkeryd to Värnamo there is a direct current link above ground. The last part of the stretch between Värnamo and Hurva consists of a 190 km buried HVDC cable. There is a transmission capacity of 2·600 MW for the stretch between Barkeryd and Hurva which is 250 km. A total of four parallel underground cables was installed in cable trenches at a depth of at least 1.2 m. There are two cable types used in this project, one standard cable and one high performance cable with a conductor cross sectional area of 2010 mm^2 and 2590 mm^2 respectively.

For the northern part the route was commissioned in the beginning 2015 and for the southern link the planned date is set to the beginning of 2016. The expected cost of the whole project is estimated to be approximately 7.3 billion Swedish kronor with the power net stations in Hurva and Barkeryd included.

In 2008 the decision was made to build the northern part with alternate current technology and the southern part with direct current. The plan was also at that time to include a cable route connection to the Oslo area, which explains the name of the project, The South West Link. This cable route was later decided, in consultation with the Norwegian state-owned company Statnett, not to be realised. The reason was that the benefits with the link had heavily decreased in comparison with earlier analyses although the name the South West Link has been remained for the project. There are plans to install a cable between the power station in Barkeryd and the station in Ekhyddan in order to connect the South West Link with the Gotland Connection (Svenska kraftnät, 2014). This link increase the operational reliability in the national grid and the link of 150 km is projected to be commissioned at the end of 2019.

2.2 The Gotland Connection – Gotlandsförbindelsen

In 2009 the board of the Swedish state-owned company Svenska kraftnät made the decision to start planning for a 110 km high voltage cable route between Oskarshamn and Gotland (Svenska kraftnät, 2012). The project is called The Gotland Connection and is planned to be built in two phases where each cable will have a capacity of 500 MW. A HVDC technology will be used and it shall reach a capacity of 300 kV.

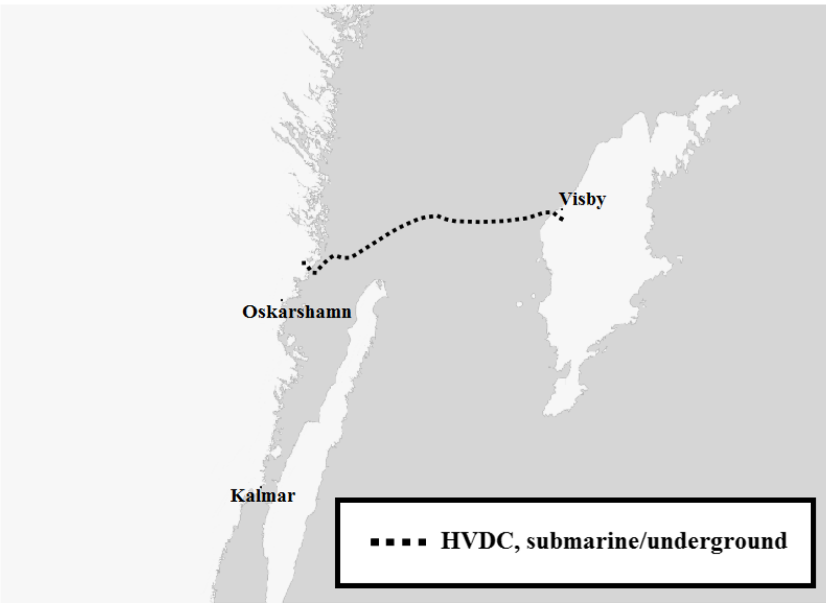


Figure 3. Map displaying the cable for The Gotland Connection

An outline of the planned route can be seen in Figure 3. The cable route consists of 6 km buried cable between Simpevarp, located southwest of the nuclear power plant of Oskarshamn, and Misterhult. There is approximately 100 km sea cable between Simpevarp and Ygne followed by a 4-5 km buried link on Gotland from Ygne to Forse. A power station will be located in Forse. The first cable is planned to be commissioned in 2017 and the second in 2020.

The main reasons behind this project are to enable a wide expansion of the wind power on Gotland and to connect the regional power net on Gotland to the national grid on the Swedish mainland. Today the electricity from wind power on Gotland contributes with 110 MW. The objective is to increase the wind power electricity on Gotland to reach an effect of approximately 1000 MW.

2.3 Estlink submarine HVDC

The Estlink HVDC project is a submarine cable from Espoo in Finland to Harku in Estonia, covering some 105 km of which 74 is below the Gulf of Finland. A geographic sketch of the stretch can be seen in Figure 4. As a as part of the European Union's strategy to maintain a stable and efficient power supply the project was finished by the end of 2006. The motivation for the venture was to connect the Nordic and the Baltic energy grids and to establish a safe supply of power to the Baltics (Ronström, et al., 2007).

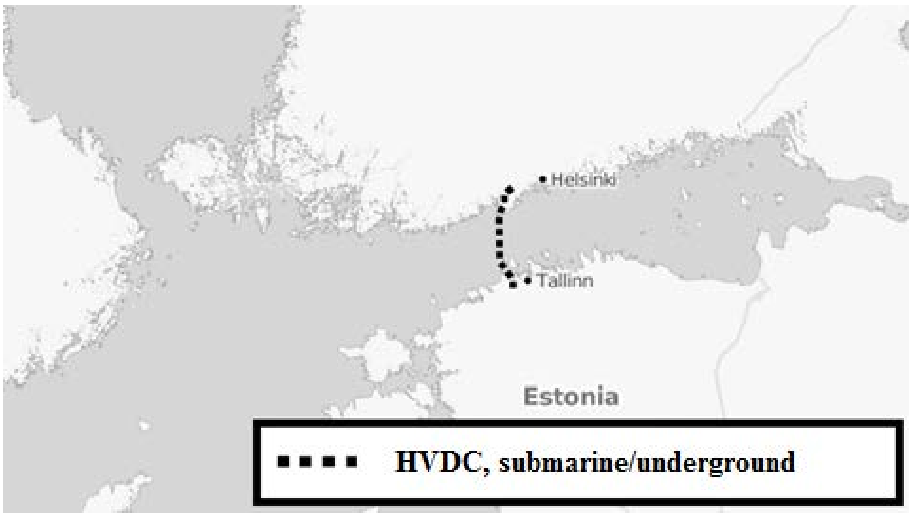


Figure 4. Map displaying the cable route for Estlink.

The cables have an electric potential of 150 kV and a transmission capacity of 350 MW. Both ends of the route consist of land based underground cable, similar to the setup of the Gotland Connection. The HVDC is connected to the Finnish 400 kV power grid at Espoo converter station and to the Estonian 330 kV power grid in Harku.

The two cables are 105 km long each, 22 km on mainland Finland, 74 km submarine and 9 km on Estonian mainland. The underwater cable has a maximum depth of 100 m, is buried 1 m below the sea floor and use a 1000 mm^2 copper conductor. The cable on land utilises a 2000 mm^2 aluminium conductor.

During construction on land a technique similar to the Swedish projects was used. Cables are laid down roughly one metre below the surface in cable trenches, cable sand with high thermal conductivity is used to fill the area around the cables, and the original soil is thereafter used to refill.

The geological conditions on the Finnish mainland is dominated by forest and arable land (Bengtsson, et al., 2006). In the northern part of the stretch there is mainly granite bed rock and some parts with wetland. The geological properties of the cable stretch in Estonia is similar to the ones in Finland. However, it also consists of 2 km with limestone.

3 Factors affecting cable temperature

3.1 Heat transfer in the context

The investigation of the temperature of the cable is costly since the landscape often has very varied conditions along the stretch with different thermal properties (Sundberg, 2012). To design the cable route for the maximum acceptable temperature, it is not the average temperature along the stretch that is used. The cable needs to fulfil the temperature requirements for every section of the route down to the scale of 1-5 m. Therefore the cable needs to be designed for the section with the highest thermal conductivity. A limited section with coarse grained sand and low groundwater level could therefore be the designing soil in an area where the rest consists of silty till. The main factors affecting cable temperature are the following:

- Cross-sectional area of the conductor
- Cable separation
- Cable depth
- Thermal conductivity of the soil
- Electrical effect of the cable
- Ground temperature

The main factors affecting thermal conductivity of the soil are the following:

- Water content
- Density
- Mineral type
- Organic content

Thermal conductivity is the inverse of thermal resistivity. The relationship between thermal conductivity, heat capacity and thermal diffusion can be seen in Equation (1). Thermal conductivity (λ, [W/(m·K)]) is the ability of the material to transfer heat and the heat capacity (C, [J/m^3·K]) depends on the material's ability of storing energy. Thermal diffusivity (κ, [m^2/s]) is the ability to even out temperature differences within the material.

$$\lambda = \kappa \cdot C \tag{1}$$

A factor that affects the temperature of the cables is the distance between them in the ground. It is advantageous with increased distance in terms of keeping the cables below the restricted temperature but it requires a wider excavation area, extended land consumption and more cable sand. Also the number of cables, the cable area and the depth of the cables in the ground will have an impact of the cable temperature. For construction cost reasons the cable is installed as shallow as possible whilst maintaining the minimal depth which is often set to 1.2 m. This is however decided by the terrain and practical reasons.

Besides the protecting properties of the surrounding cable sand also the thermal properties of it are of importance since it is the closest layer of material to the cable. Cable sand with high thermal conductivity is recommended and it could to a certain extent compensate for a low thermal conductivity in the ground. The thermal effect of the cable sand depends on the quality, the mass, the mineral type and the geometry.

It is important that the cable sand has good ability of storing sufficient water content during dry periods to prevent it from dehydration. If the sand gets dehydrated it will lose heat convection capacity. During unsaturated conditions and increased temperatures the heat from the cable can generate vapour diffusion but as long as it is balanced by the capillary forces, which work in the opposite direction, dehydration can be avoided (Sundberg, 1985).

The factors affecting the thermal conductivity of cable sand is almost the same as for soil. This includes grain density, grain size distribution and compaction ability. Also the water-bearing capacity and the thermal conductivity at different water contents are vital properties.

Natural undisturbed temperature and temperature variations in the ground has an impact on the cable temperature. The electrical effect in the cable and the duration of the effect is of significance when designing the cables for the maximum accepted temperature. These factors are often decided on forehand.

3.2 Thermal properties

3.2.1 Thermal properties of soils

There are significant variations in heat conductivity of different soils which mainly depend on the porosity, grain size distribution and the water content. Soils with high porosity have low heat conductivity because of the low thermal conductivity of air. The impact of water content in soil is important since it replaces this air and therefore increases thermal conductivity in the soil. This is especially true for the contact surfaces between grains where the water acts as a bridge for the heat transport. The porosity depends on grain size and compaction ability which makes the coarse soils less heat conductive.

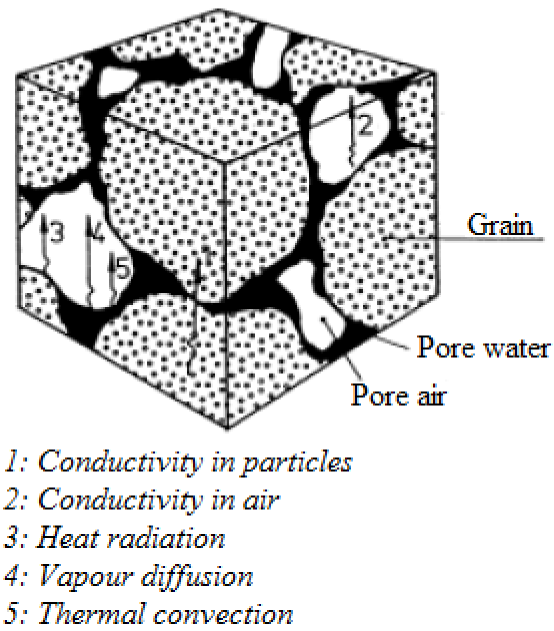


Figure 5. Heat transfer mechanisms in soil. (Sundberg, 2012)

Large grain size distribution leads to high thermal conductivity since it increases the compaction ability which is the case for till. Till can include a grain distribution from clay to boulder. Heat transport in soil depend on the mechanisms visualised in Figure 5. Vapour diffusion is primarily a factor in higher temperatures, and convection predominately occurs below the groundwater table (Sundberg, 2012). The definition of soil type with respect to the grain size is illustrated in Table 1.

Table 1. Classification of soil types (Karlsson & Hansbo, 1984).

Soil class	Subclass	Grain size [mm]
Clay	Fine clay	<0.0006
		<0.002
Silt	Fine silt	0.002-0.006
	Medium silt	0.006-0.02
	Coarse silt	0.02-0.06
Sand	Fine sand	0.06-0.2
	Medium sand	0.2-0.6
	Coarse sand	0.6-2
Gravel	Fine gravel	2-6
	Medium gravel	6-20
	Coarse gravel	20-60
Cobble	Medium cobble	60-200
	Coarse cobble	200-600
Boulder		>600
	Coarse boulder	>2000

The thermal conductivity of clay differs depending on the water content (Sundberg, 1991). Clay with high water content has a thermal conductivity of 0.85-1.1 W/(m·K). Close to the ground surface it is common that clay is in drier state called crust clay. This clay has a thermal conductivity of 1.1-1.4 W/(m·K). The density of the crust clay is higher than the underlying unaffected clay (Sundberg, 1985). In conditions where the clay is frozen the thermal conductivity is almost doubled which can be seen in Table 2.

Silt is more thermal conductive than clay with 1.2-2.4 W/(m·K) in unfrozen state. It depends on the higher thermal conductivity in the silt particles compared to the clay particles. As for the clay also the thermal conductivity of silt is heavily increased when it is frozen. In frozen condition the conductivity is 2.3-3.2 W/(m·K).

The thermal conductivity of sand and gravel varies depending on if it is lying above or below the groundwater table. Above the groundwater table it has a thermal conductivity of approximately 0.4-1.1 W/(m·K) and below the groundwater table it increases to 1.5-2.6 W/(m·K). Sand or gravel in a condition with high water content can lead to six times higher thermal conductivity compared to low water content (Sundberg, 1985). The thermal conductivity is even higher in frozen condition but it does not affect the properties above the groundwater table which is illustrated in Table 2.

The thermal conductivity of till varies greatly depending on its composition of grain fractions. Normally the conductivity above the groundwater table is 1.5-2.5 W/(m·K) but in a sandy till the conductivity in the area of 0.6-1.8 W/(m·K). Till is an unsorted soil due to its direct deposition from the ice sheet and has often a high density. In natural moisture condition above the groundwater table the till normally has a higher thermal conductivity than silt and sand. The conductivity is on the contrary lower than these soils during conditions when they have the same volumetric water content. This is explained by the lower grain conductivity in till.

In peat the conductivity is very low above the groundwater table due to its high porosity. The porosity of approximately 90 % gives a conductivity of 0.2-0.6 W/(m·K). Below the groundwater table the conductivity of peat is almost the same as for water which is 0.6 W/(m·K). The rate of humus is also factor for the conductivity. Peat with low humus content has a lower water holding capacity which decreases the thermal conductivity.

Table 2. Thermal conductivity of soil types (Sundberg, 1988).

Soil type	Thermal conductivity [W/(m·K)]	
	Unfrozen	Frozen
Clay with high clay content	0.85-1.1	2.0-2.2
Dry crust clay with high clay content	1.1-1.4	1.7-2.3
Silty clay	1.1-1.5	2.3-2.8
Dry crust silty clay	1.2-1.6	1.9-2.9
Silt	1.2-2.4	2.3-3.2
Sand, gravel below gw-table	1.5-2.6	2.7-3.3
Sand, gravel above gw-table	0.4-1.1	0.4-1.0
Till below gw-table	1.5-2.5	2.3-2.7
Sandy till above gw-table	0.6-1.8	0.5-1.6
Peat below gw-table	0.6	1.7
Peat above gw-table	0.2-0.5	0.4-1.5

3.2.2 Thermal properties of rocks and minerals

The thermal conductivity of rocks depends on the degree of metamorphosis and the mineral composition. In Sweden the two most common rock types are granite and gneiss where 42.4 % consists of granite and 23.7 % consists of gneiss (Sundberg, et al., 1984). The mean thermal conductivity of both these crystalline rock types is 3.5 W/(m·K). In Table 3 overleaf the thermal conductivity for some of the common crystalline rocks are displayed.

Table 3. Mean value of thermal conductivity in some crystalline rocks (Sundberg, 1988).

Rock type	Thermal conductivity [W/(m·K)]
Granite	3.47
Granodiorite	3.34
Tonalite	3.16
Aplite, pegmatite	3.31
Quartzdiorite	2.87
Syenite, diorite	2.67
Porphyry	3.55
Porphyrite	2.54
Ryolite	3.37
Trachyte	2.83
Quartzite	6.62
Gneiss	3.47
Leptite	3.58

Variations in thermal conductivity for crystalline rock depend mainly on the mineral content (Sundberg, 1991). The mineral quartz has a high conductivity with 7.7 W/(m·K) which explains the high conductivity of quartzite who mainly consists of quartz. Granite consists of plagioclase, feldspar, quartzite and biotite. The thermal conductivity of some of the most common minerals in Sweden is showed in Table 4. For the metamorphic rocks the variation in conductivity is higher compared to the magmatic rocks. This is explained by the foliation in metamorphic rock that creates anisotropy. Anisotropy means that the properties are different depending on the direction in the material.

Table 4. Thermal conductivity for some of the most common minerals in Sweden (Horai, 1971).

Mineral type	Thermal conductivity [W/(m·K)]
Quartz	7.7
Microcline	2.5
Plagioclase	1.9[1]
Biotite	2.0
Muscovite	2.3

[1]Mean value, varies depending on the anorthite content.

In comparison with crystalline rocks the sedimentary rocks are more dependent on the water content and porosity when deciding the thermal conductivity. Sedimentary rock is mainly located in Skåne and on Gotland and Öland. The thermal conductivity also depends on from what age the sedimentary rock origins. In Table 5 the conductivity of the sedimentary rocks are showed and also the differences depending on from what age it origins has been taken into account. The Mesozoic era lasted between 251-65.5 million years ago and the Cambro-Silur lasted in the period 542-416 million years ago (University of California, 2011). Pre-Cambrium is a geological era that lasted between 4600-542 million years ago.

Table 5. Thermal conductivity of sedimentary rocks (Sundberg, 1988).

Rock type	Thermal conductivity (W/(m·K)
Sandstone (Mesozoic)	2.3-4.5
Sandstone (Cambro-Silur)	4.0-6.0
Sandstone (Pre-Cambrium)	4.0-6.5
Shale (Mesozoic)	1.5-3.0
Shale (Cambro-Silur)	2.0-3.5
Limestone (Mesozoic)	1.5-2.8
Limestone (Cambro-Silur)	2.8-3.3

3.3 Water saturation

The soils water content is one of the major factors affecting thermal conductivity. The lowest conductivities are generally found above the groundwater table, especially in organic soils such as peat and loam. Finding low groundwater levels is therefore of interest when searching for a hotspot on the stretch that could possibly be designing for the entire cable.

The groundwater level depends on rainfall, snow melting and surrounding recharge conditions. It also varies over time, as it follows the hydrological cycle and the degree of variation is affected by the aquifers physical characteristics and dimensions. The groundwater table is lowest during summer and highest after snow melting. To not obtain two separate max values of the groundwater level in two consecutive years from the same peak the hydrological year starts the first of October and ends in September.

The groundwater table is generally shallower in areas of discharge than in areas of recharge, as it is not only refilled by precipitation but also from upstream groundwater (Haaf, 2014). This leads to higher fluctuations on heights than in valleys. Generally the groundwater level follows the topography and is the higher on hills than in valleys (Svensson, 1984). However, due to the flow towards lower areas, the depth of the groundwater table compared to the surface level is generally larger on heights. The amplitude of the difference in groundwater level is affected by the soil type and its hydrological characteristics. The groundwater table is especially high after the snow melting and low after drought periods.

Since water has a high thermal conductivity compared to air it is advantageous with a high groundwater level in terms of keeping a low cable temperature. The groundwater level varies throughout the year and it is therefore important to calculate the probability of extreme levels by looking at historical groundwater levels in the area. Variations in groundwater level leads to convection below the water surface. The thermal condition around the cable is heat sluggish which means that it requires a long period of low heat convection in order to establish increased cable temperature.

When the cable is located above the groundwater level the evaporation rate of the soil and the distance from the groundwater level is crucial. The evaporation rate increases with increased temperature. Another essential factor for deciding the water content in the soil is the water-holding capacity that depends on the capillary ability of the soil. A water retention curve illustrates how the water-bearing capacity of the soil reduces with increased water tension above the groundwater level. This is displayed in Figure 6. In water retention curves the volumetric water content is used, however our acquired values will be stated in gravimetric water content. Gravimetric water content is the ratio between mass of water and solid mass in a sample. Changes in water content over time are less for fine-grained soils such as clay and silt compared to more draining soils such as gravel and sand. Generally soils with high organic content have a low heat convection capacity.

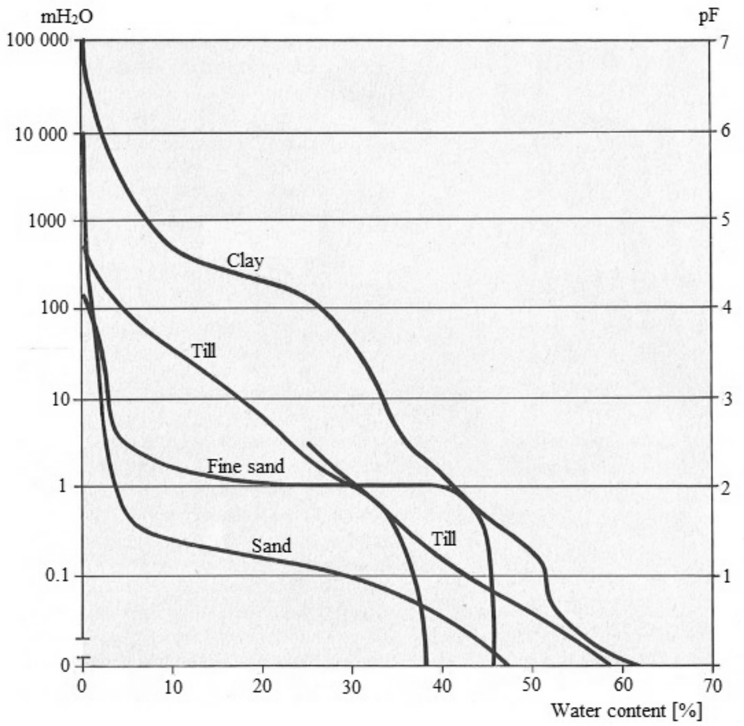


Figure 6. Example of water retention curves of different soil types (Löfgren, 2008).

3.4 Ground temperature

The natural temperature in the ground varies throughout the year which makes certain periods more exposed for high cable temperature which needs to be designed for. Besides the air temperature the depth is also an important factor to determine the ground temperature. The temperature variation decreases with an increased depth which can be seen in Figure 7. This figure shows how the ground temperature fluctuates during the year in the Ljungby region at the depth of 0.5 and 1.5 m compared to the air temperature. The graph shows how the heat sluggish in the ground creates a phase shift of the annual air temperature variation. This phase shift increases with the depth until the ground temperature is not affected by the yearly temperature variations. The fluctuations are theoretical for a ground only dependent on air temperature variations and the parameters that can be seen in Table 6. In reality the ground temperature variations depend on the groundwater table fluctuations. Furthermore the figure does not take into account the extra energy needed for transition between frozen and unfrozen state in the ground which leads to slower temperature variation.

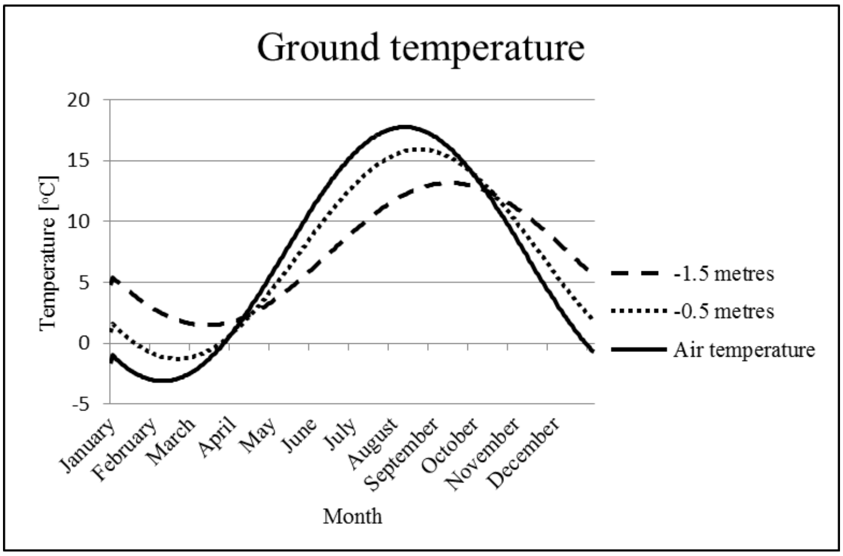


Figure 7. The annual ground temperature variation in the Ljungby region.

The line chart is based on Equation (2) (SLU, 2002) for temperature variations in the ground where *t* is the time and *z* is the depth. Besides these variables the formula contains T_{mean} and T_{amp}, which is the mean temperature of the year and the biggest annual temperature amplitude respectively. The formula also contains t_p which is the day number when the biggest temperature amplitude occurs during the year. Finally d is decided by the thermal diffusivity of the soil, κ.

$$T(t,z) = T_{mean} - T_{amp} \cdot e^{-\frac{z}{d}} \cdot \cos\left(\left(t - t_p\right)\frac{2\pi}{365} - \frac{z}{d}\right) \quad (2)$$

Where;

$$d = \sqrt{2\kappa / \frac{2\pi}{365}}$$

The temperature data is based on day mean values during a 10-year period for the Ljungby region between 1997-2007 (SMHI, 2015). All input values for Figure 7 can be seen in Table 6. This calculation is based on a soil with low thermal diffusivity (Nofziger, 2015).

Table 6. Input values for the calculation of the annual ground temperature variation in the Ljungby region.

Parameter	Value
T_{mean} [°C]	7.3
T_{max}[°C]	17.8
T_{min}[°C]	-3.9
t_p [day]	40
Z_1 [m]	1.5
Z_2[m]	0.5
λ [W/(m·K)]	1
C [J/(m^3·K)]	1.5
d [m/day]	2.6
κ [m^2/day]	0.06

4 Conceptual model of thermal conductivity in soil

A simplified conceptual model is a good way of demonstrating how the factors presented in the previous chapter affect the behaviour of the soil and groundwater and in the end how they influence thermal conductivity. The conceptual model and its parameters are visualised in Figure 8. The model is a very simplified version of reality and not all influences can be taken into consideration. Only the largest contributing factors are therefore included.

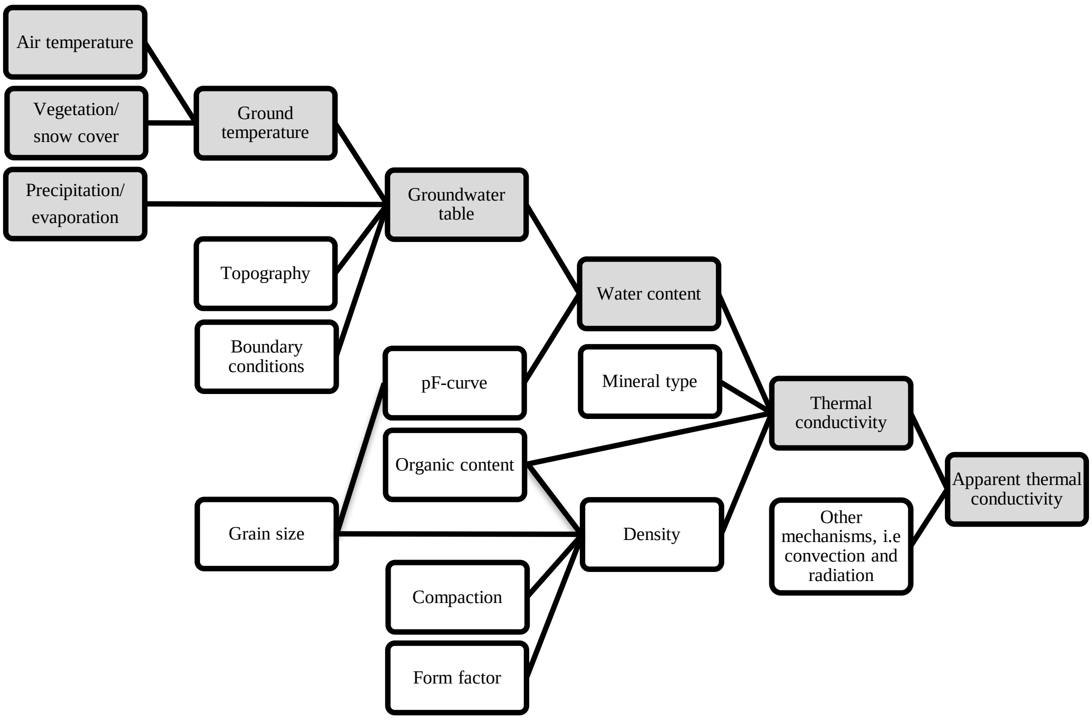


Figure 8. Conceptual model of factors affecting thermal conductivity in soil, grey boxes are parameters with time dependency.

Ground temperature is decided by air temperature and possible vegetation or snow cover. This affects the groundwater level if the temperature decreases below zero and the ground freezes thus disabling infiltration by acting as a barrier. Groundwater level is besides this mostly affected by precipitation, topography and the general boundary conditions. Boundary conditions include for example type of aquifer, inflow/outflow and other settings. The connection between groundwater table and ground temperature is two-way, since variations in groundwater table and flow also changes the temperature.

The actual water content in the soil at a given depth is dependent on the groundwater level. If the soil is located above it, the pF-curve is used to find the water content. The pF curve is dependent on grain size, which together with organic content, compaction and form factor, also affects the density of the soil. Theoretical thermal conductivity is then decided by water content, density and mineral type. The actual measured thermal conductivity is also influenced by temporary or local mechanisms such as convection from the groundwater flow and heat radiation. Because of this an apparent thermal conductivity can differ slightly from the theoretical.

The grey boxes are parameters with time dependency. Air temperature, precipitation and vegetation/snow cover changes over time and so does the parameters that are affected by these.

5 Investigation of methodology for thermal classification

The original methodology for thermal classification of cable route established which this study is based can be seen in Appendix 1. In this first version of a strategy for classifying the thermal properties of the soil is the procedure divided in four main steps; Investigation, evaluation, presentation and verification. The investigation of this methodology is performed with a field study on the South West Link project. In this strategy the main objective is to establish a methodology which is designed for variations in thermal conductivity on the scale 1-5 m.

The methodology starts with a desktop study where geological maps and groundwater conditions are studied. In a field work a soil sampler is recommended to be used every fifth metre at a depth of 0.5 m and a doctor's kit is used when it is needed. Installation of piezometers is recommended for groundwater estimations. After the field work statistical analysis and calculations of the temperature are made.

In chapter 7 the methodology for thermal classification is evaluated and a new methodology is proposed which implements the observational method. A general description of the observational method can be seen in appendix 6.

5.1 Workflow

This chapter describes the workflow used when testing the proposed method.

5.1.1 Pre-study

The stretch is studied in order to find hotspots for further investigations. On this stretch are data from the South West Link project and soil maps analysed. Also the groundwater table along the stretch is analysed by data from earlier measurements in the area. Provided AutoCAD drawings of the cable type and soil classification along the stretch is studied in order to find parts where the smaller cable size is located in dry soil. These parts are illustrated in ArcGIS which gives an overview of potential hotspots for further investigations at site.

5.1.2 Field study

By studying a chosen stretch with potential hotspots at site further investigations with more detailed data is possible. During the field study a soil sampler is used to discover differences in soil type along the investigated stretch. The thermal conductivity is measured at interesting sites using a handheld thermal conductivity measurement system. At the sites where the thermal conductivity is measured soil samples are collected for further investigation in laboratory. Along the stretch the topography and groundwater condition are studied to get an estimation of the groundwater table.

The thermal conductivity of the soil samples from the field study is measured again in laboratory. Before the measurement are the soil compacted with a proctor compaction. The water content is measured by drying the soils in an oven and measure the weight difference of the samples before and after the drying procedure. Finally are the grain size distribution measured by doing a sieve analysis in order to get a more detailed soil classification.

5.1.3 Analysis of field study

The results from the field study is analysed by using statistical methods and study how the different parameters affect the thermal conductivity of the soil. By grouping soil types and compare them regarding the thermal conductivity can the importance of the different parameters be analysed. The result from the field study and laboratory measurement is also compared with the result of the study made by Vectura for the South West Link project.

5.1.4 Evaluation of methodology for thermal classification

In this part are the analysis of the field study discussed and the strategy for thermal classification is evaluated. Also the annual variations of thermal conductivity is discussed. The parameters affecting the thermal conductivity are evaluated for future investigations. By studying the analysis of the results an improved strategy for thermal classification of cable route shall be designed. This strategy applies the observational method.

5.2 Pre-study

5.2.1 Geological description

The underground part of the South West Link stretches from Värnamo in Småland to Hurva in Skåne. The 190 km long route passes through many different areas but geologically the area is relatively homogenous. The dominant soil type is till throughout the entire route, with a significant amount of glacial river formations, primarily heading in a north-north eastern direction. There is also a fair quantity of peat bogs in the vicinity of the cable as well as some post glacial clay, silt, sand and gravel in the river valleys. The bedrock, consisting primarily of different derivate of granitic and gneissic rocks with limestone in the southernmost part, is visible on some locations. The soil layer is however generally deep ranging from several metres up to 30-40 metres in the river valleys.

The forest in the area is dominated by spruce, with substantial amounts of pine trees and some deciduous. Generally the area is fairly flat, with an altitude spanning from around 75 to 180 metres above mean sea level over the course of 190 km with the lowest values in the south and the highest in the north. There are numerous lakes and rivers in the area and the cable is crossing these on several occasions.

The annual precipitation in the area was around 750 mm between the years 1961 and 1990, however an increase in rainfall has been observed between 1991 and 2008 with well above 800 mm (Johnell, 2010). Evaporation rate was 425 mm per year from 1961 to 1990.

5.2.2 Soil classification

When looking for potential hotspots to investigate, parts where the thinner standard cable was laid in coarse dry soils was of interest. For the South West link project a thermal classification of the soils was made. The soil types were divided in soil classes according to their thermal properties (Sundberg, 2012). There are 5 classes, from A to E, with C, D and E being organic soils where special measures was taken during construction. Class B has the least favourable thermal conductivity properties of the remaining. It consists of coarse grained soils with low groundwater table. More specifically it is sand, gravelly sand, gravelly and boulderly till with a groundwater table constantly 1.5 m below the surface.

The classification of the soil is following:

Thermal soil class A – Normal Soil

Consists of clay, silt and clayey, silty and sandy till. The class does not depend on the groundwater table but expects to keep normal soil moist content during the whole year. It is normally well graded soils and includes also excavation in rock.

Thermal soil class B – Dry soil

Consist of sand, gravely sand and gravely and boulderly till. Cohesive and friction soil filling do also belong to this class. All these soils need to have a groundwater table deeper than 1.5 m (both criteria regarding soil type and groundwater table must be fulfilled). The soil type is mainly coarse and poorly graded.

Thermal soil class C – Organic soil with normal moist content

Consists of moist or wet peat and other organic soils with a groundwater table shallower than 1.5 m in average. Soils that are wet during the whole year are not included, see Thermal soil class E.

Thermal soil class D – Dry organic soil

Consists if dry peat and other organic soils with a groundwater table deeper than 1.5 m in average. This soil class is must be handled as a special case with extended analyses before passing.

Thermal soil class E – Very wet organic soil

Consists of wet peat and other organic soil with a groundwater table shallower than 0.5 m during the whole year.

5.2.3 Investigated stretch

An overview of the entire 190 km route is displayed in Figure 9 overleaf. The light grey parts of the line represents areas where the thinner cable is laying in soil with thermal class B and the box is where this is most concentrated. It was therefore chosen as a potential hotspot to investigate further.

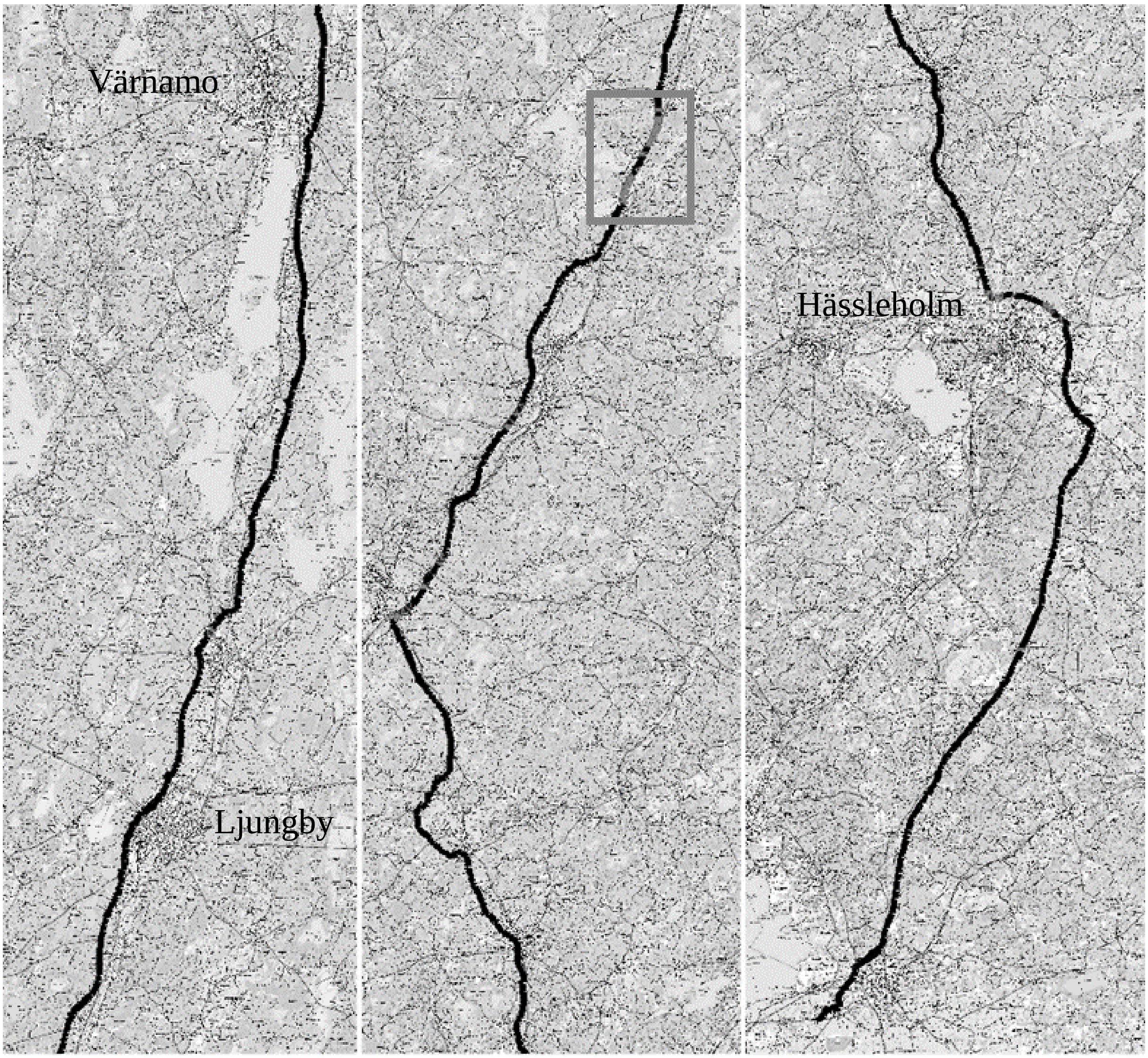


Figure 9. *Map with the standard cable in class B soil (north to south, from left to right).*

5.2.4 Geological description of investigated stretch

The selected stretch with potential hotspots is around 5.6 kilometres and located between the minor towns of Ljungby in the north and Markaryd to the south. The cable is solely located just west of the European route E4 throughout this part. As can be seen in Figure 10, it passes below four minor roads, the river Lagan and a peat moss.

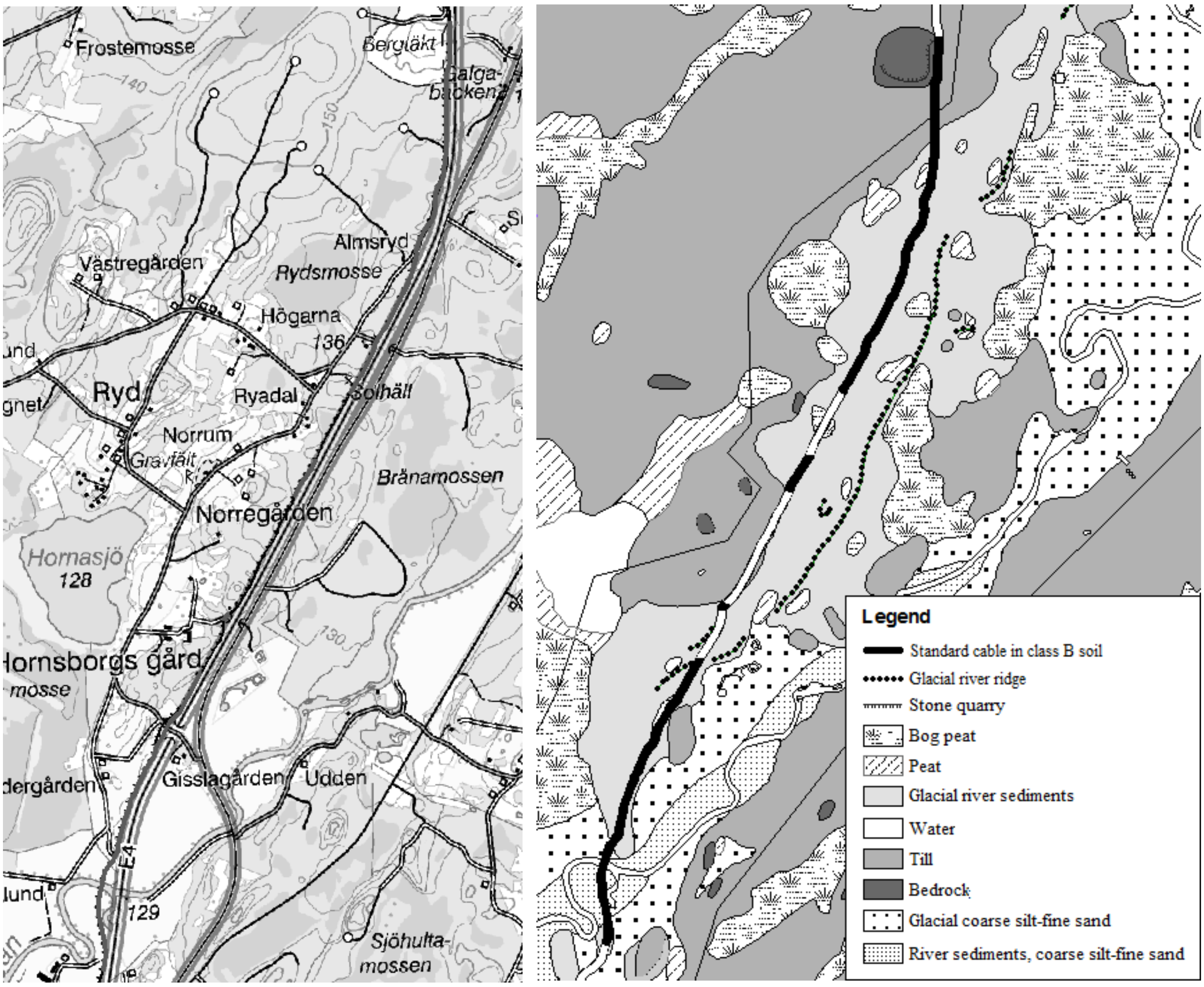


Figure 10. Investigated stretch in overview and soil map.

The majority of the cable is of the standard type with only the peat moss and its surroundings consisting of the high performance cable. As the soil map shows, a large portion of the ground is made up of glacial river sediments. The Lagan river bank is made up of glacial and river sediments of coarse silt and fine sand. In the middle of the stretch is a 1 km long part with till and just north of this a bog is located. In the far north is a stone quarry which is represented by the large dark grey area. The dotted black line is the ridge of the glacial river sediments.

5.2.5 Hydrogeological description of investigated stretch

The hydrogeological description for The South West Link project was made by WSP (Åkerlund, 2012). In this investigation the soil moisture is classified according to the classification showed in Table 7. The investigation shows that the studied stretch between Hornsborg and Hamneda mainly consist of dry soils with a groundwater table deeper than 2 m, see Appendix 7. There is totally about 1 km of the 5.6 km long stretch that not consists of dry soils according to the investigation by WSP.

Table 7. Soil moisture classification (Johansson, 2008).

Moisture class	Definition
Dry	Groundwater table deeper than 2 m, no presence of moving surface water.
Mesic	Groundwater table between 1-2 m.
Moist	Groundwater table shallower than 1 m.
Wet	Groundwater table at ground surface with permanent water bodies.

There are two piezometers located south of Hornsborgs Gård with measured groundwater data since the spring of 2012, see Figure 11 and Figure 12. These figures show that there are dry soil in the area as the groundwater table in the piezometers never are shallower than 3 m below ground surface during the measured period.

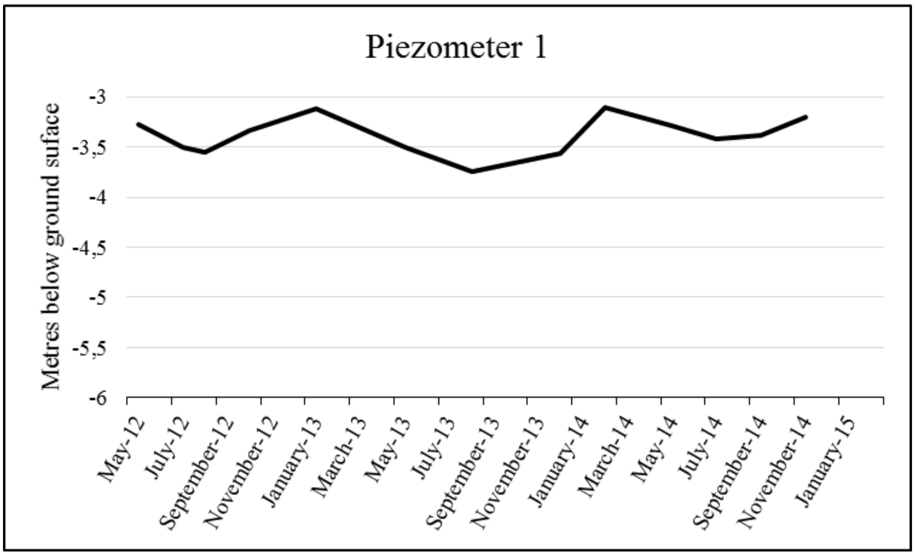


Figure 11. Groundwater table variation at Piezometer 1 south of Hornsborgs Gård.

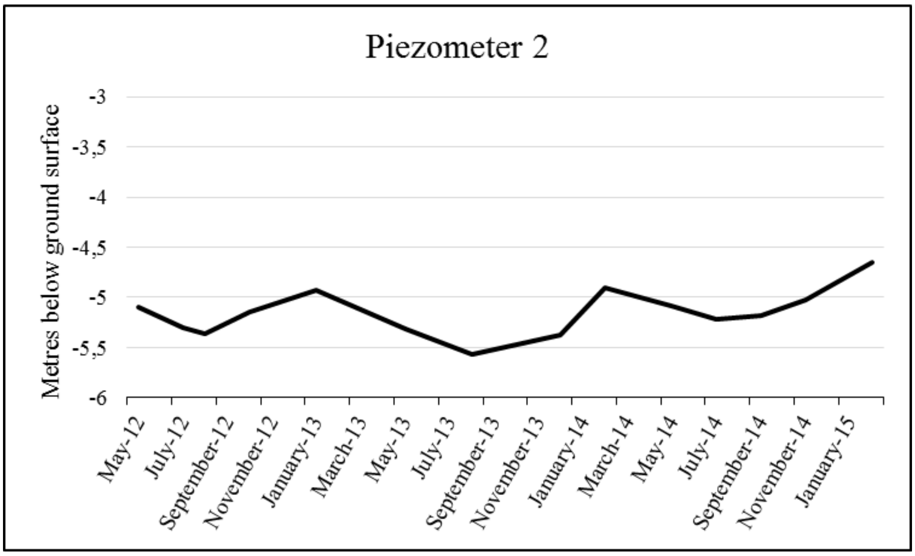


Figure 12. Groundwater table variation at Piezometer 2 south of Hornsborgs Gård.

5.3 Field study

During the field study the 5.6 km long potential hotspot between Hornsborg and Hamneda was investigated, as could be seen Figure 10. The stretch was studied by using a soil sampler. Before the field trip the plan was to use the stake every five metre along the investigated stretch to discover local differences in soil type. Due to difficulties to penetrate the soil with a soil sampler to a proper depth every five metre, this could not be carried out during the whole stretch.

The thermal conductivity was measured in 26 holes excavated along the cable route at a depth of about 50 cm depending on where the topsoil was penetrated. In order to investigate undisturbed conditions of the soil the holes were dug next to the excavated area, while still upholding a generous safety distance to the cable. The conductivity was measured by using a thermal needle connected to the KD2 Pro apparatus from Decagon Devices Inc. In every hole the conductivity was measured at least two times with 15 cm distance between the tests. If the second value of the thermal conductivity differed by more than 10 % another test was performed in the hole. A maximum of 4 tests was performed in each hole. The location of the holes was decided with regard to differences in soil type along the stretch. A distance of about 250 m between the holes was used if no apparent differences in soil type could be discovered.

The soil type in every hole was decided at site and the groundwater table was estimated by studying the surrounding landscape. These estimations were of different accuracy depending on the access of watercourses or groundwater pipes close to the hole. At every hole a soil sample of 600 g was collected for further investigation in geo lab. These investigations includes further thermal conductivity measurements and sieve analyses for a more accurate soil type determination.

5.3.1 Field description of hydrogeological conditions

In order to estimate the groundwater table along the stretch the topography of the area has been studied. The groundwater level estimation is based on the two piezometers in the area and by studying the landscape during the field study. In the southern part of the stretch the water level in the river Lagan was helpful to estimate the groundwater table in the surrounding area.

The two ridges south of Hornsborgs Gård indicates deep groundwater table since they consist of coarse grained materials. At Ryd the cable passes a peat moss where the groundwater table is in level with ground surface. In the northern part of the stretch, about 1 km south of the northern end of the stretch, there is an open well close to the cable with a water depth of about 4 m. None of the dug holes during the field study leaked in groundwater except the sample at the peat moss.

5.3.2 Thermal conductivity measurements

Thermal conductivity was measured on 26 different locations along the selected stretch of potential hotspots, which positions is illustrated in Figure 13.

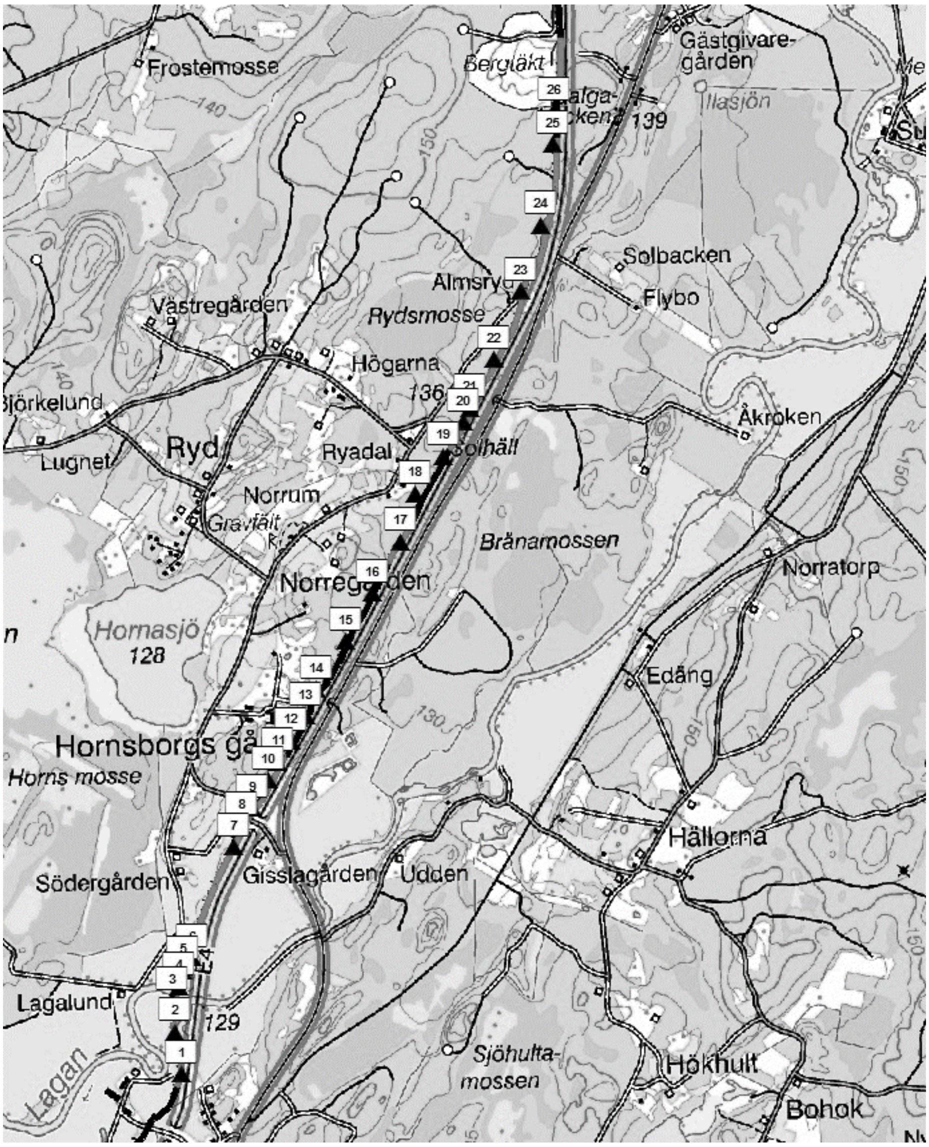


Figure 13. Location of the sample trenches.

The thermal conductivity was measured using a handheld equipment, KD2 Pro from Decagon devices. The KD2 Pro measures the thermal conductivity with a thermal sensor that can be inserted in to a wide variety of materials. The KD2 Pro and its three different sensors can be seen in Figure 14.

Figure 14. The KD2 Pro device (Decagon Devices, 2015).

When measuring the thermal conductivity in field a 50 cm deep hole was dug. The TR-1 sensor (large, single needle) was then inserted to the soil at the bottom of the hole. After letting the soil and sensor equilibrate, the five minute reading was started. A second measurement was taken in the other end of the hole and if the readings differed more than 10 % a third was performed. The average of these values is chosen to represent each sample.

A soil sample from each hole was obtained and brought to the laboratory. Each sample was proctor compacted in a cylinder as described appendix 2 to simulate extreme density conditions. The readings where performed with the SH-1 sensor (short double needle which works in a similar way as the TR-1 but with shorter reading times.

5.4 Results from field measurements

5.4.1 Field measurements

The thermal conductivity from the field works is presented in *Table 8*. A basic evaluation of the soil type and water situation was also performed on site, resulting in the table's rightmost columns. Generally the stretch consists of glacial river sand, with significant amounts of coarser fractions.

Table 8. Thermal conductivity of the field measurements.

Thermal conductivity		Soil type, field evaluation	Groundwater situation
Sample	[W/m·K]		
1	1.468	Silty clay	Mesic
2	1.287	Medium sand	Dry
3	1.588	Fine sand	Dry
4	1.195	Coarse/medium sand	Dry
5	1.535	Medium sand	Dry
6	1.924	Glacial river sediment, sand	Dry
7	1.383	Glacial river sediment, sand	Dry
8	1.035	Glacial river sediment/till, sand	Dry
9	1.305	Glacial river sediment/till, sand	Dry
10	1.679	Medium sand	Dry
11	0.699	Glacial river sediment, cobbly gravely sand	Dry
12	1.184	Fine/medium sand	n.a
13	0.669	Glacial river sediment, cobbly gravely sand	n.a
14	0.799	Glacial river sediment, cobbly gravely sand	Dry
15	1.272	Glacial river sediment, gravely silty sand	n.a
16	1.839	Glacial river sediment, boulderly cobbly gravely organic sand	Mesic
17	1.179	Glacial river sediment, clayey silty gravely boulderly sand	Moist
18	0.627	Peat moss	Wet
19	0.954	Glacial river sediment, gravely sand	Dry
20	1.184	Glacial river sediment, gravely rocky sand	n.a
21	0.834	Medium sand	Mesic
22	1.155	Glacial river sediment, gravely sand	n.a
23	1.126	Glacial river sediment, gravely medium sand	Dry
24	0.842	Organic medium sand	Dry
25	1.056	Glacial river sediment, gravely medium sand	n.a
26	0.957	Medium/fine sand	n.a
Average	1.184		

5.4.2 Laboratory measurements

A sample weighing a minimum of 500 g was obtained from the bottom of each hole. The sample was transported to the laboratory for further thermal conductivity measurements and sieving analysis. Each sample was inserted in a steel cylinder (h=100mm, r=36mm) and compressed according to the Proctor compaction. However this compaction probably yields a higher compaction than the natural condition. The conductivity was then measured using a shorter double thermal needle. Note that sample 18 containing peat moss was not analysed for practical reasons and since it is not classified as a class B soil it is of lesser interest for this project.

To evaluate the grain size distribution of the soil, a 0.063 – 20 mm sieve analysis was performed for each of the sample. The samples were dried for 48 hours in 105^{o} C before the sieve analysis. For the sieve analysis procedure, see appendix 3. The results can be seen in Table 9 where the water ratio is the weight of water divided by the weight of the dried sample. In Appendix 8 is the results of the sieve analysis displayed with a grain size distribution curve for each soil sample.

Table 9. Thermal conductivity of the laboratory measurements.

Thermal conductivity		Water ratio	Sieve analysis
Sample	[W/m·K]		Soil type
1	1.462	26 %	Silty sand
2	1.537	19 %	Silty sand
3	1.487	10 %	Fine sand
4	1.794	10 %	Fine sand
5	1.757	13 %	Fine sand
6	1.537	12 %	Gravely sand
7	1.439	11 %	Fine sand
8	1.334	11 %	Fine sand
9	1.293	7 %	Fine sand
10	1.502	14 %	Fine sand
11	0.752	6 %	Gravely sand
12	1.629	11 %	Fine sand
13	1.042	4 %	Gravely sand
14	0.983	7 %	Gravely sand
15	1.388	21 %	Fine sand
16	1.555	20 %	Gravely sand
17	1.025	40 %	Gravely sand
18	-	-	Peat moss
19	1.462	12 %	Gravely sand
20	1.549	16 %	Gravely sand
21	1.388	11 %	Medium sand
22	1.872	11 %	Fine sand
23	1.613	9 %	Fine sand
24	1.541	24 %	Fine sand
25	1.488	11 %	Medium sand
26	1.335	9 %	Fine sand
Average	1.430	14 %	

5.4.2.1 Summary of measured thermal conductivity

Table 10 and Table 11 contain a summary of the thermal conductivity results from the field and laboratory results in Table 8 and Table 9.

Table 10. Summary of thermal conductivity measured in field.

Field	Count	Average [W/(m·K)]	Median [W/(m·K)]	Min [W/(m·K)]	Max [W/(m·K)]
Sand/silty sand	17	1.229	1.195	0.834	1.679
Gravely sand	8	1.156	1.066	0.669	1.924
All sand	25	1.206	1.184	0.669	1.924

Table 11. Summary of thermal conductivity measured in laboratory.

Lab	Count	Average [W/(m·K)]	Median [W/(m·K)]	Min [W/(m·K)]	Max [W/(m·K)]
Sand/silty sand	17	1.521	1.488	1.293	1.872
Gravely sand	8	1.238	1.252	0.752	1.555
All sand	25	1.430	1.155	0.752	1.872

In order to determine if the samples are normally distributed a test of normality is performed. The test used to decide this is the Shapiro-Wilk test which utilises the null hypothesis to check whether the measured values are normally distributed (Shapiro & Wilk, 1965).

The measured values of thermal conductivity are placed in ascending order with $y_1 \leq y_2 \dots \leq y_n$. Equation (3) calculates W.

$$W = \frac{\left(\sum_{i=1}^{k} a_{n-i+1}(y_{n-i+1} - y_i)\right)^2}{\sum_1^n (y_i - \bar{y})^2} \tag{3}$$

Where a_i is depending on the number of samples and obtained from tables. When W is calculated, p can be obtained from a table of coefficients with the help of interpolation. If p is smaller than 0.05 the assumption that the distribution is normally distributed can be rejected with 95 % certainty. In other words, if p is larger than 0.05, the distribution passes the test and may be normally distributed.

Applying the test to the field and laboratory measurements shows that neither can be rejected as normally distributed as p is 0.148 and 0.069 which is above the 0.05 threshold. Thus it can be concluded that the distributions may be normally distributed.

The results from the field and laboratory measurements are represented by histograms, together with their respective normal distribution curve, in Figure 15 and Figure 16. A normal distribution curve is added to each graph to see how well they fit. Since the field measurements are not supposed to be too low, it is suspected that they are positively skewed and distributed with a log-normal curve instead. Average value and standard deviations can be seen in Table 12.

There are differences in thermal characteristics between the different soil types in regard to grain size, however, since the number of samples are only 25 a finer classification would yield untrustworthy results during statistical analysis. Therefore, to achieve a better statistical basis, all samples are analysed together.

Table 12. Mean and standard variation for the field and laboratory results from the soil samples.

	Count	Mean [W/(m·K)]	Standard deviation [W/(m·K)]
Field	25	1.206	0.334
Laboratory	25	1.430	0.258

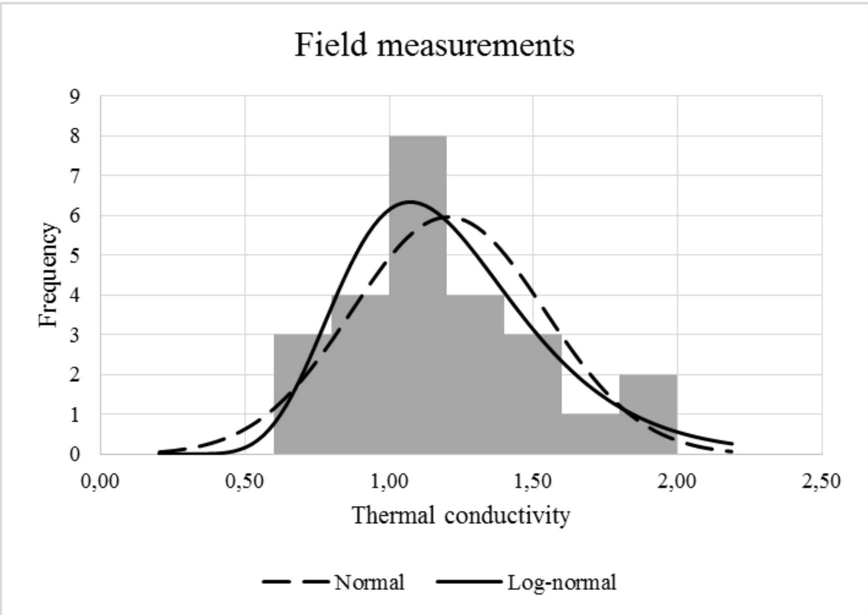


Figure 15. Histogram of the results from the field measurements.

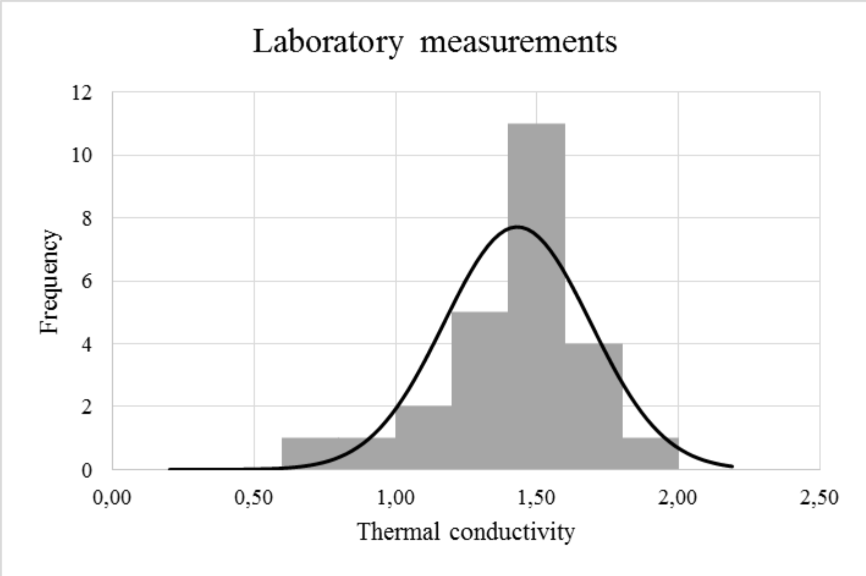


Figure 16. Histogram of the results from the laboratory measurements.

5.4.2.2 Summary of thermal conductivity from pre-study performed in 2011

Measurements of thermal conductivity was performed by the company Vectura in a similar manner before the construction of the South West Link. A summary of these values can be seen in Table 13. These values can be compared to the recently obtained ones in Table 10 to analyse seasonal variations and their impact on thermal conductivity. The data is here selected to encompass only sand, though the study also includes samples with other soil types. The measurements took place in August and September, whilst the ones obtained between Hamneda and Hornsborg where taken in March. It should also be noted that they are distributed along the entire 190 km length of the cable and that the depth of the samples varied by being either 0.65 m or 1.35 m below the surface.

Table 13. Summary of thermal conductivity results from Vectura's pre-study (Sundberg & Wrafter, 2011).

Field	N	Average [W/(m·K)]	Min [W/(m·K)]	Max [W/(m·K)]
Sand/silty sand	16	1.27	0.54	2.01
Gravely sand	7	1.44	1.10	1.80
All sand	23	1.32	0.54	2.01

6 Analysis of field study

All of the 26 soil samples from the field study have been analysed except from the wet peat sample since it mostly contained water. The results of the thermal conductivity, water content and grain size distribution have been analysed in order to evaluate the relationship between these parameters.

6.1 Soil analysis

6.1.1 Dry soil

In this analysis is the thermal conductivity of the dry soil samples compared with the thermal conductivity of all of the samples along the investigated stretch. Dry soils are defined as soils with a gravimetric water ratio less than 10 % in this classification, see Table 14. There are six dry soils of the 25 soil samples analysed. The average thermal conductivity is 23 % less for the dry soils compared with average for all of the soils from the field measurement. When comparing the thermal conductivity from the lab measurement is the average for the dry soils 18 % less than the average for all of the samples. The water ratio of the dry soils are in average almost 50 % less than the average of all of the samples.

Table 14. Thermal conductivity of the dry soils with a gravimetric water ratio less than 10 %.

Soil sample	Thermal conductivity [W/(m·K)]		Water ratio
	Field	Lab	
13	0.67	1.04	4.3 %
11	0.70	0.75	6.0 %
14	0.80	0.98	6.8 %
9	1.30	1.29	7.2 %
26	0.96	1.34	8.9 %
23	1.13	1.61	8.9 %
Average	0.93	1.17	7.0 %
Compared with the average of all the samples	77 %	82 %	51.1 %

6.1.2 Coarse soil

The average thermal conductivity of medium sand and coarser graded soils are compared with the average of all of the soil samples. In this classification are the two most coarse soil types, medium sand and gravely sand, defined as coarse soil. The comparison can be seen in Table 15 and it shows that the average thermal conductivity for coarse soils from the field measurement are 8 % less than the average for all of the sample. When analysing the lab measurement data the average thermal conductivity are 11 % less for the coarse soils in comparison with the average for all of the soil samples.

Table 15. Thermal conductivity of the coarse soils classified as medium sand or coarser.

Soil sample	Thermal conductivity [W/(m·K)]		Soil type
	Field	Lab	
6	1.92	1.54	Gravely sand
11	0.70	0.75	Gravely sand
13	0.67	1.04	Gravely sand
14	0.80	0.98	Gravely sand
16	1.84	1.55	Gravely sand
17	1.18	1.03	Gravely sand
19	0.95	1.46	Gravely sand
20	1.18	1.55	Gravely sand
21	0.83	1.39	Medium sand
25	1.06	1.49	Medium sand
Average	1.11	1.28	
Compared with the average of all samples	92 %	89 %	

6.1.3 Dry and coarse soils

The thermal conductivity of the soils that are both coarse and dry are compared with thermal conductivity for all of the soil samples, see Table 16. It means that the sample is classified as gravely sand or medium sand and has gravimetric water ratio less than 10 %. There are three samples that fulfil both of these criteria. The analysis of the field measurement shows that the average thermal conductivity for the soils that are both dry and coarse 40 % less than the average thermal conductivity for all of the soil samples. When comparing the data of the lab measurement the dry and coarse soils have 35 % less thermal conductivity in average in comparison with the average of all of the soil samples.

Table 16. Thermal conductivity for the soils that are both dry and coarse which is defined as medium sand or coarser with a water ratio less than 10 %.

Soil sample	Thermal conductivity [W/(m·K)]	
	Field	Lab
13	0.67	1.04
11	0.70	0.75
14	0.80	0.98
Average	0.72	0.93
Compared with the average of all samples	60 %	65 %

6.2 Thermal conductivity and water ratio in soils

The thermal conductivity in relation to the measured water ratio in the sand samples from 2015 and 2011 can be seen in Figure 17. The number of samples for 2015 is 25, however one of the samples from 2011 contained no value for water content, wherefore the number of samples is reduced from 23 to 22.

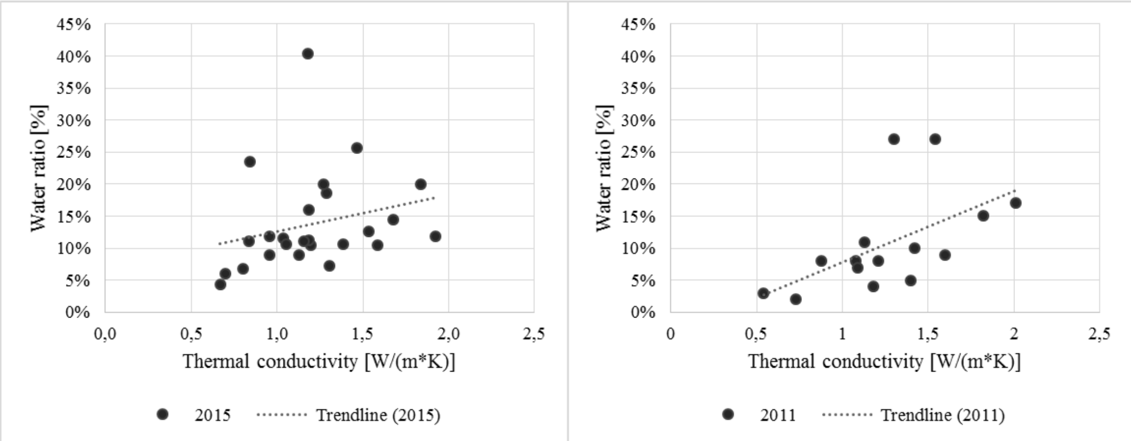


Figure 17. Thermal conductivity in relation to water ratio for the Hamneda-Hornsborg results (left) and the pre-study (right).

Figure 18 displays the graphs from Figure 17 merged to one to show the trendline differences. The result from the field study shows that for every percentage decrease in water content the average decrease in thermal conductivity is 5.8 %. This can be compared with the result from the pre-study where the average thermal conductivity decrease is 7.3 % for every percentage decrease in water content.

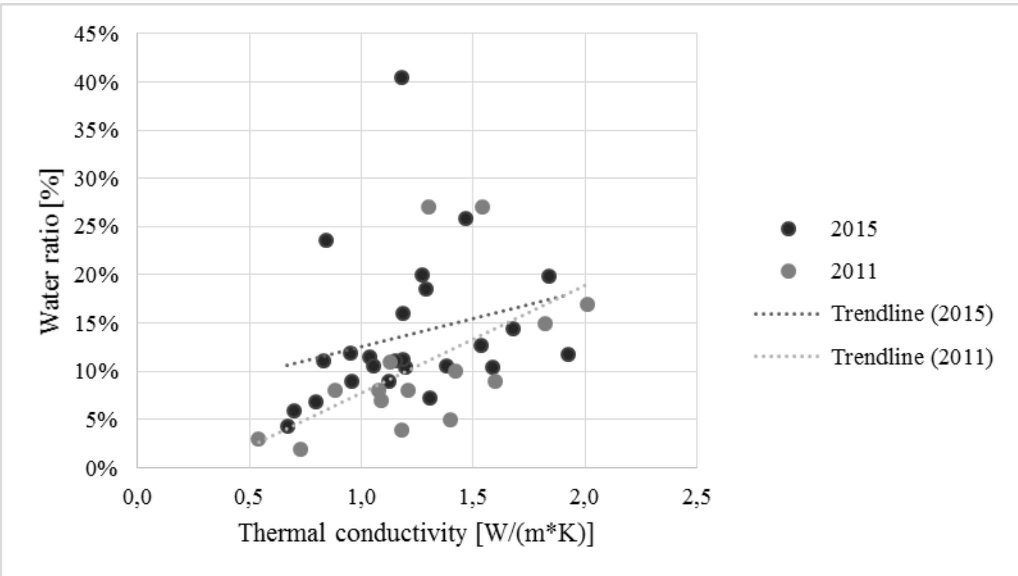


Figure 18. Comparison of the pre-study measurements in 2011 and the measurements from the field study in 2015.

6.3 Comparison of thermal conductivity results from 2011 and 2015

The measured thermal conductivity in sand is compared to the values measured in 2011 by Vectura in Table 17. The table contains values from both studies limited to samples containing different sand fractions only. Seven of the samples in the 2011 study and 8 in the 2015 study consist of gravely sand, with the rest being sand or silty sand. As is seen, the lower 5th and 1st percentile values is 13 % respectively 17 % lower in the 2015 study compared to 2011.

Table 17. 2011 and 2015 average, standard deviation and percentiles of thermal conductivity in sand, measured in field.

Study	N	Average [W/(m·K)]	Std [W/(m·K)]	5th percentile [W/(m·K)]	1st percentile [W/(m·K)]
2015	25	1.206	0.334	0.656	0.427
2011	23	1.323	0.348	0.750	0.512

In order to visualise the distribution of the results a normal distribution curve for the two separate studies are presented in *Figure 19*. There are no major differences in the resulting normal distribution curves, with the difference being in that the 2015 thermal conductivity values are slightly lower in average and the standard deviation is marginally higher in 2011. Hence the lateral adjustment of the curves and the slightly flatter top on the 2011 results.

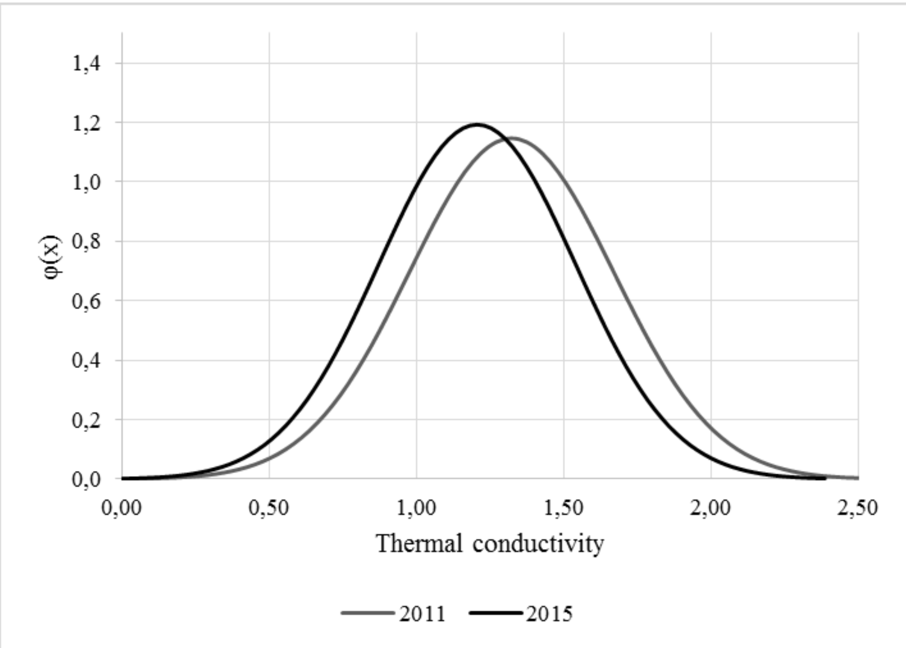


Figure 19. Normal distribution curve of measured thermal conductivity from Vecturas' 2011 study and the 2015 results

6.4 Ground temperature

The ground temperature at the potential hotspot has been analysed regarding the annual air temperature variations in the area. In this analysis has Equation (2) been used and all of the input values can be seen in Table 18. The air temperature data is based on the average of the daily mean temperature in Ljungby during the period 1997-2007 from the database of SMHI (SMHI, 2015). In this analysis the soil sample with the lowest thermal conductivity has been used. The input value of thermal capacity is based on the table Guideline of thermal properties of soil (Sundberg, 1988) where sand and gravel above the groundwater table in unfrozen state has a thermal capacity in the range of 1.2-1.7 J/(m^3·K).

Table 18. Input values for calculation of annual ground temperature variations at the investigated stretch.

Parameter	Value
T_{mean} [°C]	7.3
T_{max}[°C]	17.8
T_{min}[°C]	-3.9
t_p [day]	40
Z_1 [m]	1.5
Z_2[m]	0.5
λ [W/(m·K)]	0.67
C [J/(m^3·K)]	1.5
d [m/day]	2.1
κ [m^2/day]	0.04

Figure 20 shows that the period where the air temperature affects the heating of the soil at 1.5 m below the surface the most is in the end of September. At this time of the year the ground temperature peaks with about 12.5 degrees Celsius at 1.5 m below surface. This analysis takes into account the air temperature, soil type and the groundwater table but is preferably used to show the annually temperature variations in the ground in a generally way instead of accurate temperatures to use as input values when designing. The groundwater table fluctuations and the isolation properties of snow covered ground are not included in this analysis.

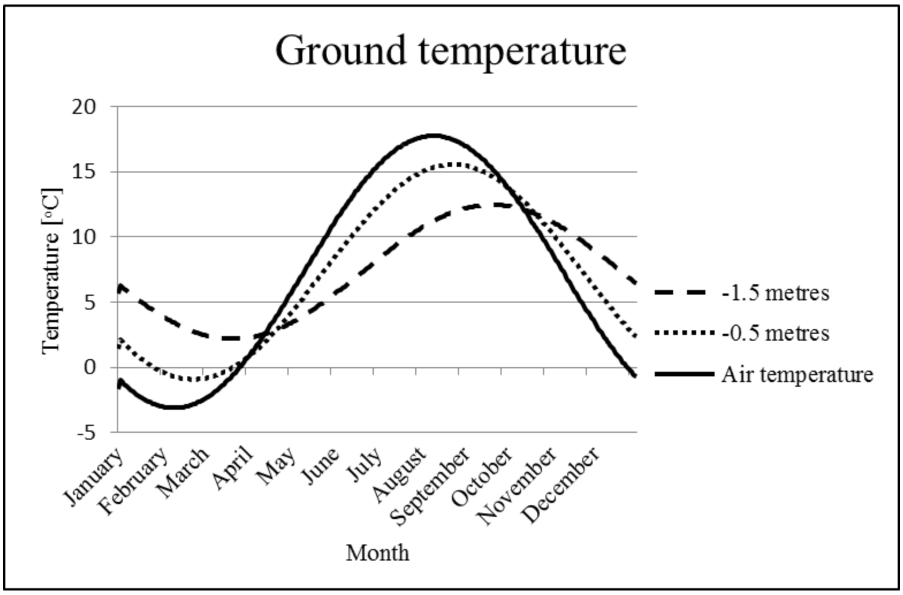


Figure 20. The annual ground temperature variations on three different depths in Ljungby for a soil with thermal conductivity of 1 W/(m·K)

6.5 Groundwater table

In order to estimate the deepest groundwater table during a 50-year drought for the investigated stretch the Chalmers method is used, which is explained in appendix 5. The reference piezometer is located in Liatorp where the soil type is sand (SGU, 2015). In the analysis is Piezometer 2 used as prognosis piezometer. The input data and result can be seen in Table 19 where the prognosis for a 50-year drought is 5.65 m below surface level compared to the observed 5.57 m during the observational period. The reason for this is that during the observational period a year almost as dry as what can be expected in 50 years occurred. When comparing how similar the groundwater table variations are in the reference piezometer and the prognosis piezometer the correlation is 75 %. The estimation gets better the higher the correlation is. The lowering of the groundwater table is expected to be of the same magnitude throughout the analysed stretch where similar terrain and ground conditions occur, during a 50-year drought.

Table 19. Estimated deepest groundwater table below ground level in Piezometer 2 during a year with 50-year drought.

Parameter	[m]
P_{min}	5.57
S_R^X	0.12
r_P	0.92
r_R	1.41
y_{min}^{50}	2.67
y_{min}	2.79
P_{min}^{50}	5.65

6.6 Monte Carlo simulation of thermal conductivity

To simulate the results for a larger sample size, a Monte Carlo simulation of 50 000 iterations is performed with the yielded results for the field and laboratory measurements. From these simulations, new percentiles can be obtained and compared with the theoretical. The Monte Carlo method is described in appendix 4 and histograms of the results can be viewed in Figure 21, Figure 22 and Figure 23. These results is then compared to the pre-study results from 2011.

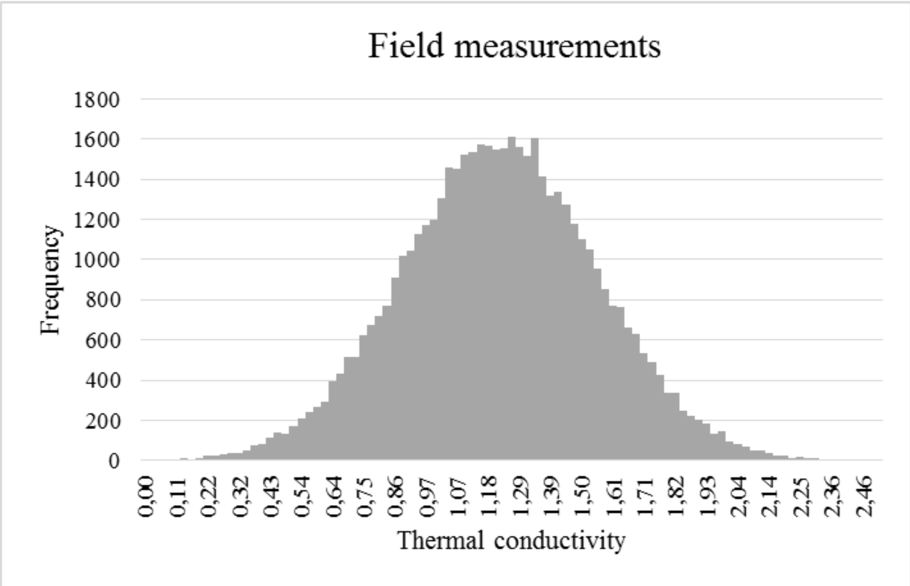


Figure 21. Monte Carlo simulation of field results, normal distribution.

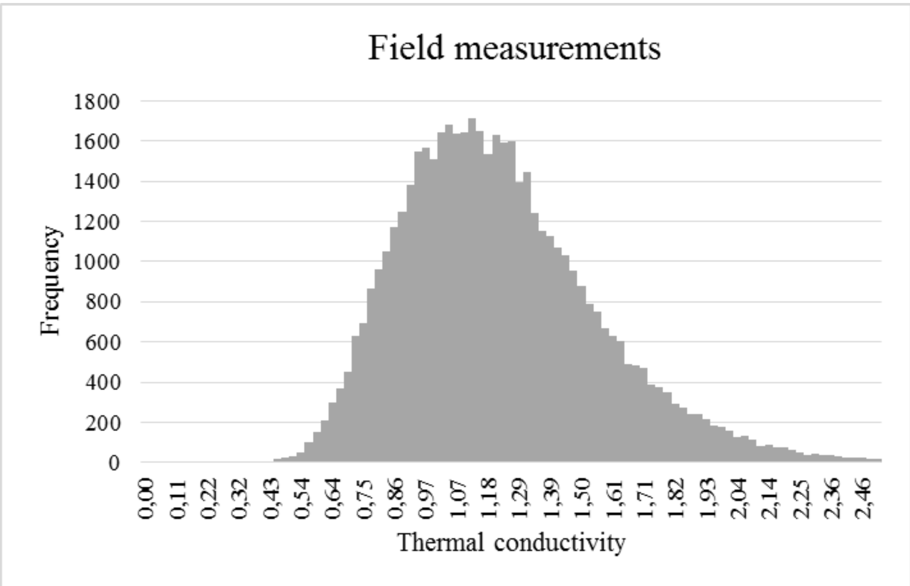


Figure 22. Monte Carlo simulation of field results, log-normal distribution.

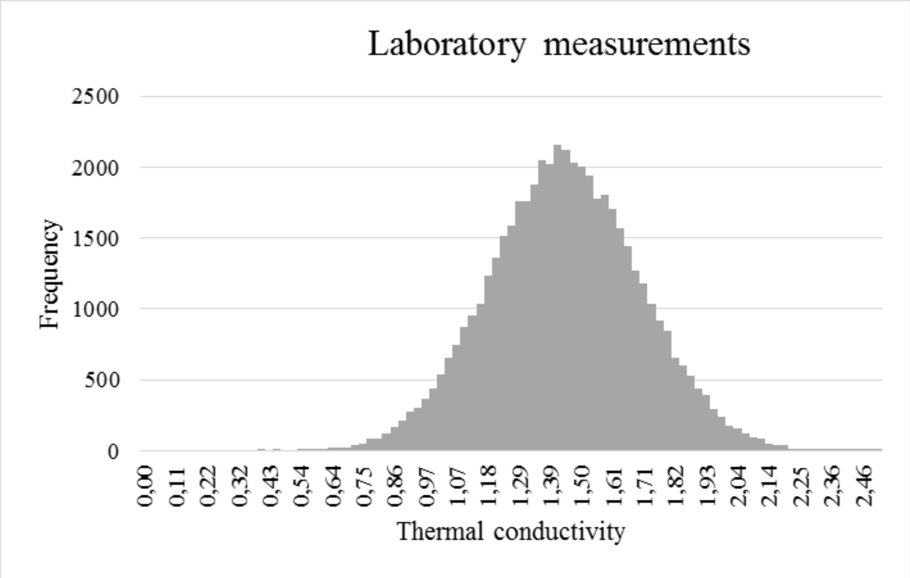


Figure 23. Monte Carlo simulation of laboratory results, normal distribution.

From the Monte Carlo simulations, new average, standard deviations and percentiles can be calculated. These values is summarised in Table 20. Note that the more iterations, the closer the simulated results will be to the theoretical values, which is why these values are near to identical as it is based on 50 000 samples.

Table 20. Simulated average, standard deviation and percentiles of thermal conductivity from Monte Carlo simulations.

	Average [W/(m·K)]	Std [W/(m·K)]	5th percentile [W/(m·K)]	1st percentile [W/(m·K)]	Max [W/(m·K)]	Min [W/(m·K)]
Field	1.204	0.334	0.659	0.427	2.631	-0.166
Lab	1.429	0.258	1.008	0.829	2.531	0.371
Field (log)	1.208	0.349	0.731	0.605	3.795	0.351

These values can be compared to the results from the pre-study performed in 2011 where the simulated Monte Carlo results for field measurements of thermal conductivity in sand can be seen in Table 21.

Table 21. Simulated average, standard deviation and percentiles of thermal conductivity from Monte Carlo simulations performed in 2011.

	Average [W/(m·K)]	Std [W/(m·K)]	5th percentile [W/(m·K)]	1st percentile [W/(m·K)]
Field	1.32	0.35	0.75	0.52

7 Evaluation of methodology for thermal classification

7.1 Annual variations of thermal conductivity

From a theoretical point of view is the critical period of the year in southern Sweden regarding high cable temperatures in the beginning of the autumn. This is explained by naturally low groundwater table in combination with high ground temperature. In Figure 24 are the principled groundwater table variations of Sweden divided in four different regions displayed. The measurements from this period of the year shall therefore be designed for regarding high cable temperatures. However, the comparison between the thermal conductivity measurements on soil class B from the field study in March and the investigation made by Vectura in September shows that the thermal conductivity is in average higher in September which is displayed in Table 10 and Table 13. Although the lowest value of the thermal conductivity is lower in September than in March, 0.54 W/(m·K) compared to 0.67 W/(m·K). The generally higher thermal conductivity of Vectura's values can be explained by local variations since just two of the measurements is located on the stretch investigated in March. Also the mild winter could affect the results measured in March (SMHI, 2015). The two measurements made by Vectura located at the investigated stretch have a thermal conductivity of 1.08 W/(m·K) and 1.43 W/(m·K) which can be compared to the average of the field measurements in soil class B showed in Table 10 which is 1.21 W/(m·K).

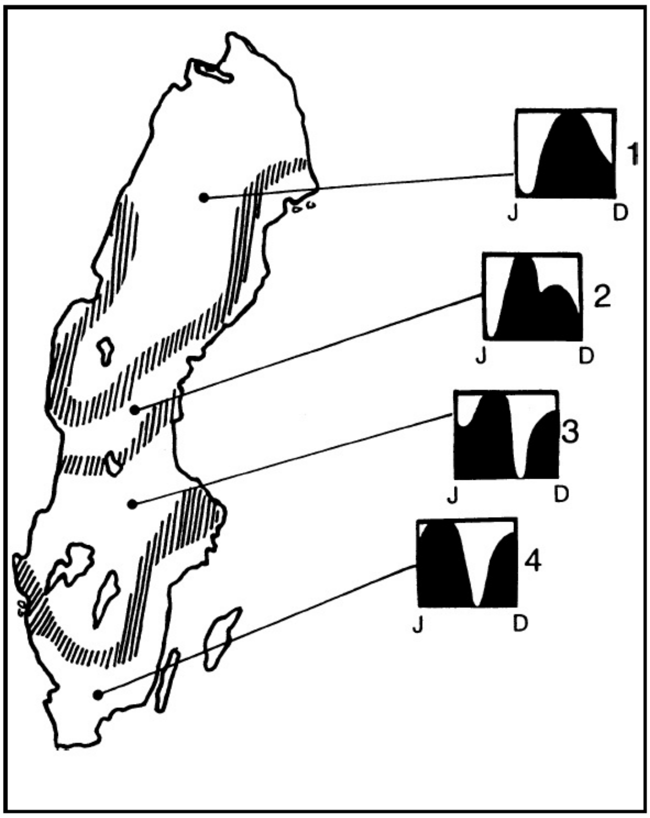


Figure 24. Principled annual groundwater table variations of Sweden divided in four different regions (Nordberg & Persson, 1979).

7.2 Evaluation of parameters for future studies

When the thermal conductivity of the soil samples with low water content and coarse grain types are compared with average thermal conductivity in chapter 6.1 there are clear differences with lower conductivity for both of these groups. The conductivity is especially low when the soils are both dry and coarse where Table 16 shows that this group has a 40 % lower mean conductivity than the average for the field measurements. The combination of coarse soils with low ground water content is therefore interesting for future studies in order to further evaluate these parameters impact on the thermal conductivity. For deciding the water content of the soil both the ground water table and the pF-curve is important. However, in coarse soil the water bearing capacity is low at more than 30 cm above the ground water table which is displayed in table Figure 6. This means that water content mainly depends on the groundwater fluctuations in coarse soils.

There are variations in thermal conductivity for coarse soils concerning the density and mineral type. The increased compaction after the Proctor compaction lead to an increase average of the conductivity of the soil samples but further investigation is recommended in the area for a more accurate analysis. This study does not include the significance of the mineral type for the conductivity which would be interesting to investigate in future studies.

A more detailed analysis of the yearly variations of thermal conductivity is recommended in order to know the impact of yearly climate variations. These climate variations includes both air temperature and groundwater fluctuations but also the isolation effect from snow covered ground. The snow cover has a high content of air which gives good isolation properties with a thermal conductivity of about 0.1-0.5 W/(m·K) where the variations mainly depends on the density (Zhan, 2005).

The parameters that are crucial for the thermal conductivity in the soil are suitable to evaluate in a simulation program where the climate variables show how the yearly variations affect the conductivity.

7.3 Strategy for thermal classification of cable route

The proposed method, a first version of a strategy for *thermal classification of cable in natural ground conditions* compiled by Ph. D Jan Sundberg, can be found in Appendix 1 and is subject of evaluation. The method has been tested by the authors with the aim to find possible areas of improvement.

This assessment will follow the general order of work, starting with *Investigations in several steps and levels* and ending with *verification and control* – just as in the proposed method – as the authors agree with this workflow. After the discussion of the changes, a new updated version is presented. It is also suggested that further iteration of the method is performed *pari passu* with the implementation of the same. More information about the observational method that is suggested for inclusion can be found in appendix 6.

7.3.1 Proposed changes from Version 1

1. **Investigations in several steps and levels**

    1.1 Desktop study

    In addition to the proposed actions it could be a good idea to acquire hydrological data for a better groundwater analysis.

    1.2 Field work – General

    It is in the original method suggested that the stretch is mapped using a soil sampler every fifth metre with a depth of 0.5 m. The attempts to map and uphold a 5 m cc distance during field work under reasonable working conditions has however proven futile due to the substantial friction resistance in coarse soils. It is instead suggested that soil mapping is performed with a larger cc distance and complementing where the soil is suspected to change and otherwise deemed necessary. A suitable cc distance could be 20 m excluding the complementary mapping. The use of more advanced handheld tools such as a Doctor's kit when the ground conditions are suspected to change below the 0.5 m remains.

    1.3 Field work – Detailed

    It is suggested that ground water piezometers is installed as soon as possible for the project. Longer time series always produce more reliable results and the use of methods such as Svensson's method for estimating droughts with longer return periods will also become more precise (Svensson, 1984). The locations for these should be carefully assessed, and placed primarily on locations where it is expected to be an ambiguous call between two different cable types. This is typically on parts of the stretch where no clear determination can be made between thermal soil class A and B, as soil class with high organic content or known low groundwater table will likely already be well-designed. The placement of piezometers should take into consideration water courses and other indications where the level of the ground water is known. Extra respect should be paid to hills and other highly located parts of the stretch where the groundwater table may locally be significantly farther from the ground surface.

    The idea of measuring thermal conductivity during the autumn, where design values is likely to occur, remains. This is however probable to be the effects of several coincidences which was previously explained.

2. **Evaluation and property modelling**

    2.1 Evaluation

    The thermal conductivity in the soil should be statistically evaluated according to the soil types occurring along the stretch. The soil types should be separated in a way such that the differences between their thermal characteristics are distinct. The existing soil classification should be utilised, with extra consideration taken to dry and coarse soil, soil class B, as very short stretches may be designing the entire length of a cable reel that is otherwise in soil with better thermal characteristics.

2.2 Parameterisation

From the evaluated results and existing theory, a range for every parameter that affects thermal properties should be set up. The parameters are set up along the stretch in order to find design values for the cable construction.

3. **Presentation**
   From the evaluation of the geotechnical conditions different scenarios can be created. These should be presented to the consultants so they can prepare designs for them. This reduces the need for active design later in the construction phase.

2.3 Numerical modelling

The effects on the cable can then be modelled with simulation software such as COMSOL where all parameters can easily be changed to produce different scenarios. These different scenarios should be constructed in such a way that they encompass all possible situations from good to bad. This is where the first step of the observational method comes in – *prediction*.

4. **Verification and control**
   In a perfect world there would exist no situation not covered by the scenarios. However, there will always be circumstances making this untrue, and active design based on local conditions and engineering workarounds has to be performed -*action*. For this to work smoothly, the procedure should be monitored continuously and in a way such that it is possible to discover this in an early enough stage - *observation*. This new "special scenarios" can then be included with the existing scenarios should the same problems occur again, and the contractors have yet another tool in their toolbox.

7.3.2 New methodology – Version 1.1

With the changes proposed in 7.3.1 as a basis, a new version of the method for thermal classification of cable route is hereby presented.

Problem
Determination of the designing thermal conductivity for a cable route. The designing properties are on the scale 1-5 m. For a long stretch this implies that the designing properties are in the tail of a normal distribution.

1. **Investigations in several steps and levels**

   1.1 Desktop study

   Map studies of geological maps and terrain conditions. Create a plan where expected design values occurs with the expected ground and groundwater conditions.

   1.2 Field work - General

   Mapping of the soil along the projected stretch using a soil sampler every 20 metres and where the soil type is expected to change. Pointwise use of handheld equipment such as a Doctor's kit where the ground conditions are suspected to change below 0.5 m. Expected groundwater table is estimated based on the conditions of the lakes, watercourses, ditches, typical discharge areas, ground conditions and the terrain. Deviations regarding the potential hotspots on the stretch are noted and the plan is updated.

   1.3 Field work – Detailed

   Pointwise verification of ground and groundwater conditions by excavating field samples at relevant depth and/or installation of piezometer. Groundwater piezometers should be installed in an early stage of the project in order to yield as long time series as possible, at the very least three months. Areas where the general field study cannot show reliable results for the groundwater level should be prioritised and locations where it is uncertainties about the groundwater level. Groundwater readings should then be taken twice a month or continuous with automatic groundwater readers during the time (autumn) where the deepest groundwater table is expected. Thermal conductivity measurements should be carried out during the same time frame as the critical values is expected to coincide with the lowest groundwater levels. The depth of the holes used for thermal conductivity measurements should be at least 0.5 m, deeper if the first soil layer is not penetrated. Update of plan for expected ground and groundwater conditions. Presentation of deviations regarding the earlier step.

   1.4 Field work – complementary.

   If needed.

2. **Evaluation and property modelling**

2.1 Evaluation

Statistical evaluation of the thermal conductivity according to soil type and prognosis of the designing groundwater table. Grouping of soil types according to the existing soil classification with distinct difference in thermal characteristics. Special consideration should be given to short stretches of thermal soil class B in areas dominated by class A as they may still be critical for the design.

2.2 Parameterisation

A range for each parameter affecting thermal condition, according to measured values and theory, is set up along the stretch.

3. **Presentation**

The possible scenarios based on various geotechnical conditions should be presented to the consultants in order for them to design accordingly.

3.1 Numerical modelling

Based on the parameters set up along the stretch the thermal effects on the cable is modelled with a simulation software such as COMSOL. The modelling shall cover all possible situations (within reasonable limits) and designs handling all scenarios should thereafter be compiled.

4. **Verification and control**

Should a situation arise which is not covered in the scenarios it is important to be prepared. Constant monitoring during construction in order to discover deviations from the plan in an early phase, and actively design after the new local conditions. This new scenario is to be added to the existing scenarios in case the same situation arises elsewhere.

8 Uncertainties

In this study there are uncertainties about the results where many factors can affect the measurements. When a potential hotspot was chosen for further investigation the approach was to find parts where the thinner cable type, *Standard cable*, is located in the dry soil stated as *Thermal soil class B*. The largest part of the stretch with this condition was found in the investigated stretch between Hornsborg and Hamneda however there are more parts of cable route with this condition. There is therefore an uncertainty that the *Standard cable* is located in soils with lower thermal conductivity than the soils investigated. This study is only focusing on the *Thermal soil class B* though there are other possible low thermal conductivity soils such as dry peat moss which has been excluded in this study.

During the field trip the measurements was performed at 25 sites that was interesting in terms of low thermal conductivity by doing an ocular assessment of the stretch. Since there are no measurement of the whole stretch at the scale of 1-5 m there is an uncertainty about soils with lower thermal conductivity between the measured sites. When measuring the thermal conductivity in coarse soil the hole for thermal needle needed to be pre-drilled at some places to be able to stick the needle down in the soil to a sufficient depth, this could affect the measurement due to the change of soil condition it causes. All of the holes made for measurement had a minimum depth of 35 cm where at least the top soil layer was passed. Although it was not possible to dig down to the preferable depth of 50 cm at all sites due to hard penetrated soils. This can lead to uncertainties when comparing the different samples. The comparison with values from Vectura could be misleading since the depth and locations of the sampling differed from the field study.

In the laboratory measurement of the thermal conductivity a proctor compaction was made to recompact the soil samples from the field study. The proctor compaction probably causes a harder compaction than the natural state which explains the higher average thermal conductivity of the soil samples measured in the laboratory measurement compared with the field measurement. In the sieve analysis the sieves use the American Krumbein Phi Scale standards instead of the International scale. The American standard has slightly different limits compared to the international standards and the ratio of the various grain sizes can therefore be marginally inaccurate however not enough to offset the results.

For the estimation of groundwater table during a year with a 50-year drought the Chalmers method is used with a reference piezometer. The chosen reference piezometer and the prognosis piezometer shall have as similar properties as possible for a good estimation. Since there were no reference piezometer close to the stretch there are uncertainties about the groundwater table estimation. The correlation between the reference piezometer and prognosis piezometer is 75 %. A higher correlation would give a more accurate estimation. The critical depth during a 50-year drought is calculated for the piezometer with deepest groundwater along the investigated stretch. A similar groundwater table lowering can be expected in the same soil class but there are uncertainties about the groundwater table variation in other soil types. The small estimated lowering of groundwater table is explained by a small variance in the reference piezometer in combination with the deepest groundwater table, in the database of 45 year (SGU, 2015), occurring during the evaluation period in the reference piezometer.

9 Conclusions and recommendations

Based on results from recent measurements as well as the pre-study on the South West Link, it may be concluded, in line with the theory, that coarse and dry soils yields the lowest thermal conductivity of inorganic soils. Coarse soils with a gravimetric water content lower than 10 % have in average 40 % lower thermal conductivity compared to the average sample. For every percentage decrease in water content, thermal conductivity is lowered by 0.17 W(m·K). This shows how important the parameters water content and density are for the thermal conductivity in soil. It is also the authors' experience, based on measurements, that soil thermal conductivity fits a lognormal distribution rather than a normal distribution.

In general the test of the original proposed method for *Thermal classification of cable in natural ground conditions* worked well, however some alterations are recommended. The evaluation resulted in a new version. In this altered and proposed version it is recommended to start off with a pre-study where geological maps, groundwater situation and thermal conductivity is analysed. It is also suggested that groundwater piezometers are installed as soon as possible to produce more accurate groundwater estimations. Furthermore, soil sampling should be carried out every 20th metre instead of every 5th metre for practical reasons. Thermal conductivity measurements should be performed where low values are expected to be found based on the pre-study and the soil sampler. A depth of 50 cm is aimed for when measuring thermal conductivity. The main point of this depth is to ensure that the first soil layer is penetrated while still maintaining the possibility to dig the hole by hand.

Because thermal conductivity is difficult to predict and general soil conditions can vary significantly on a small scale, it is recommended to utilise the observational method for thermal soil classification. This means there should be prepared instructions of the different scenarios and problems that could possibly arise. In addition to this, a geological expert should be available when uncertainties during the construction phase occur.

For further development of the methodology for thermal classification of cable route it is recommended to implement the following steps:

- Generalisation of the method to include all soil types
- Density measurement of undisturbed soil samples
- Water retention curve analysis of soil samples
- Thermal conductivity measurement and sieve analysis in laboratory

10 Bibliography

Åkerlund, U., 2012. *Markteknisk undersökningsrapport Sydvästlänken, block 3,* Halmstad: WSP Sverige AB.

ASTM D422-63, 2007. *Standard Test Method for Particle-Size Analysis of Soils,* West Conshohocken: ASTM International.

ASTM D698-00a, 2000. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort,* West Conshohocken, PA: ASTM International.

Avén, S., 1984. *Handboken Bygg, Geoteknik.* 1984: SGI.

Bengtsson, J. & Boström, J., 2008. *Prognostisering av höga grundvattennivåer med Chalmersmodellen,* Gothenburg: Chalmers University of Technology.

Bengtsson, J., Ivansson, P. & Werner, C., 2006. *Kraftkabelförläggning i mark - En studie av produktionsmetoder,* Växjö: Växjö Univeristet.

COWI, 2013. *Miljökonsekvensbeskrivning. Planerad likströmsförbindelse mellan Gotland och fastlandet,* Sundbyberg: Svenska kraftnät.

Decagon Devices, 2015. *KD2 Pro.* [Online]
Available at: http://www.decagon.com/products/thermal/instruments/KD-2-Pro-Thermal-Properties-Analyzer/?utm_source=reorg
[Accessed 30 04 2015].

Geological Survey of Sweden, n.d. *Quartenary geology.* [Online]
Available at: http://www.sgu.se/en/geology-of-sweden/quaternary-geology/
[Accessed 27 01 2015].

Haaf, E. M., 2014. *Extremvärdesanalys av grundvattenmätserier,* Stockholm: Royal Institute of Technology (KTH).

Horai, K.-I., 1971. Thermal Conductivity of Rock-Forming Materials. *Journal of Geophysical Research,* 76(5), pp. 1278-1308.

IEG, 2010. *Obervationsmetoden inom Geotekniken - Tillämpningsdokument,* Stockholm: IEG.

James, R. E. & Su, Q., 2008. *Condition Assessment of High Voltage Insulation in Power System Equipment.* Stevenage: Institution of Engineering and Technology.

Johansson, M., 2008. *Skogsstyrelsen.* [Online]
Available at:
http://www.skogsstyrelsen.se/Global/myndigheten/Om%20oss/V%C3%A5r%20verksamhet/Inventeringar/F%C3%A4ltinstruktion%20P57%20ver%202.0.pdf
[Accessed 16 April 2015].

Johnell, A., 2010. *Klimat- och sårbarhetsanalys Kronobergs Län,* Växjö: Länsstyrelsen Kronobergs Län.

Karlsson, R. & Hansbo, S., 1984. *Jordarternas indelning och benämning,* Stockholm: Statens råd för byggnadsforskning.

Länsstyrelsen Kalmar län, n.d. *Naturgeografiska regioner i östra Småland.* [Online] Available at: http://www.lansstyrelsen.se/kalmar/sv/om-lansstyrelsen/om-lanet/fakta-kalmar-lan/lanets-natur/natur-o-smaland/Pages/naturgeogr_regioner.aspx [Accessed 27 01 2015].

Lind, B., Persson, H., Lundström, K. & Hågeryd, A.-C., 2010. *Släntsäkerhet vid förändrat klimat - prognosmetoder för grundvattentryck och portryck,* Linköping: Swedish Geotechnical Institute.

Löfgren, E., 2008. *Evaluation of a groundwater remediation at the Sundsvall Port for petroleum products,* Stockholm: Institutionen för geovetenskaper, Uppsala Universitet.

Nofziger, D., 2015. *Soil Temperature Changes with Time and Depth.* [Online] Available at: http://soilphysics.okstate.edu/software/SoilTemperature/document.pdf [Accessed 4 February 2015].

Nordberg, L. & Persson, G., 1979. *Vårt vatten - tillgång, utnyttjande,* Stockholm: LT:s förlag.

Reddy, C. & Ramu, T., 2007. *Estimation of Thermal Breakdown Voltage of HVDC,* Bangalore: Indian Institute of Science.

Ronström, L., Hoffstein, M. L., Pajo, R. & & Lahtinen, M., 2007. *The Estlink HVDC Light® Transmission System,* CIGRÉ Regional Meeting on Security and Reliability of Electric Power Systems: s.n.

SGU, 2015. *Kartvisare för grundvattenobservationer.* [Online] Available at: http://apps.sgu.se/kartvisare/kartvisare-grundvattenniva-sv.html

Shapiro, S. S. & Wilk, M. B., 1965. An analysis of variance test for normality (complete samples). *Biometrika,* 52(3/4), pp. 591-611.

SLU, 2002. *Marktemperatur.* [Online] Available at: http://www-vaxten.slu.se/marken/marktemperatur.htm [Accessed 22 June 2015].

SMHI, 1990. *Temperatur.* [Online] Available at: http://www.smhi.se/klimatdata/meteorologi/temperatur [Accessed 4 February 2015].

SMHI, 2015. *Månadsmedeltemperaturens avvikelse från den normala, mars.* [Online] Available at: http://www.smhi.se/klimatdata/meteorologi/kartor/monYrTable.php?par=tmpAvv&month=3 [Accessed 11 May 2015].

SMHI, 2015. *SMHI Öppna data.* [Online] Available at: http://opendata-catalog.smhi.se/explore/ [Accessed 8 May 2015].

Sundberg, A. & Wrafter, J., 2011. *Termiska egenskaper Sydvästlänken, Mätningar in-situ och i laboratorium samt statistisk analys,* Göteborg: Vectura / Mark & Samhälle.

Sundberg, J., 1985. *Värmeöverförande egenskaper i svenska jordarter,* Göteborg: Chalmers Tekniska Högskola.

Sundberg, J., 1988. *Thermal properties of soils and rocks.* Göteborg: Chalmers University of Technology and University of Göteborg.

Sundberg, J., 1991. *Termiska egenskaper i jord och berg,* Linköping: Swedish Geotechnical Institute.

Sundberg, J., 2012. *Termiska egenskaper för mark - Sydvästlänken,* Göteborg: Vectura.

Sundberg, J., Thunholm, B. & Johnson, J., 1984. *Värmeöverförande egenskaper i svensk berggrund,* Göteborg: Chalmers University of Technology.

Svenska kraftnät, 2012. *Samrådsunderlag planerad stamnätsförbindelse mellan Gotland och fastlandet.* [Online]
Available at: http://www.svk.se/Projekt/Utbyggnadsprojekt/Gotlandsforbindelsen/
[Accessed 21 01 2015].

Svenska kraftnät, 2014. *Bakgrund Sydvästlänken.* [Online]
Available at: http://www.svk.se/Projekt/Utbyggnadsprojekt/Sydvastlanken/Information/
[Accessed 20 01 2015].

Svenska kraftnät, 2014. *Ekhyddan-Barkeryd.* [Online]
Available at: http://www.svk.se/Projekt/Utbyggnadsprojekt/Ekhyddan-Barkeryd/
[Accessed 21 01 2015].

Svenska kraftnät, 2014. *Nu rullas den sista kabeltrumman ut.* [Online]
Available at: http://www.svk.se/projekt/Utbyggnadsprojekt/Sydvastlanken/Nyheter/Nu-rullas-den-sista-kabeltrumman-ut/
[Accessed 03 02 2015].

Svensson, C., 1984. *Analysis and use of ground-water level observations,* Göteborg: Chalmers University of Technology and University of Göteborg.

University of California, 2011. *Geologic time scale.* [Online]
Available at: http://www.ucmp.berkeley.edu/help/timeform.php
[Accessed 29 01 2015].

University of Illinois, 2015. *Soil water retention.* [Online]
Available at: http://age-web.age.uiuc.edu/classes/age357/ABE459_08/html/Soil%20Water%20Retention.pdf
[Accessed 7 May 2015].

Vattenmyndigheten Södra Östersjön, 2010. *Förvaltningsplan Södra Östersjöns vattendistrikt 2009-2015,* Kalmar: Vattenmyndigheten i Södra ÖStersjöns vattendistrikt vid Länsstyrelsen Kalmar län.

Zhan, T., 2005. *Influence of the seasonal snow cover on the ground thermal regime: An overwiev,* Boulder: University of Colorado.

11 Appendices

Appendix 1 – Strategy for thermal classification of cable in natural ground conditions

Appendix 2 – Proctor compaction test

Appendix 3 – Sieve analysis method

Appendix 4 – Monte Carlo simulation method

Appendix 5 – Groundwater statistics

Appendix 6 – The observational method

Appendix 7 – Groundwater table maps

Appendix 8 – Sieve analysis results

Appendix 1 – Strategy for thermal classification of cable in natural ground conditions

This document is the first version of a strategy for thermal classification of cable in natural ground conditions. The original document written by Jan Sundberg has been translated.

General methodology – Version 1

Problem
Determination of the designing thermal resistivity for a cable route. The designing properties are on the scale 1-5 m. For a long stretch this implies that the designing properties are in the end of a normal distribution.

1. Investigations in several steps and levels

1.1 Desktop study. Map studies of geological maps and terrain conditions. Create a plan where expected design values occurs with the expected ground and groundwater conditions.

1.2 Field work – General. Mapping the soil and rock condition along the projected stretch using a soil sampler every fifth metre at a depth of 0.5 m. Where other ground conditions are expected at the cable depth is a probe made with handheld equipment such as a Doctor's kit. Expected groundwater table is estimated based on the conditions of the lakes, watercourses, ditches, typical discharge areas, ground conditions and the terrain. Deviations regarding the potential hotspots on the stretch are noted and the plan is updated.

1.3 Field work – Detailed. Pointwise verification of ground and groundwater conditions by excavating field samples at relevant depth and/or installation of piezometer. Measurement of thermal resistivity during a time period where design values may occur. Determination of the water bearing capacity of the expected designing soil types at spots with deep ground water table. Registration of ground water tables during available time period (preferably automatic), yet still during minimum the 3 month period when the deepest groundwater table is expected. Update of plan for expected ground and groundwater conditions. Presentation of deviations regarding the earlier step.

1.4 Field work – Complementing. If needed.

2. Evaluation and modelling

2.1 Evaluation of the thermal resistivity result from the field work by using statistical analysis. Prognosis of the designing ground water table with statistical analysis.

2.2 Parameterisation of the stretch. Deterministic or via modelling, for example stochastic modelling where many conditions that control the thermal resistivity can be varied.

3. Presentation. Substrate for calculation of temperature and configuration of cables and cable sand.

4. Verification and control

4.1 During construction are properties of the ground controlled in order to match the expected properties. All deviations are noted and is reported to the thermal planner. The standardized observational method is used.

4.2 Presentation. Substrate for revised calculation of temperatures and configuration of cables and cable sand.

Appendix 2 – Proctor compaction test

An adaption of the standard ASTM D698-00a, proctor compaction test, is used to determine the relationship between molding water content and dry unit weight of soils. The usage of the proctor test is in this case primarily to compact the soil in order to simulate field conditions in situ before measuring thermal conductivity and proceeding with the sieve analysis.

The procedure is as follows:

- The soil sample is inserted in a stainless steel cylinder mold in three layers. The cylinder has a height of 100mm and a radius of 36mm.
- Each layer is compacted 25 times using a rammer dropped from a distance of 305mm. The rammer pattern is visualised in Figure 1.
- The dry weight of the sample is measured.
- Thermal conductivity is measured on each sample using the method described in chapter 5.3.2.

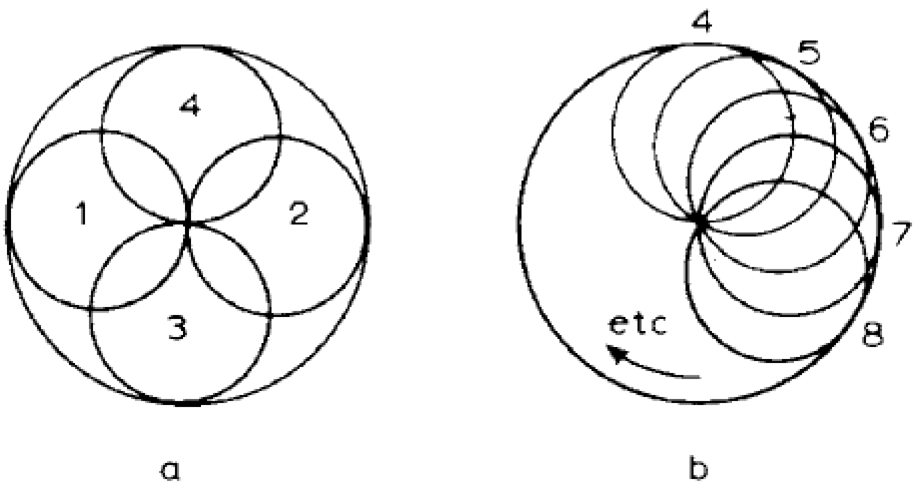


Figure 1. Rammer pattern for compaction (ASTM D698-00a, 2000).

Appendix 3 – Sieve analysis method

The soil samples from the field study were analysed according to the Standard Test Method for Particle-Size Analysis of Soils (ASTM D422-63, 2007) in order to make a more detailed classification of the soils. Before the sieve analysis the soil samples were dried in an oven for 48 hours at 105 degrees Celsius. The samples were then poured in the top sieve of the sieve stack and put in a sieve shaker. Every sample were shaken for 7 minutes. By weighing the remaining grains at each sieve level after the shake a grain size distribution of the soil samples were possible. The grain size distribution analysis contained 12 sieves with a sieve size range of 20-0.063 mm. These sieves are of American standard, see the sieve sizes in Appendix 3, but the soil classification in this study is according to Swedish standard. Therefore are the sieves sizes rounded to the closest soil class. The soil types are classified according to the guidelines in Table 1.

Table 1. Guideline for soil classification (Avén, 1984).

Grain fraction	Content of the fraction in weight percentage of the total amount	Content of the fraction in weight percentage of coarse and fine soil	Content of clay in weight percentage of the fine soil	Soil classification	
				Prefix	Main class
Boulder	5-20			Boulderly	
	>20			Very boulderly	1)
Cobble	10-20			Cobbly	
	>20			Very cobbly	1)
Gravel		20-40		Gravelly	
		>40			Gravel
Sand		20-40		Sandy	
		>40			Sand
Silt and Clay		15-40	<20	Silty	
			≥20	Clayey	
			<10		Silt
			10-20	Clayey	Silt
			20-40	Silty	Clay
			>40		Clay

1) When the content of boulder and cobble exceeds 40 % is boulder or cobble the main class depending on which is the largest of them.

Appendix 4 – Monte Carlo Simulation

When obtaining field and laboratory measurements the number of samples is often limited. It is difficult to find designing values from the measured samples and therefore statistical analysis is often required. Given the average and standard deviation, one can simulate a distribution of randomised values with a set number of iterations using the Monte Carlo method. This yields a new set of results with more data distributed according to the average and standard deviation of the measured samples. This can then for example be visualised using a histogram displaying the distribution of the function. Using more iterations as well as more starting samples produce a more reliable end result.

The method is simple and the program used to produce the distributions is Microsoft excel. First the average value of the starting samples is calculated together with the corrected sample standard deviation. The formula for corrected sample standard deviation can be seen in Equation (4).

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{k=1}^{n}(x_k - \mu)^2} \tag{4}$$

Where;

σ is the standard deviation

μ is the average

$\{x_1, x_2, \ldots, x_N\}$ are the measured sample values

The probability density function of the normal distribution is given by Equation (5).

$$f(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{5}$$

In order to simulate samples distributed normally, the probability density is randomised with the random values and the *x* is sought for. The inverse of the cumulative normal distribution instead yields *x* given a probability. Excel handles this by using an iterative method to find an *x* that satisfies the formula for a known probability.

A table of any arbitrary amount of random values between 0 and 1 can now be set up. By using the inverse normal distribution function with these random values, a column of randomised sample values is the result. The distribution of the result can then be presented in histograms.

Appendix 5 – Groundwater statistics

According to the Swedish Geotechnical Institute there are primarily two methods used to estimate groundwater levels; making a qualified estimation as an engineer or using the Chalmers method (Lind, et al., 2010). The basics of the Chalmers method is to compare the groundwater level of a piezometer with short data series on the desired location, the *prognosis piezometer*, with a *reference piezometer* where extreme values levels are known. The reference piezometer must be located in the same climate zone, and in an aquifer with similar characteristics, for the assumption that they behave similar to be valid. The Swedish Geotechnical Institute keeps a database of more than 300 piezometers where the groundwater level is tracked one or two times every month that may be used as reference piezometers.

Equation (1) and Equation (2) display the calculations used to find the minimal groundwater level in the prognosis piezometer using the Chalmers method;

$$P_{min}^{\mathrm{X}} = P_{min} + S_R^{\mathrm{X}} \cdot \frac{r_P}{r_R} \tag{1}$$

$$S_R^{\mathrm{X}} = \left| y_{min}^{\mathrm{X}} - y_{min} \right| \tag{2}$$

P_{min}^{X}	Estimated minimum groundwater level for a return period of X years in the prognosis piezometer [m]
P_{min}	Minimum groundwater level in the prognosis piezometer during the evaluation period [m]
S_R^X	Difference between minimum groundwater level during the evaluation period and minimal groundwater level for a return period of X years in the reference piezometer [m]
r_P	Range of groundwater variation during the evaluation period in the prognosis piezometer [m]
r_R	Range of groundwater variation during the evaluation period in the reference piezometer [m]
y_{min}^{X}	Minimum groundwater level for a return period of X years in the reference piezometer [m]
y_{min}	Minimum groundwater level during the evaluation period in the reference piezometer [m]

Since the existing piezometers have fairly short time series, the Chalmers method is deemed suitable for estimating longer return periods. Bengtsson and Boström mentions that with longer observation periods, a more precise application of the Chalmers model can be made and consequently also a better approximation of the extreme values of the groundwater level (Bengtsson & Boström, 2008). According to Haaf, comparing different statistic methods for extreme value approximation, the generally accepted normal distribution is a solid method as a large portion of the analysed data series could be used (Haaf, 2014).

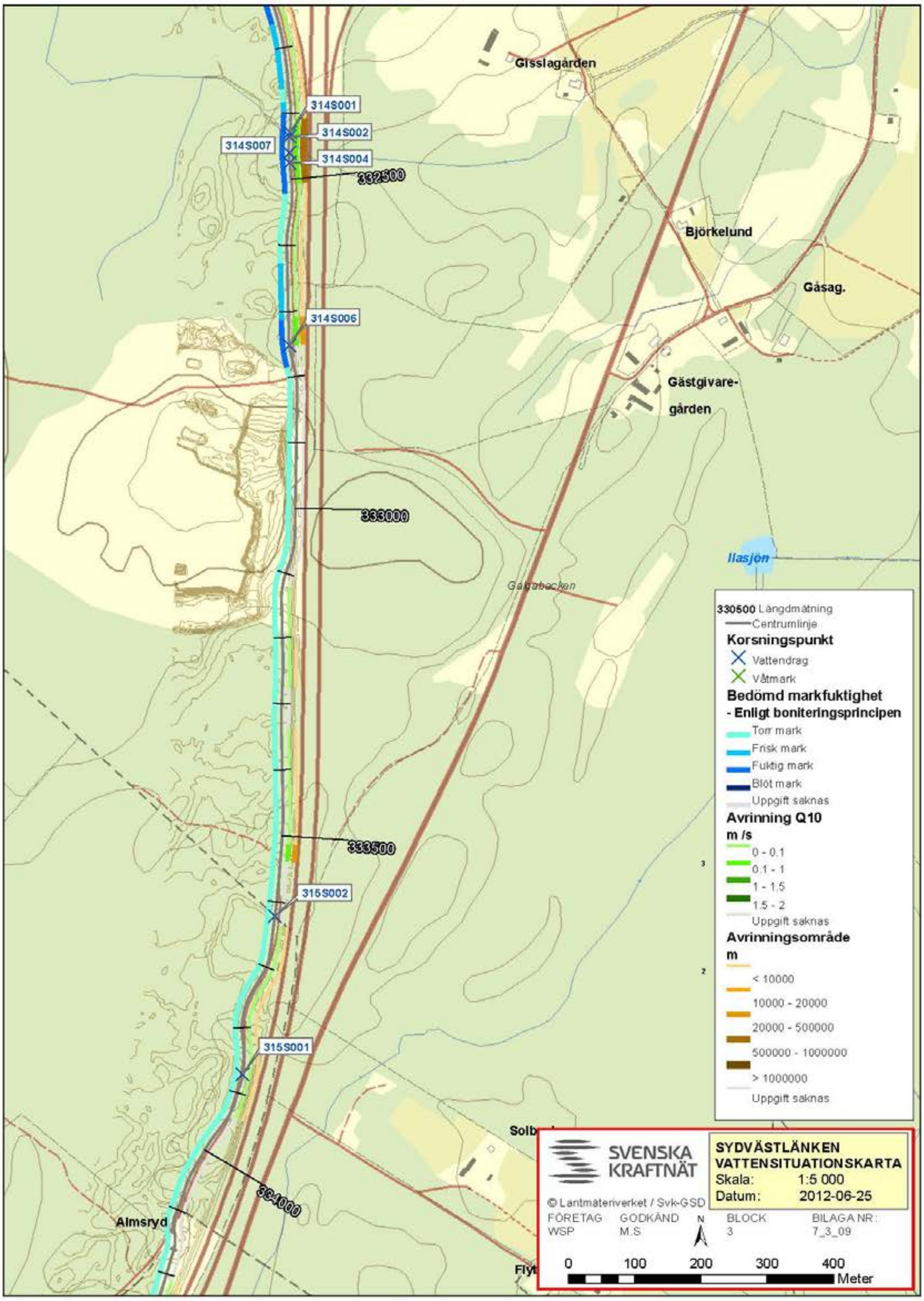
Appendix 6 – The observational method

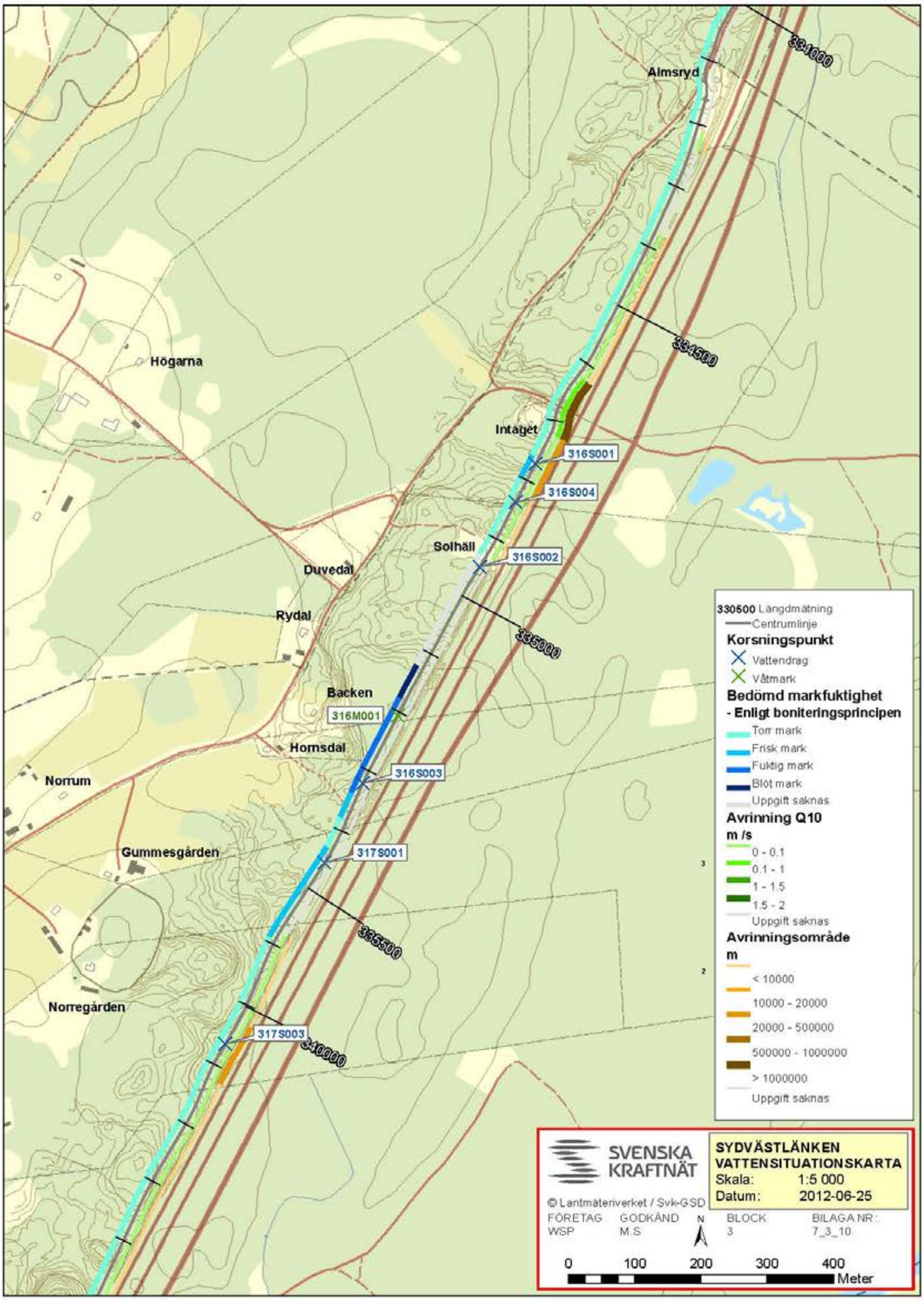
The standard method SS-EN 1997-1 is a method to verify the quality of a geotechnical construction (IEG, 2010). This observational method contains both advices and requirements regarding the routines during the project planning and the construction phase. The method is suitable to use when there are uncertainties about the geotechnical conditions. It means that that there are limit states that need to be controlled for the design of the construction.

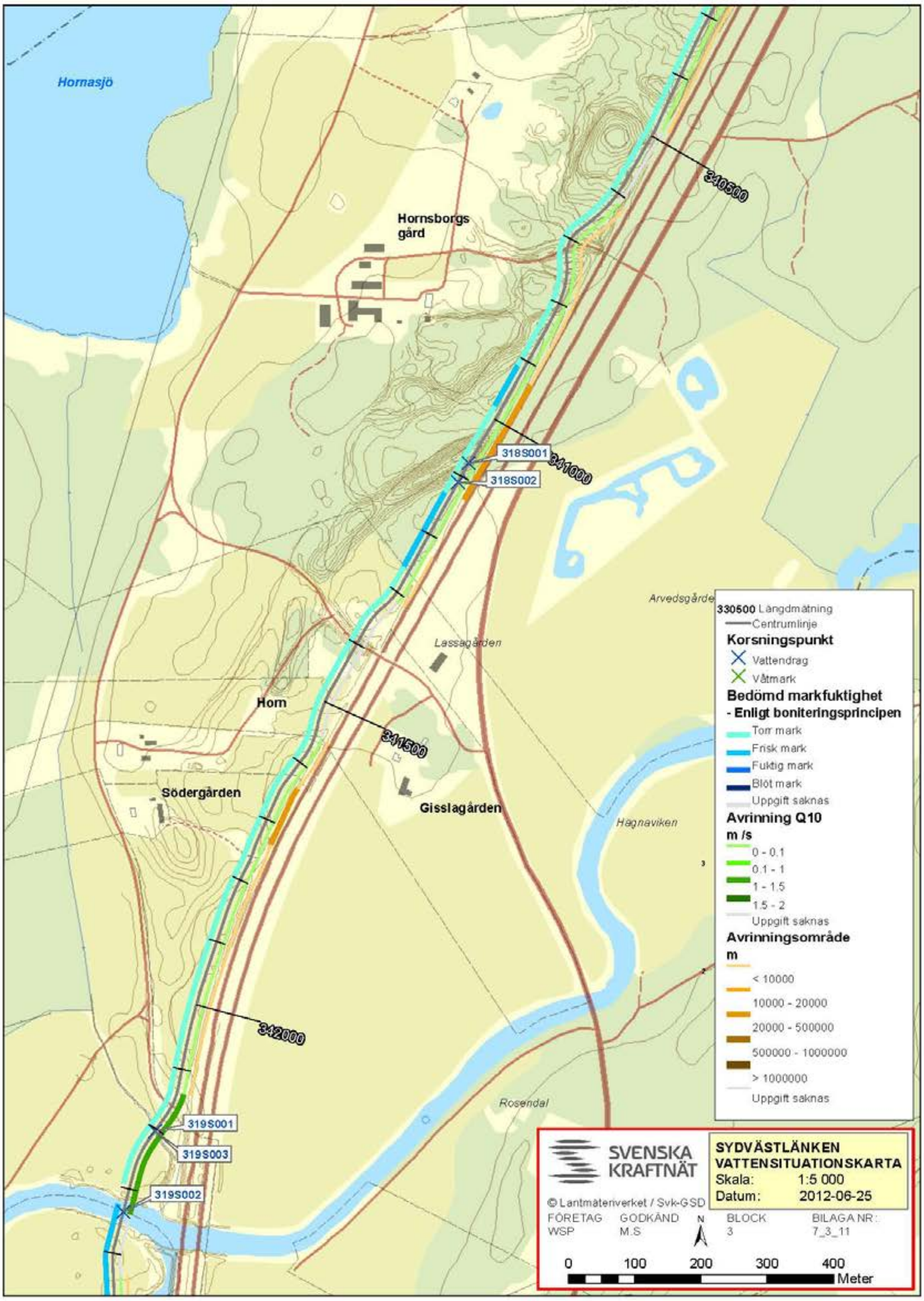
The three main steps in the observational method are prediction, observation and action. Before the construction phase shall acceptable limits of the condition be stated and the design fulfil the requirements with acceptable probability. In order to follow up that the conditions are within the stated limits a monitoring plan is made. The monitoring plan shall be formed in a way that makes it possible to discover unsatisfying conditions at an early stage and be able to take actions by changing the design. A short measuring and analyse time are important to efficiently notice conditions where changes in the design need to be done. The observational method shall also contain a plan for which corrective actions that are needed when the conditions are not within the acceptable limits.

Geotechnical uncertainties contains parameters regarding the behaviour of both the soil and the construction. The number of prepared alternate technical solutions depends on the uncertainty of the conditions during the project planning phase. By using the observational method and reduce the uncertainties the construction cost can be optimized. An evaluation of the technical and economic aspects shall be done in order to find verifying methods that leads to the lowest construction and maintenance cost. The observational method requires that the construction documents states how the geotechnical uncertainties should be handled. It must contain how the uncertainties shall be identified and which technical solutions that needs to be done at different conditions.

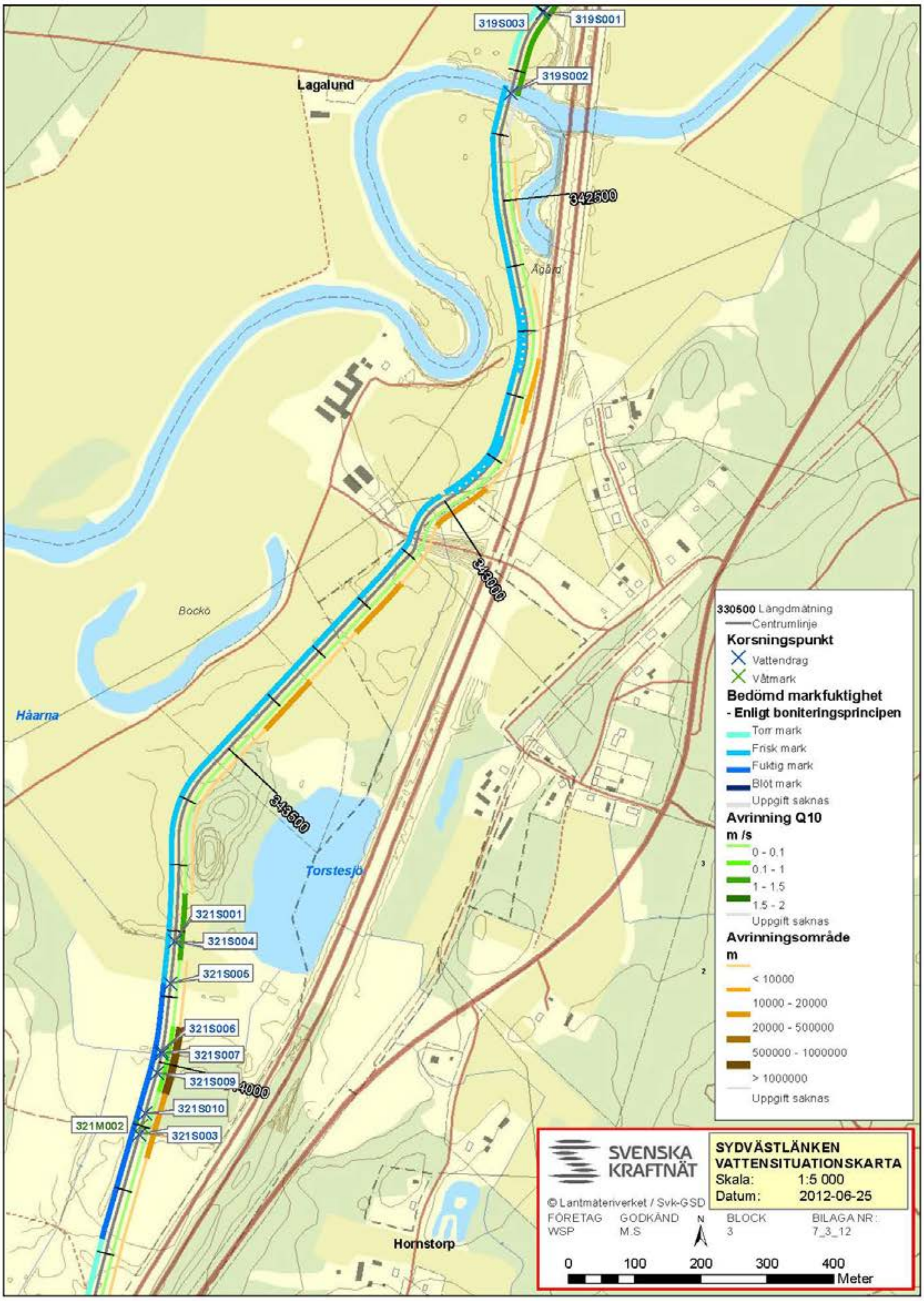
Appendix 7 – Groundwater table maps




334000
Almsryd
334500
Högarna
Intaget
316S001
316S004
Solhäll
316S002
Duvedal
Rydal
335000
Backen
316M001
Hornsdal
316S003
Norrum
Gummesgården
317S001
335500
Norregården
317S003
340000
330500 Längdmätning
Centrumlinje
Korsningspunkt
Vattendrag
Våtmark
Bedömd markfuktighet
- Enligt boniteringsprincipen
Torr mark
Frisk mark
Fuktig mark
Blöt mark
Uppgift saknas
Avrinning Q10
m /s
0 - 0.1
0.1 - 1
1 - 1.5
1.5 - 2
Uppgift saknas
Avrinningsområde
m
< 10000
10000 - 20000
20000 - 500000
500000 - 1000000
> 1000000
Uppgift saknas
SVENSKA KRAFTNÄT
SYDVÄSTLÄNKEN
VATTENSITUATIONSKARTA
Skala: 1:5 000
Datum: 2012-06-25
© Lantmäteriverket / Svk-GSD
FÖRETAG WSP
GODKÄND M.S
N
BLOCK 3
BILAGA NR: 7_3_10
0 100 200 300 400 Meter



Hornasjö
Hornsborgs gård
340500
318S001
318S002
341000
Arvedsgården
Lassagården
Horn
341500
Södergården
Gisslagården
Hagnaviken
342000
Rosendal
319S001
319S003
319S002
330500 Längdmätning
Centrumlinje
Korsningspunkt
Vattendrag
Våtmark
Bedömd markfuktighet
- Enligt boniteringsprincipen
Torr mark
Frisk mark
Fuktig mark
Blöt mark
Uppgift saknas
Avrinning Q10
m /s
0 - 0.1
0.1 - 1
1 - 1.5
1.5 - 2
Uppgift saknas
Avrinningsområde
m
< 10000
10000 - 20000
20000 - 500000
500000 - 1000000
> 1000000
Uppgift saknas
SVENSKA KRAFTNÄT
© Lantmäteriverket / Svk-GSD
FÖRETAG WSP
GODKÄND M.S
N
SYDVÄSTLÄNKEN
VATTENSITUATIONSKARTA
Skala: 1:5 000
Datum: 2012-06-25
BLOCK 3
BILAGA NR: 7_3_11
0 100 200 300 400 Meter

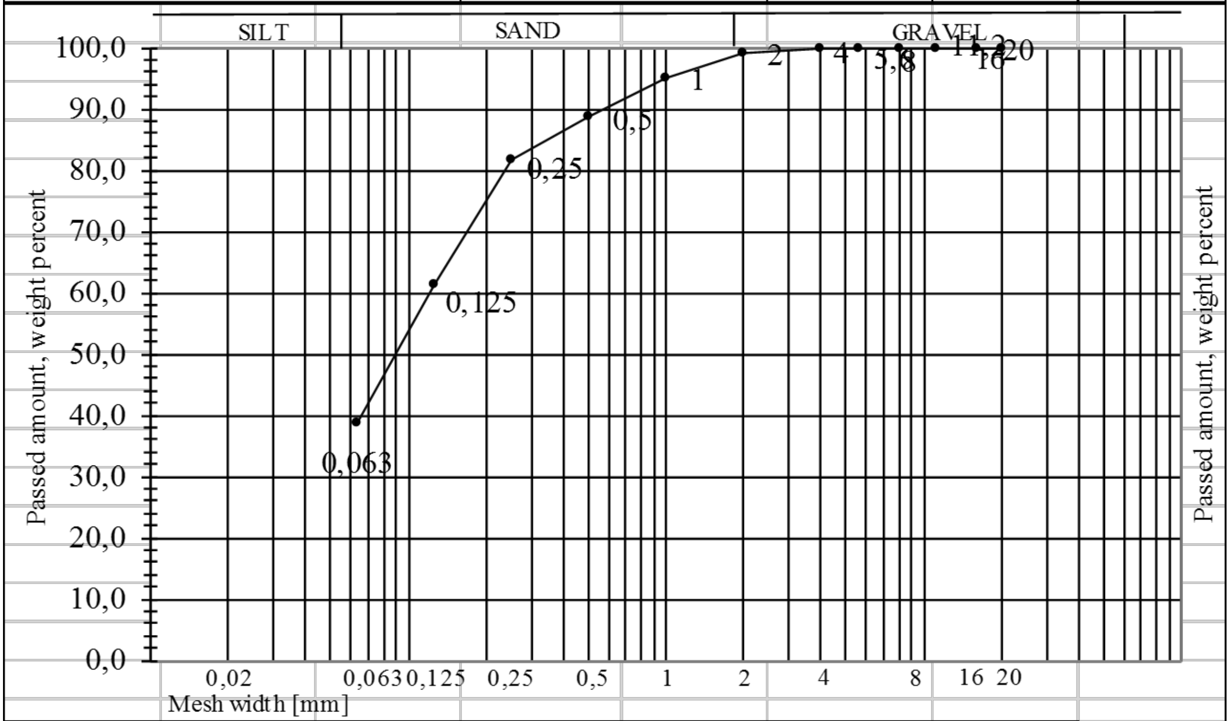


319S003
319S001
319S002
Lagalund
342500
Ågård
343000
Bockö
Håarna
343500
Torstesjö
321S001
321S004
321S005
321S006
321S007
321S009
344000
321S010
321M002
321S003
Hornstorp
330500 Längdmätning
Centrumlinje
Korsningspunkt
Vattendrag
Våtmark
Bedömd markfuktighet
- Enligt boniteringsprincipen
Torr mark
Frisk mark
Fuktig mark
Blöt mark
Uppgift saknas
Avrinning Q10
m /s
0 - 0.1
0.1 - 1
1 - 1.5
1.5 - 2
Uppgift saknas
Avrinningsområde
m
< 10000
10000 - 20000
20000 - 500000
500000 - 1000000
> 1000000
Uppgift saknas
SVENSKA KRAFTNÄT
© Lantmäteriverket / Svk-GSD
SYDVÄSTLÄNKEN
VATTENSITUATIONSKARTA
Skala: 1:5 000
Datum: 2012-06-25
FÖRETAG WSP
GODKÄND M.S
N
BLOCK 3
BILAGA NR: 7_3_12
0 100 200 300 400
Meter

Appendix 8 – Sieve analysis results

Sieve analysis

Project	1	Total sample weight [g]	643,5	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	0,0	0,0	100,0
4	0,4	0,1	99,9
2	4,0	0,8	99,1
1	20,5	4,0	95,1
0,5	33,2	6,5	88,6
0,25	35,4	6,9	81,7
0,125	103,3	20,3	61,4
0,063	116,6	22,9	38,5
Rest	196,4	38,5	
Sum	509,8	100,0	

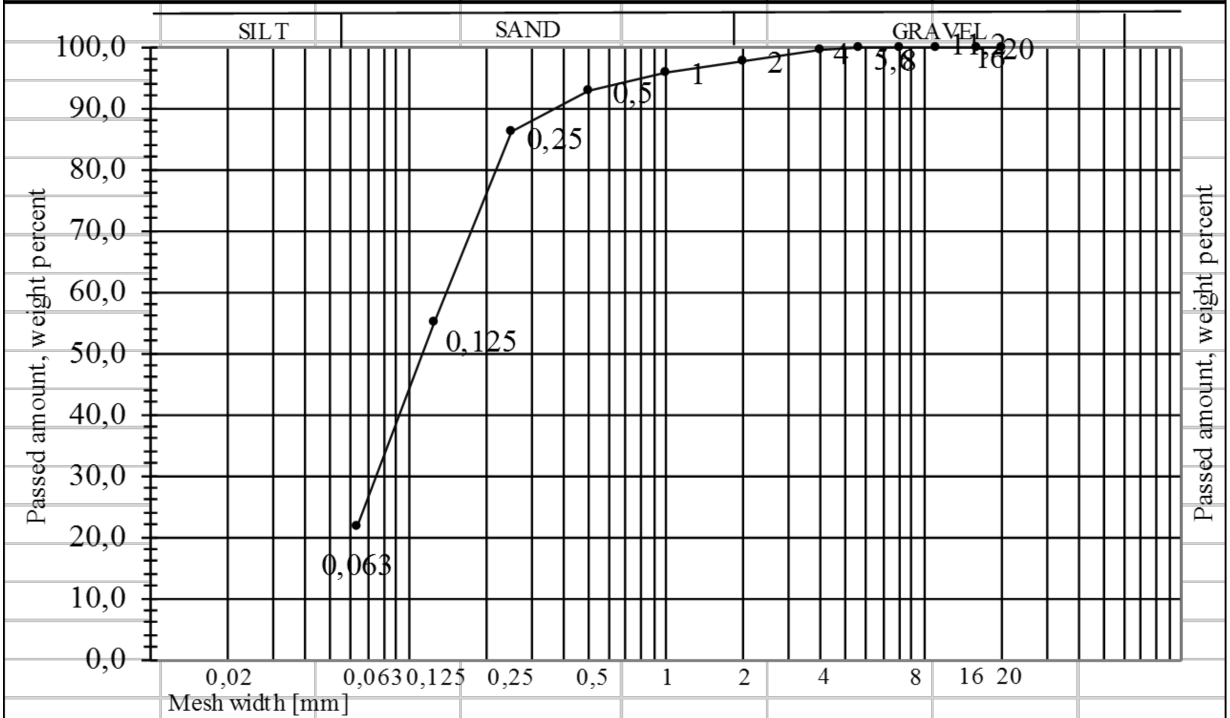
Bowl	
Before drying [g]	643,5
After drying [g]	511,8
Water [g]	131,7
Natural water ratio [%]	26

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	1%	61%	39%
fine	1%	43%	39%
medium	0%	7%	
coarse	0%	11%	
	100%		
	Silty sand		

Sieve analysis

Project	2	Total sample weight [g]	567,6	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	1,1	0,2	99,8
4	1,1	0,2	99,6
2	8,8	1,8	97,8
1	9,6	1,9	95,8
0,5	15,5	3,1	92,7
0,25	31,9	6,5	86,2
0,125	154,8	31,4	54,9
0,063	163,5	33,1	21,7
Rest	107,2	21,7	
Sum	493,5	100,0	

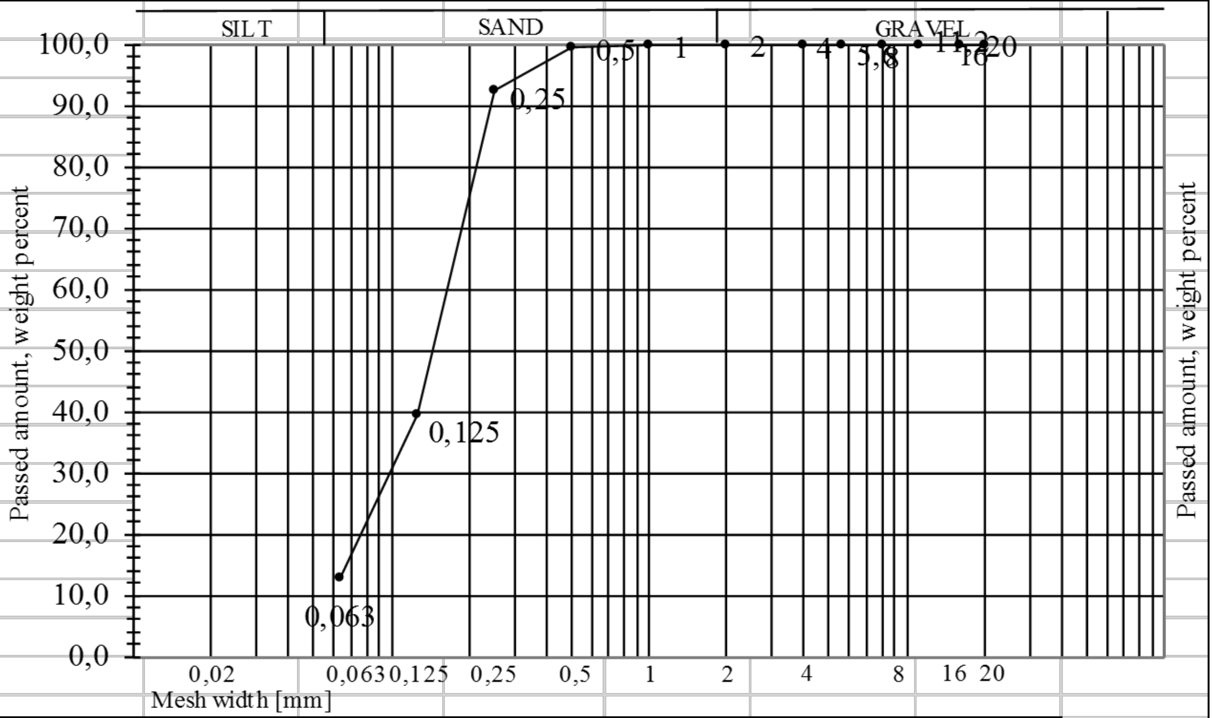
Bowl	
Before drying [g]	567,6
After drying [g]	491,4
Water [g]	76,2
Natural water ratio [%]	16

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	2%	76%	22%
fine	2%	64%	22%
medium	0%	6%	
coarse	0%	5%	
	100%		
	Silty sand		

Sieve analysis

Project	3	Total sample weight [g]	633,8	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	0,0	0,0	100,0
4	0,0	0,0	100,0
2	0,3	0,1	99,9
1	1,0	0,2	99,8
0,5	2,5	0,4	99,3
0,25	40,2	7,0	92,3
0,125	302,8	52,9	39,5
0,063	153,1	26,7	12,7
Rest	73,0	12,7	
Sum	572,9	100,0	

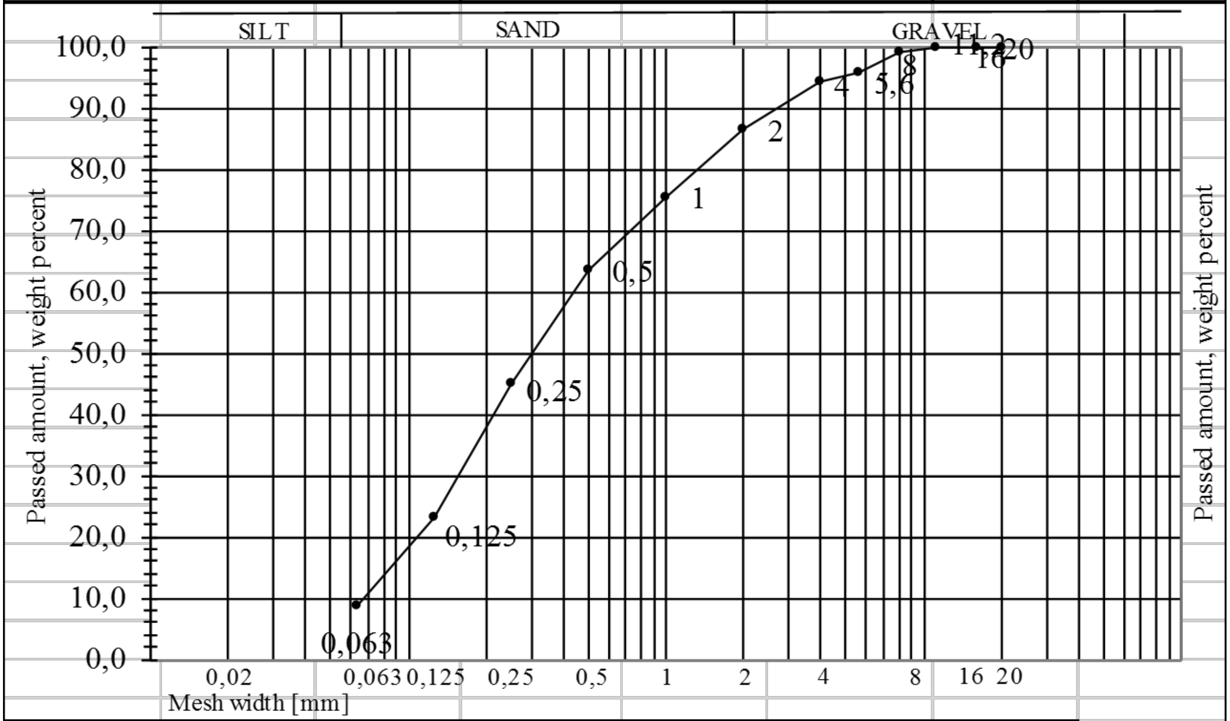
Bowl	
Before drying [g]	633,8
After drying [g]	574,0
Water [g]	59,8
Natural water ratio [%]	10

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	0%	87%	13%
fine	0%	80%	13%
medium	0%	7%	
coarse	0%	1%	
	100%		
	Fine sand		

Sieve analysis

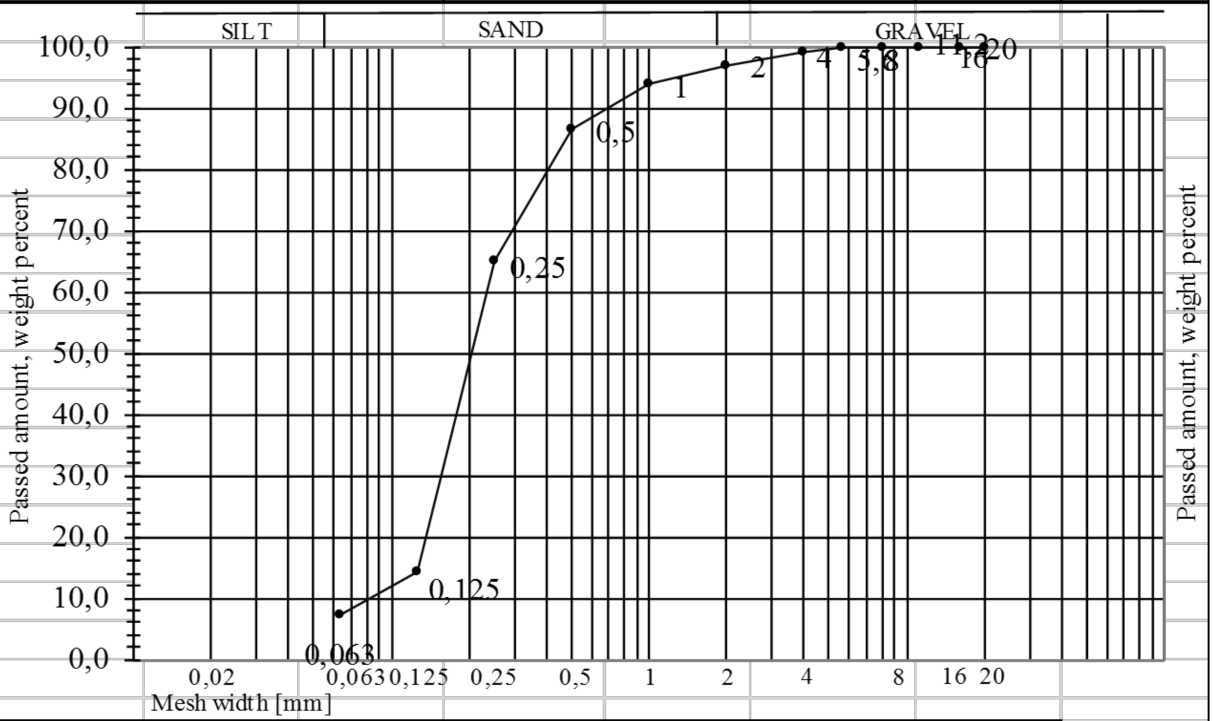
Project	4	Total sample weight [g]	517,8	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]	Bowl			
20	0,0	0,0	100,0	Before drying [g]		517,8	
16	0,0	0,0	100,0	After drying [g]		468,6	
11,2	0,0	0,0	100,0	Water [g]		49,2	
8	4,3	0,9	99,1	Natural water ratio [%]		10	
5,6	15,4	3,3	95,8	Analysis is performed by	J. Utas, A. Lilliestierna		
4	7,0	1,5	94,3	on	2015-04-14		
2	36,3	7,7	86,6				
1	51,7	11,0	75,5		gravel	sand	silt/clay
0,5	56,3	12,0	63,5	total	13%	78%	9%
0,25	86,3	18,4	45,1	fine	9%	36%	9%
0,125	103,6	22,1	23,0	medium	4%	18%	
0,063	66,5	14,2	8,8	coarse	0%	23%	
Rest	41,4	8,8			100%		
Sum	468,8	100,0			Fine sand		

Sieve analysis

Project	5	Total sample weight [g]	553,0	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	1,7	0,4	99,6
4	3,0	0,6	99,0
2	9,8	2,1	96,9
1	14,6	3,2	93,7
0,5	34,2	7,4	86,3
0,25	97,9	21,2	65,2
0,125	235,8	51,0	14,2
0,063	33,0	7,1	7,1
Rest	32,8	7,1	
Sum	462,8	100,0	

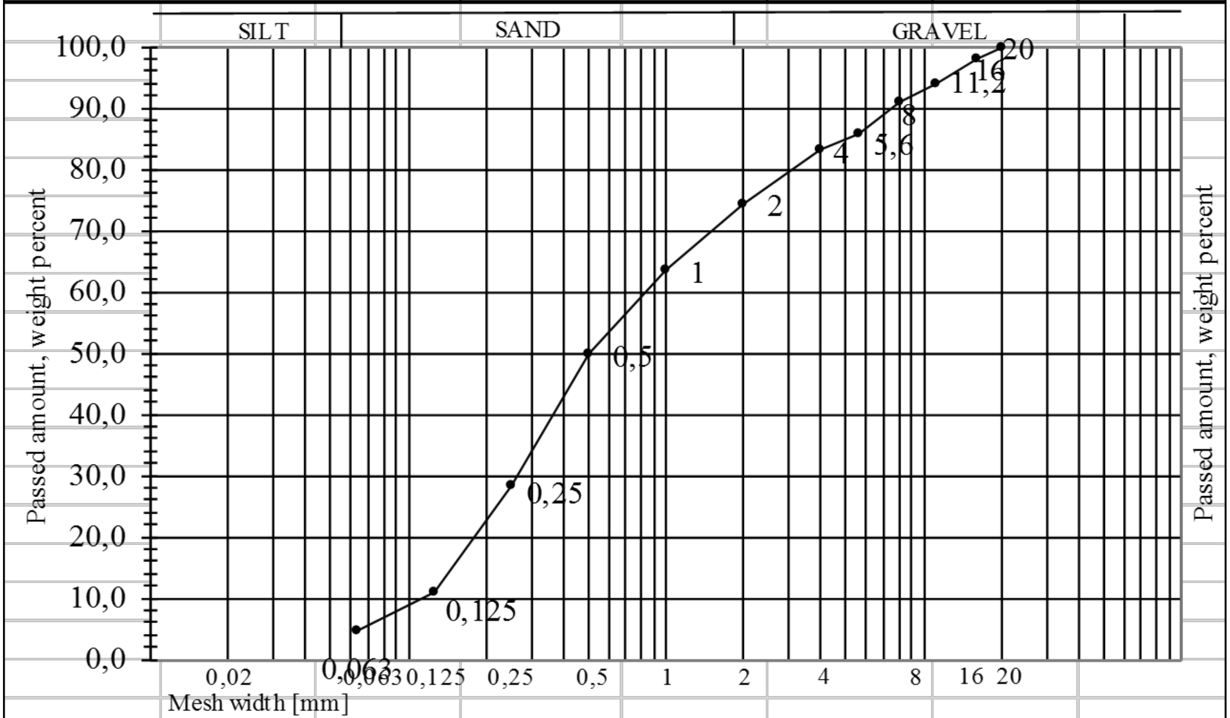
Bowl	
Before drying [g]	553,0
After drying [g]	490,8
Water [g]	62,2
Natural water ratio [%]	13

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	3%	90%	7%
fine	3%	58%	7%
medium	0%	21%	
coarse	0%	11%	
	100%		
	Fine sand		

Sieve analysis

Project	6	Total sample weight [g]	485,6	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	8,7	2,0	98,0
11,2	18,2	4,2	93,8
8	12,4	2,8	91,0
5,6	22,2	5,1	85,9
4	11,3	2,6	83,3
2	38,9	8,9	74,4
1	47,8	11,0	63,4
0,5	59,6	13,7	49,7
0,25	92,6	21,3	28,5
0,125	77,0	17,7	10,8
0,063	26,3	6,0	4,8
Rest	20,7	4,8	
Sum	435,7	100,0	

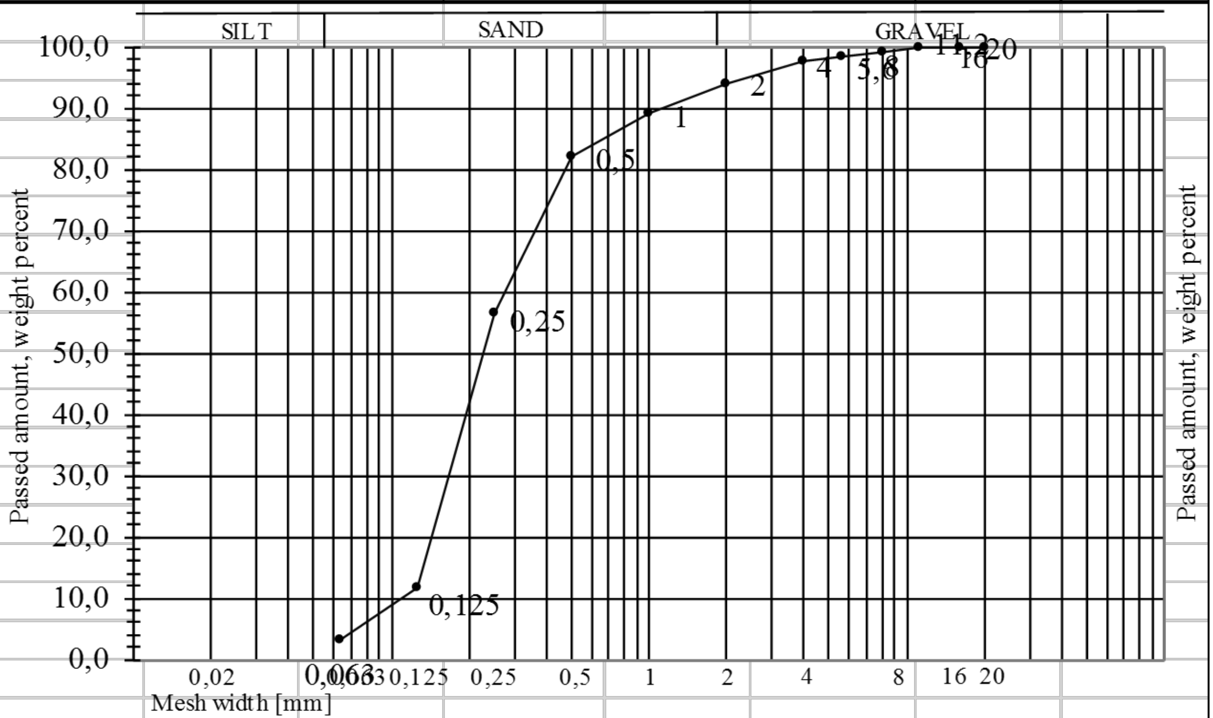
Bowl	
Before drying [g]	485,6
After drying [g]	434,3
Water [g]	51,3
Natural water ratio [%]	12

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	26%	70%	5%
fine	12%	24%	5%
medium	14%	21%	
coarse	0%	25%	
	100%		
	Gravely sand		

Sieve analysis

Project	7	Total sample weight [g]	719,9	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	[%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	6,4	1,0	99,0
5,6	5,2	0,8	98,2
4	5,1	0,8	97,4
2	22,2	3,4	94,0
1	33,3	5,1	88,9
0,5	45,5	7,0	81,9
0,25	165,3	25,4	56,5
0,125	290,5	44,7	11,8
0,063	56,4	8,7	3,1
Rest	20,2	3,1	
Sum	650,1	100,0	

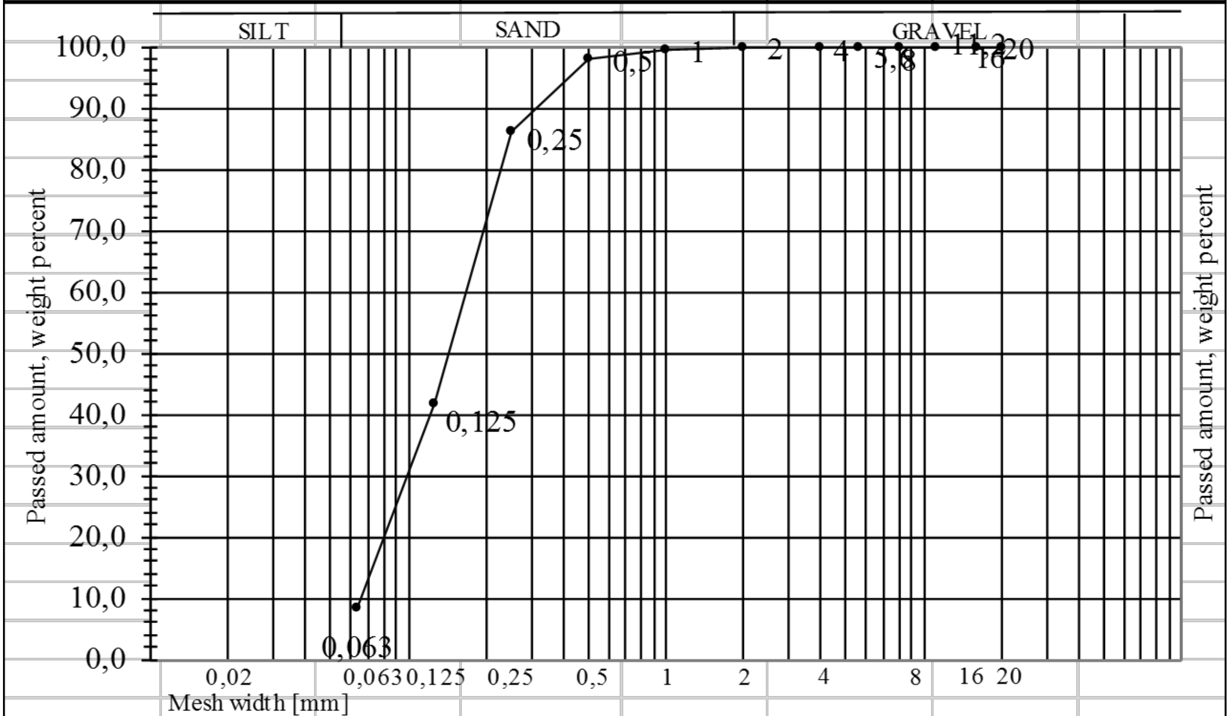
Bowl	
Before drying [g]	719,9
After drying [g]	650,8
Water [g]	69,1
Natural water ratio [%]	11

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	6%	91%	3%
fine	4%	53%	3%
medium	2%	25%	
coarse	0%	12%	
	100%		
	Fine sand		

Sieve analysis

Project	8	Total sample weight [g]	513,4	Depth [m]	0,45
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	[%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	0,0	0,0	100,0
4	0,0	0,0	100,0
2	0,6	0,1	99,9
1	1,7	0,4	99,5
0,5	7,5	1,6	97,9
0,25	54,4	11,8	86,1
0,125	204,5	44,4	41,7
0,063	154,0	33,4	8,2
Rest	37,8	8,2	
Sum	460,5	100,0	

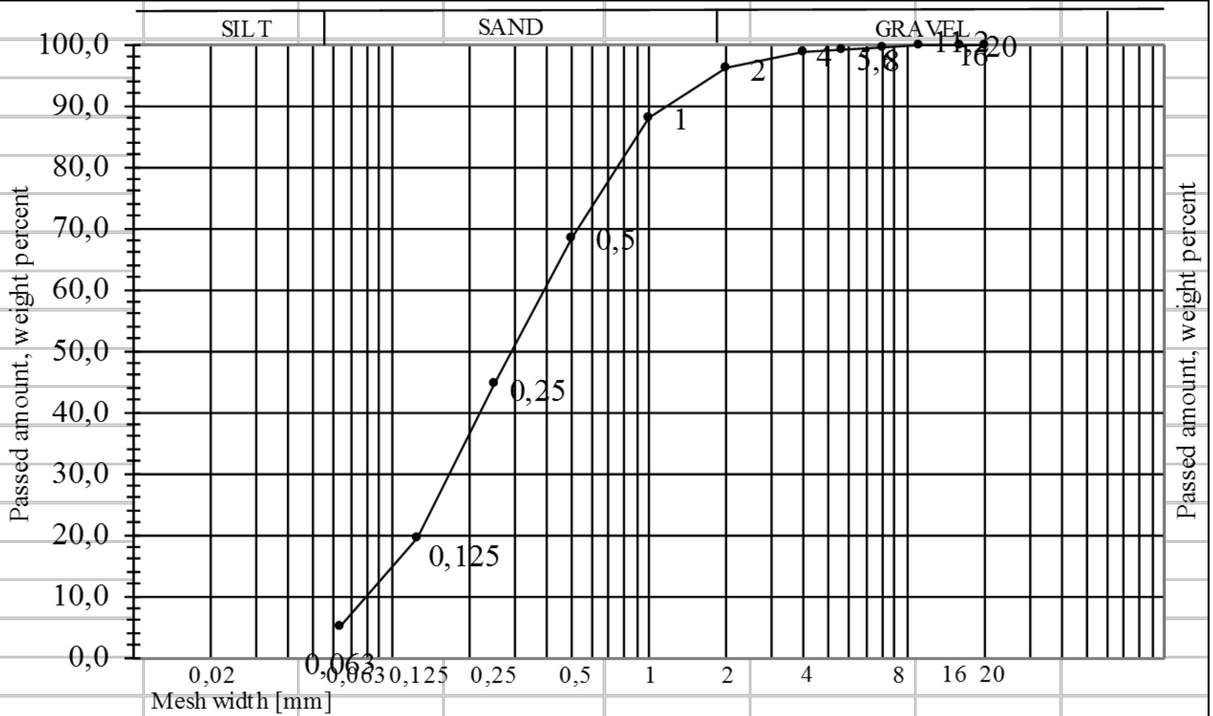
Bowl	
Before drying [g]	513,4
After drying [g]	460,5
Water [g]	52,9
Natural water ratio [%]	11

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	0%	92%	8%
fine	0%	78%	8%
medium	0%	12%	
coarse	0%	2%	
	100%		
	Fine sand		

Sieve analysis

Project	9	Total sample weight [g]	590,6	Depth [m]	0,55
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	2,9	0,5	99,5
5,6	1,2	0,2	99,3
4	2,7	0,5	98,8
2	15,2	2,8	96,0
1	43,5	7,9	88,1
0,5	107,5	19,6	68,5
0,25	130,4	23,8	44,7
0,125	138,6	25,2	19,5
0,063	78,7	14,3	5,2
Rest	28,3	5,2	
Sum	549,0	100,0	

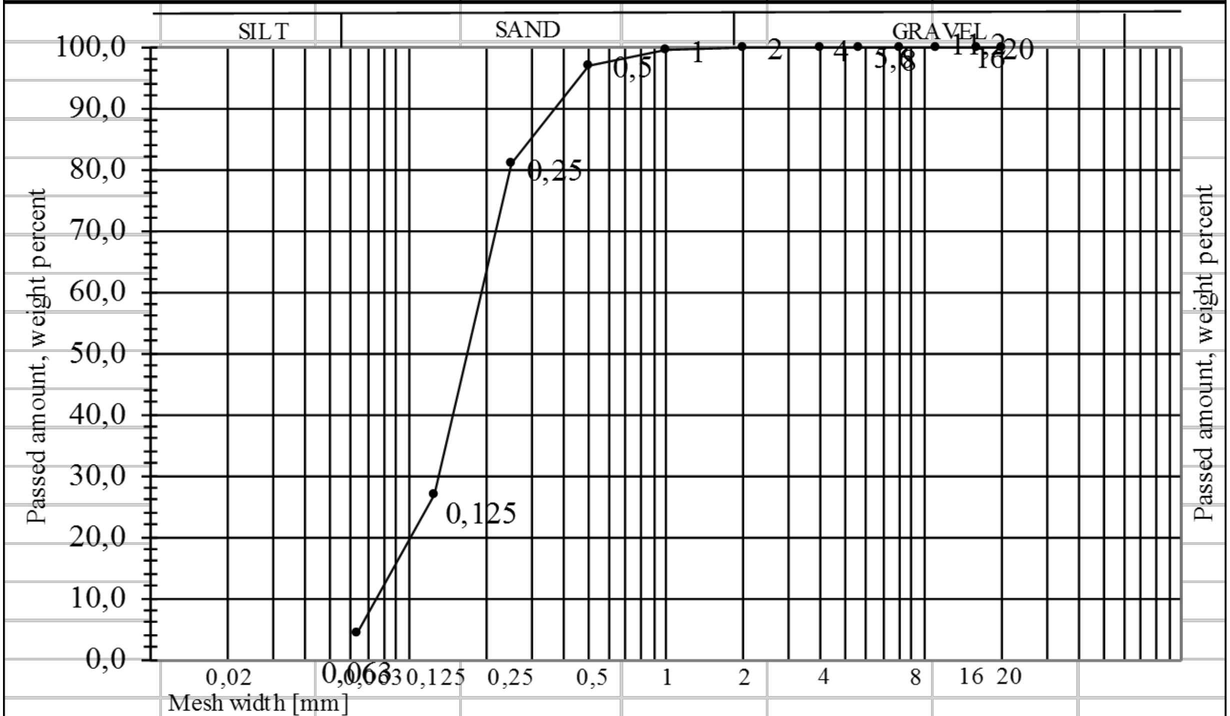
Bowl	
Before drying [g]	590,6
After drying [g]	550,8
Water [g]	39,8
Natural water ratio [%]	7

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	4%	91%	5%
fine	3%	40%	5%
medium	1%	24%	
coarse	0%	28%	
	100%		
	Fine sand		

Sieve analysis

Project	10	Total sample weight [g]	447,4	Depth [m]	0,6
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	0,0	0,0	100,0
4	0,0	0,0	100,0
2	0,4	0,1	99,9
1	1,6	0,4	99,5
0,5	10,1	2,6	96,9
0,25	62,0	15,8	81,1
0,125	212,8	54,3	26,8
0,063	88,8	22,7	4,1
Rest	16,0	4,1	
Sum	391,7	100,0	

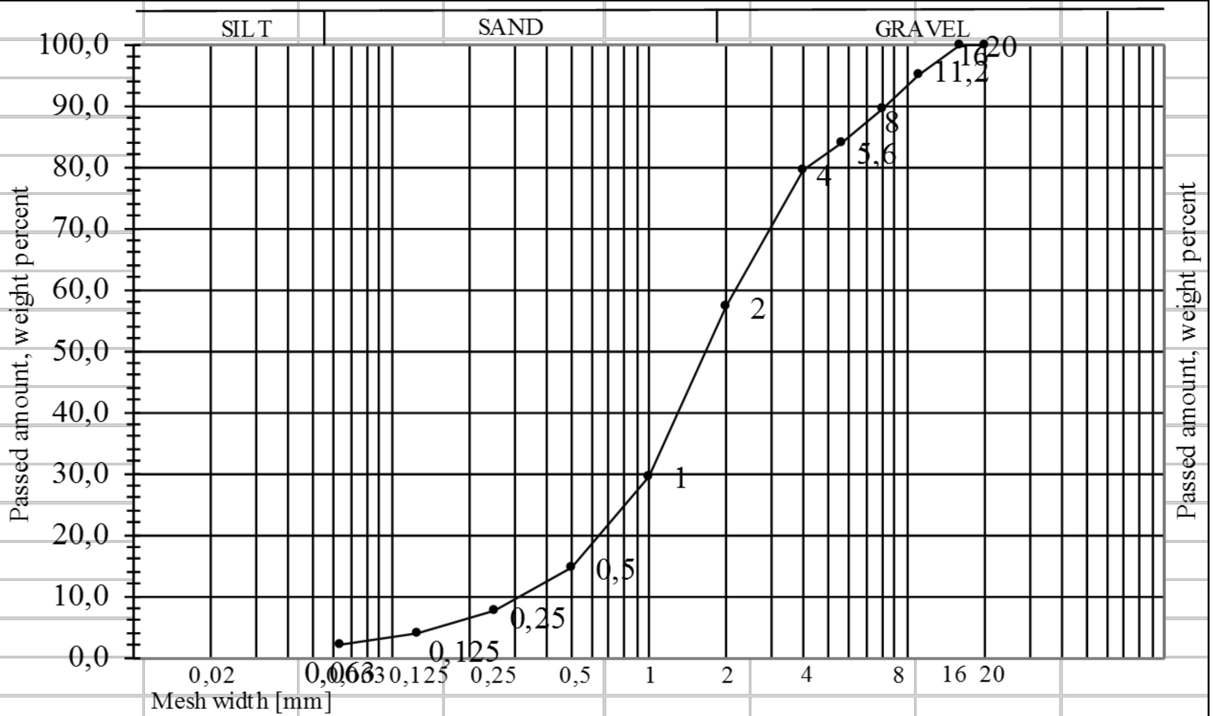
Bowl	
Before drying [g]	447,4
After drying [g]	390,8
Water [g]	56,6
Natural water ratio [%]	14

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	0%	96%	4%
fine	0%	77%	4%
medium	0%	16%	
coarse	0%	3%	
	100%		
	Fine sand		

Sieve analysis

Project	11	Total sample weight [g]	663,5	Depth [m]	0,35
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	30,3	4,8	95,2
8	35,9	5,7	89,5
5,6	34,2	5,4	84,0
4	29,7	4,7	79,3
2	139,3	22,2	57,1
1	173,3	27,6	29,6
0,5	93,7	14,9	14,7
0,25	43,6	6,9	7,7
0,125	24,8	3,9	3,8
0,063	10,6	1,7	2,1
Rest	13,3	2,1	
Sum	628,7	100,0	

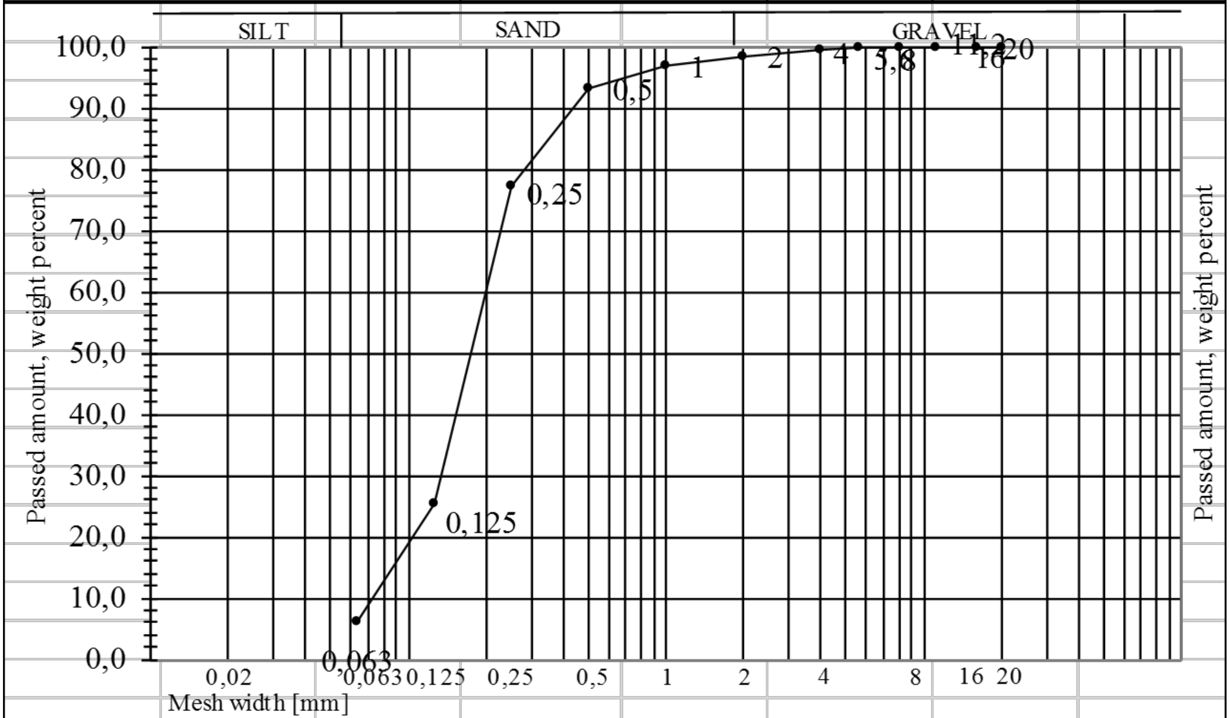
Bowl	
Before drying [g]	663,5
After drying [g]	626,2
Water [g]	37,3
Natural water ratio [%]	6

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	43%	55%	2%
fine	27%	6%	2%
medium	16%	7%	
coarse	0%	42%	
	100%		
	Gravely sand		

Sieve analysis

Project	12	Total sample weight [g]	536,9	Depth [m]	0,5
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	1,6	0,3	99,7
4	0,5	0,1	99,6
2	5,4	1,1	98,5
1	7,5	1,5	96,9
0,5	18,3	3,8	93,1
0,25	77,2	15,9	77,2
0,125	252,1	52,0	25,2
0,063	93,2	19,2	6,0
Rest	29,0	6,0	
Sum	484,8	100,0	

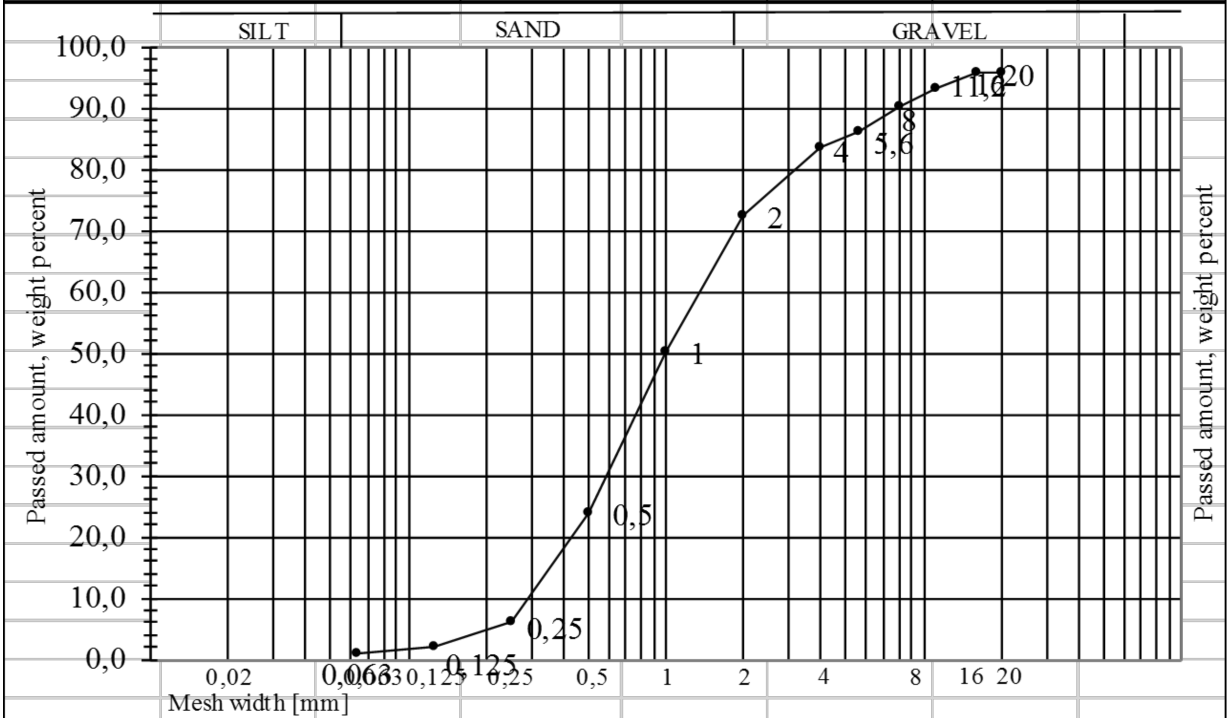
Bowl	
Before drying [g]	536,9
After drying [g]	482,7
Water [g]	54,2
Natural water ratio [%]	11

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	2%	92%	6%
fine	1%	71%	6%
medium	0%	16%	
coarse	0%	5%	
	100%		
	Fine sand		

Sieve analysis

Project	13	Total sample weight [g]	710,1	Depth [m]	0,55
		Weight >20mm [g]	29,7	Shake time	7min

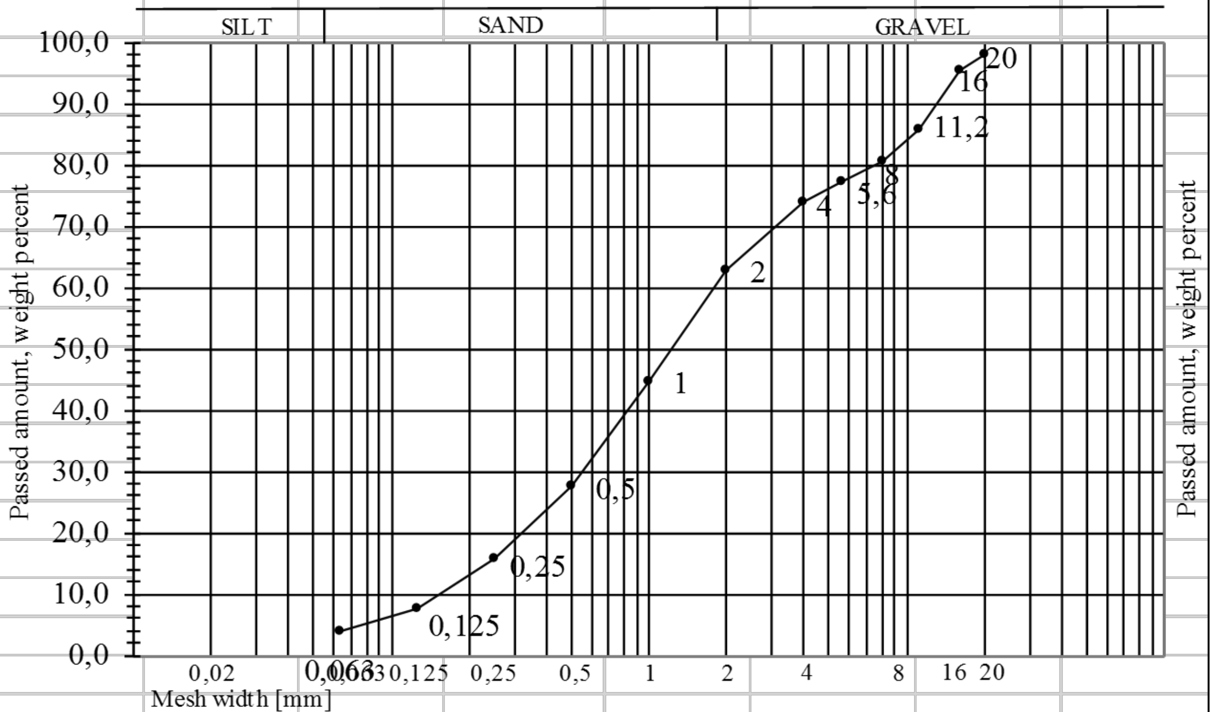


Sieve mesh width [mm]	Retained aggregate [g]	[%]	Total passed weight [%]	Bowl	
20	29,7	4,4	95,6	Before drying [g]	710,1
16	0,0	0,0	95,6	After drying [g]	680,7
11,2	17,3	2,6	93,1	Water [g]	29,4
8	20,3	3,0	90,1	Natural water ratio [%]	4
5,6	27,6	4,1	86,0	Analysis performed by	J. Utas, A. Lilliestierna
4	17,3	2,6	83,5	on	2015-04-14
2	75,2	11,1	72,4		
1	150,5	22,2	50,2		
0,5	178,8	26,4	23,8		
0,25	119,0	17,5	6,3		
0,125	28,8	4,2	2,0		
0,063	7,7	1,1	0,9		
Rest	5,9	0,9			
Sum	678,1	100,0			

	gravel	sand	silt/clay
total	28%	71%	1%
fine	14%	5%	1%
medium	10%	18%	
coarse	4%	49%	
	100%		
	Gravely sand		

Sieve analysis

Project	14	Total sample weight [g]	689,7	Depth [m]	0,35
		Weight >20mm [g]	14,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	14,0	2,2	97,8
16	15,3	2,4	95,5
11,2	61,9	9,6	85,9
8	33,8	5,2	80,6
5,6	22,6	3,5	77,1
4	20,5	3,2	73,9
2	71,7	11,1	62,8
1	116,5	18,1	44,8
0,5	111,8	17,3	27,4
0,25	74,8	11,6	15,8
0,125	52,0	8,1	7,8
0,063	25,5	4,0	3,8
Rest	24,5	3,8	
Sum	644,9	100,0	

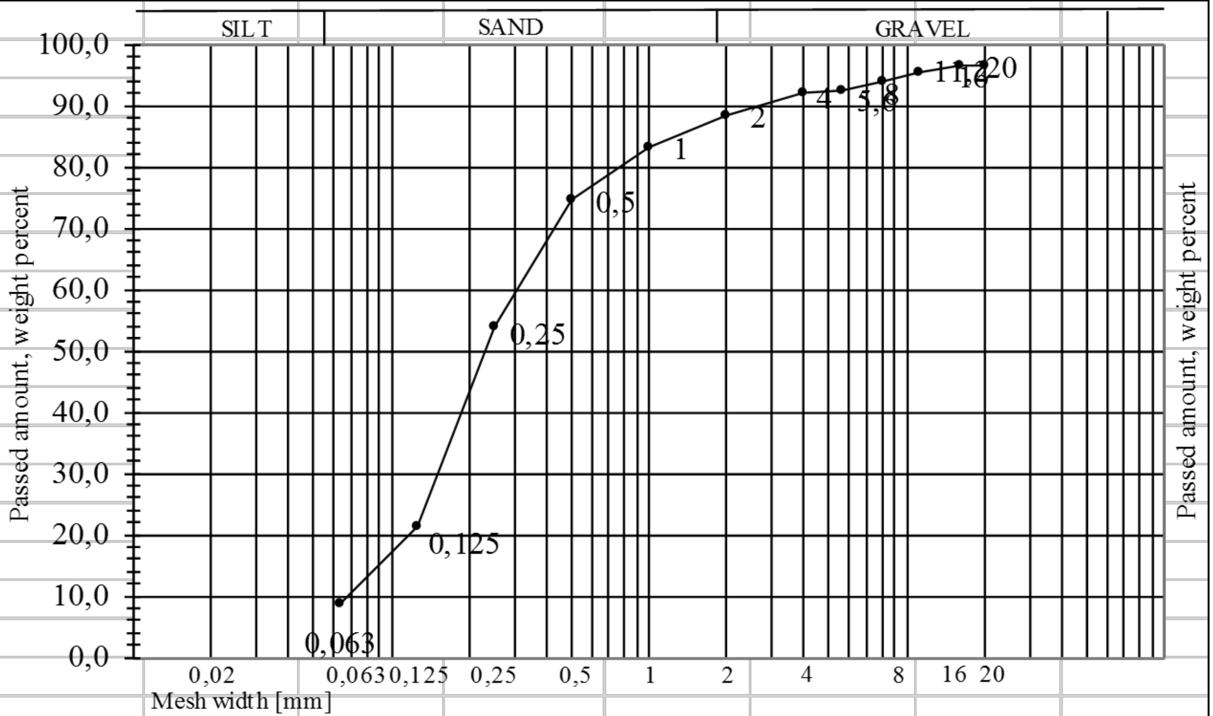
Bowl	
Before drying [g]	689,7
After drying [g]	645,8
Water [g]	43,9
Natural water ratio [%]	7

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	37%	59%	4%
fine	14%	12%	4%
medium	21%	12%	
coarse	2%	35%	
	100%		
	Gravely sand		

Sieve analysis

Project	15	Total sample weight [g]	615,1	Depth [m]	0,4
		Weight >20mm [g]	18,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	18,0	3,5	96,5
16	0,0	0,0	96,5
11,2	6,4	1,3	95,2
8	6,1	1,2	94,0
5,6	7,5	1,5	92,6
4	3,2	0,6	91,9
2	18,1	3,5	88,4
1	26,3	5,1	83,2
0,5	44,8	8,8	74,5
0,25	104,2	20,4	54,1
0,125	166,6	32,6	21,4
0,063	65,4	12,8	8,6
Rest	44,1	8,6	
Sum	510,7	100,0	

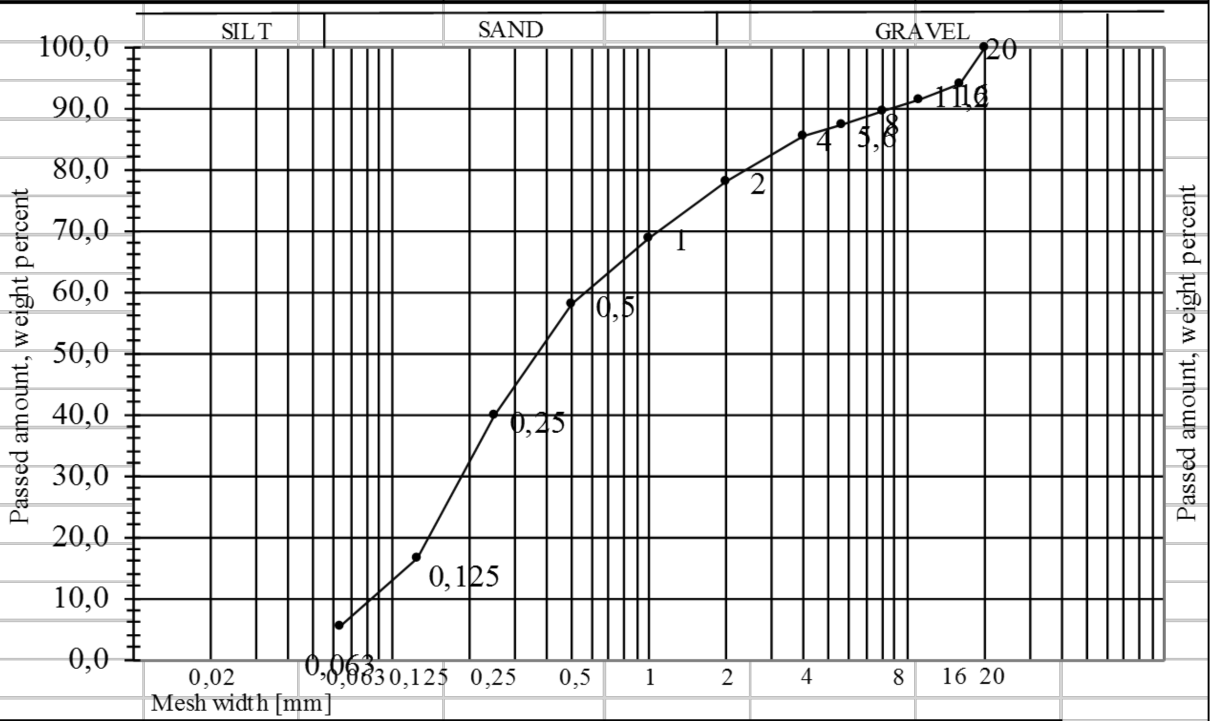
Bowl	
Before drying [g]	615,1
After drying [g]	512,8
Water [g]	102,3
Natural water ratio [%]	20

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	12%	80%	9%
fine	4%	45%	9%
medium	4%	20%	
coarse	4%	14%	
	100%		
	Fine sand		

Sieve analysis

Project	16	Total sample weight [g]	648,0	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	33,0	6,1	93,9
11,2	13,2	2,4	91,5
8	10,5	1,9	89,5
5,6	13,3	2,5	87,0
4	9,4	1,7	85,3
2	39,5	7,3	78,0
1	49,7	9,2	68,8
0,5	59,0	10,9	57,9
0,25	96,8	17,9	40,0
0,125	127,0	23,5	16,5
0,063	59,9	11,1	5,4
Rest	29,1	5,4	
Sum	540,4	100,0	

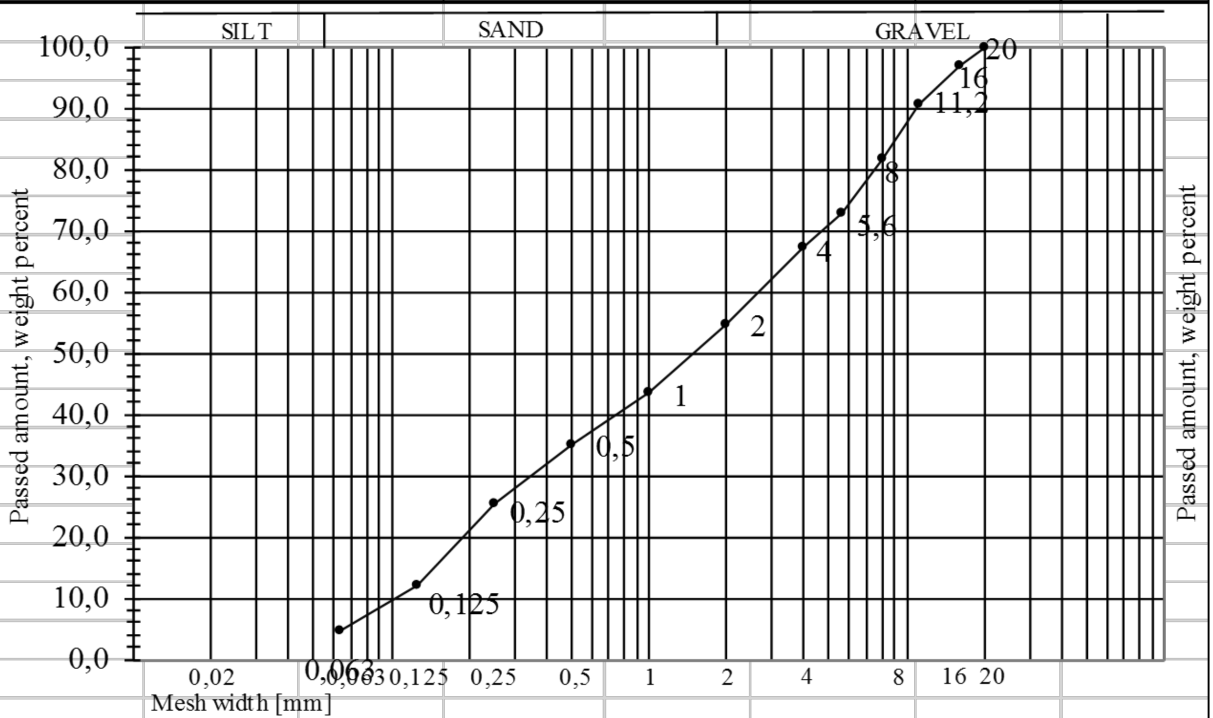
Bowl	
Before drying [g]	648,0
After drying [g]	540,4
Water [g]	107,6
Natural water ratio [%]	20

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	22%	73%	5%
fine	9%	35%	5%
medium	13%	18%	
coarse	0%	20%	
	100%		
	Gravely sand		

Sieve analysis

Project	17	Total sample weight [g]	607,2	Depth [m]	0,4
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	14,2	3,3	96,7
11,2	26,9	6,2	90,5
8	38,5	8,9	81,6
5,6	39,2	9,0	72,6
4	23,1	5,3	67,3
2	54,3	12,5	54,8
1	49,5	11,4	43,3
0,5	35,7	8,2	35,1
0,25	42,4	9,8	25,3
0,125	58,0	13,4	12,0
0,063	32,3	7,4	4,5
Rest	19,6	4,5	
Sum	433,7	100,0	

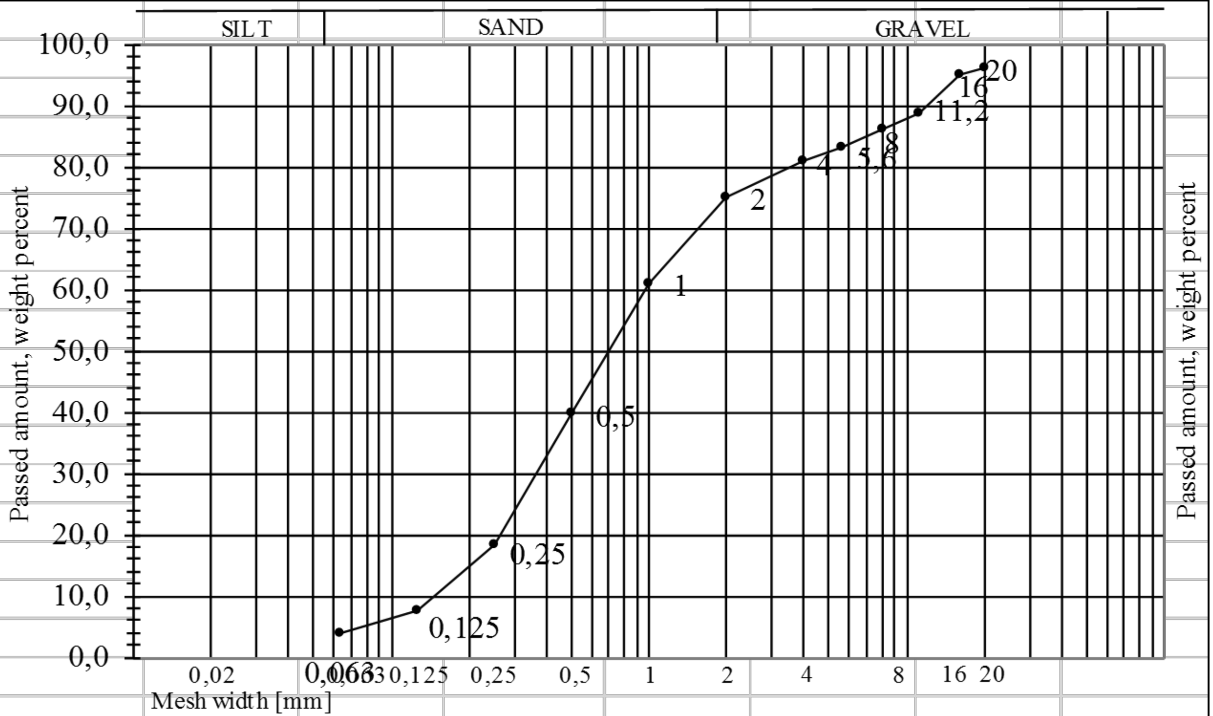
Bowl	
Before drying [g]	607,2
After drying [g]	432,5
Water [g]	174,7
Natural water ratio [%]	40

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	45%	50%	5%
fine	18%	21%	5%
medium	27%	10%	
coarse	0%	20%	
	100%		
	Gravely sand		

Sieve analysis

Project	19	Total sample weight [g]	625,2	Depth [m]	0,4
		Weight >20mm [g]	21,7	Shake time	7min

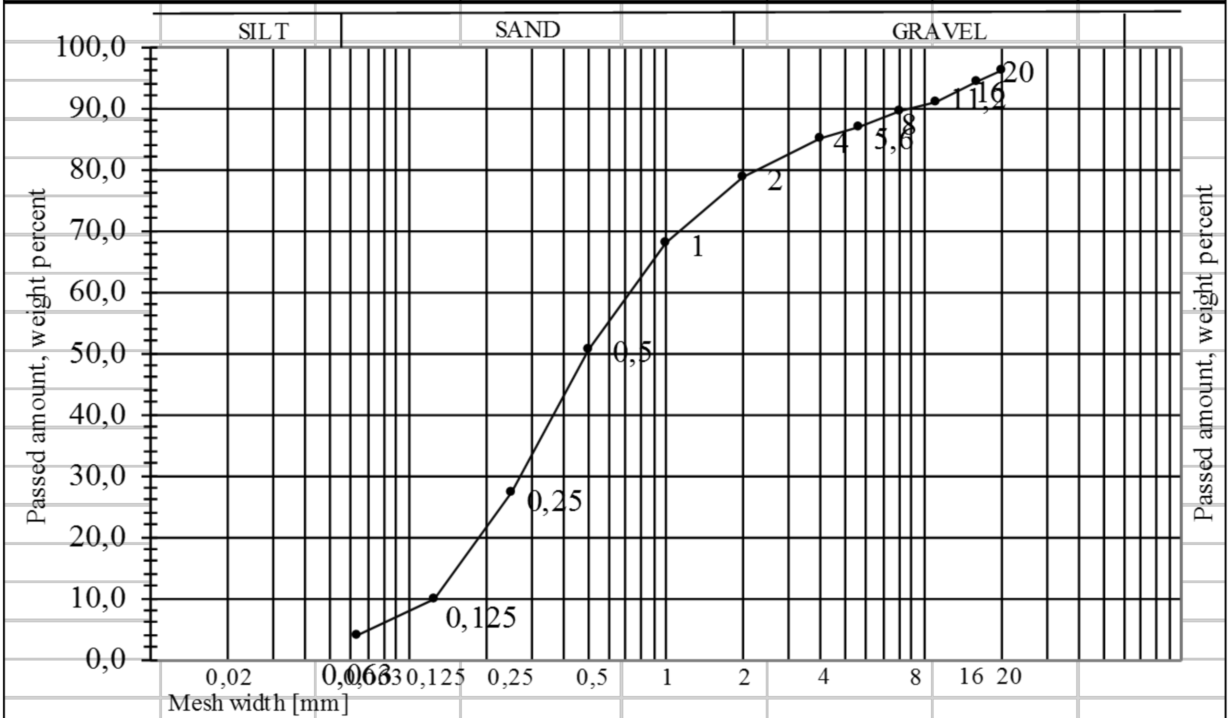


Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]	Bowl	
20	21,7	3,9	96,1	Before drying [g]	625,2
16	7,3	1,3	94,8	After drying [g]	559,0
11,2	34,3	6,1	88,7	Water [g]	66,2
8	15,0	2,7	86,0	Natural water ratio [%]	12
5,6	16,2	2,9	83,1	Analysis performed by	J. Utas, A. Lilliestierna
4	11,8	2,1	81,0	on	2015-04-14
2	34,1	6,1	74,9		
1	78,3	14,0	61,0		
0,5	119,4	21,3	39,6		
0,25	120,1	21,4	18,2		
0,125	59,0	10,5	7,7		
0,063	22,0	3,9	3,7		
Rest	21,0	3,7			
Sum	560,2	100,0			

	gravel	sand	silt/clay
total	25%	71%	4%
fine	8%	14%	4%
medium	13%	21%	
coarse	4%	35%	
	100%		
	Gravely sand		

Sieve analysis

Project	20	Total sample weight [g]	707,3	Depth [m]	0,55
		Weight >20mm [g]	23,3	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	23,3	3,8	96,2
16	10,6	1,7	94,4
11,2	20,8	3,4	91,0
8	9,3	1,5	89,5
5,6	16,9	2,8	86,7
4	10,5	1,7	85,0
2	39,3	6,4	78,6
1	65,6	10,8	67,8
0,5	105,6	17,3	50,5
0,25	142,6	23,4	27,1
0,125	105,7	17,3	9,8
0,063	36,9	6,0	3,8
Rest	23,0	3,8	
Sum	610,1	100,0	

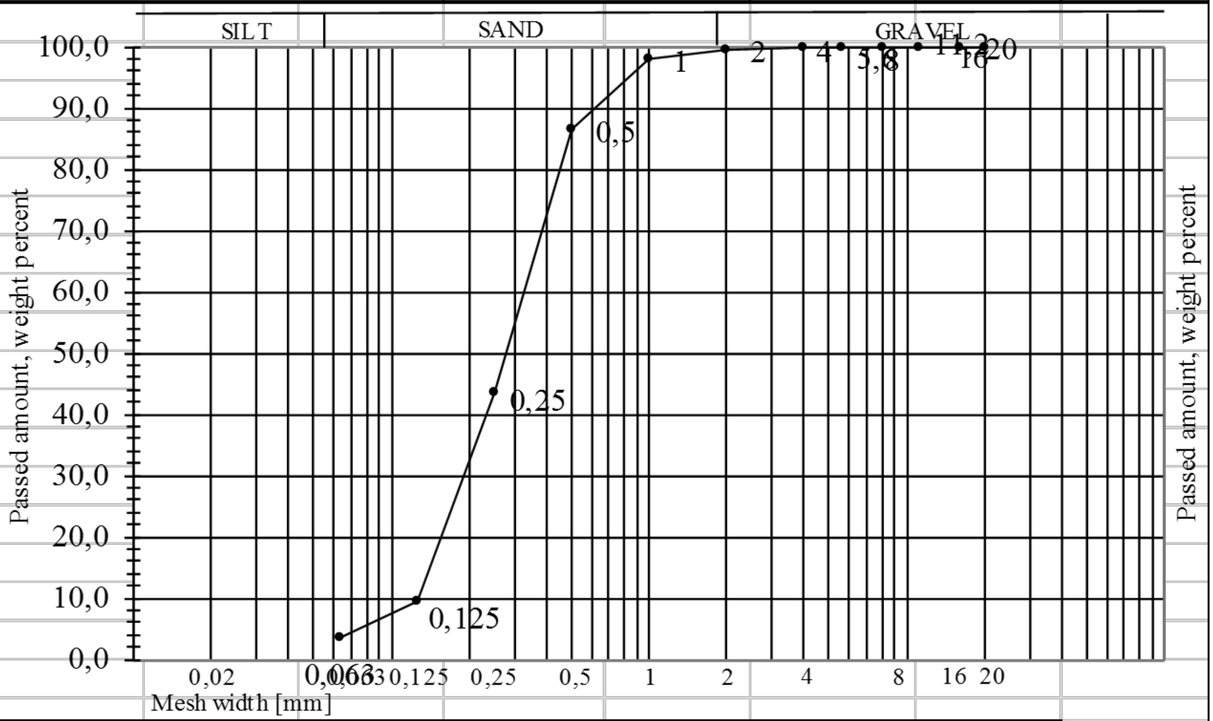
Bowl	
Before drying [g]	707,3
After drying [g]	610,0
Water [g]	97,3
Natural water ratio [%]	16

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	21%	75%	4%
fine	8%	23%	4%
medium	9%	23%	
coarse	4%	28%	
	100%		
	Gravely sand		

Sieve analysis

Project	21	Total sample weight [g]	554,0	Depth [m]	0,55
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	0,3	0,1	99,9
4	0,3	0,1	99,9
2	1,9	0,4	99,5
1	8,1	1,6	97,9
0,5	57,6	11,5	86,3
0,25	213,8	42,8	43,6
0,125	169,8	34,0	9,6
0,063	30,4	6,1	3,5
Rest	17,4	3,5	
Sum	499,6	100,0	

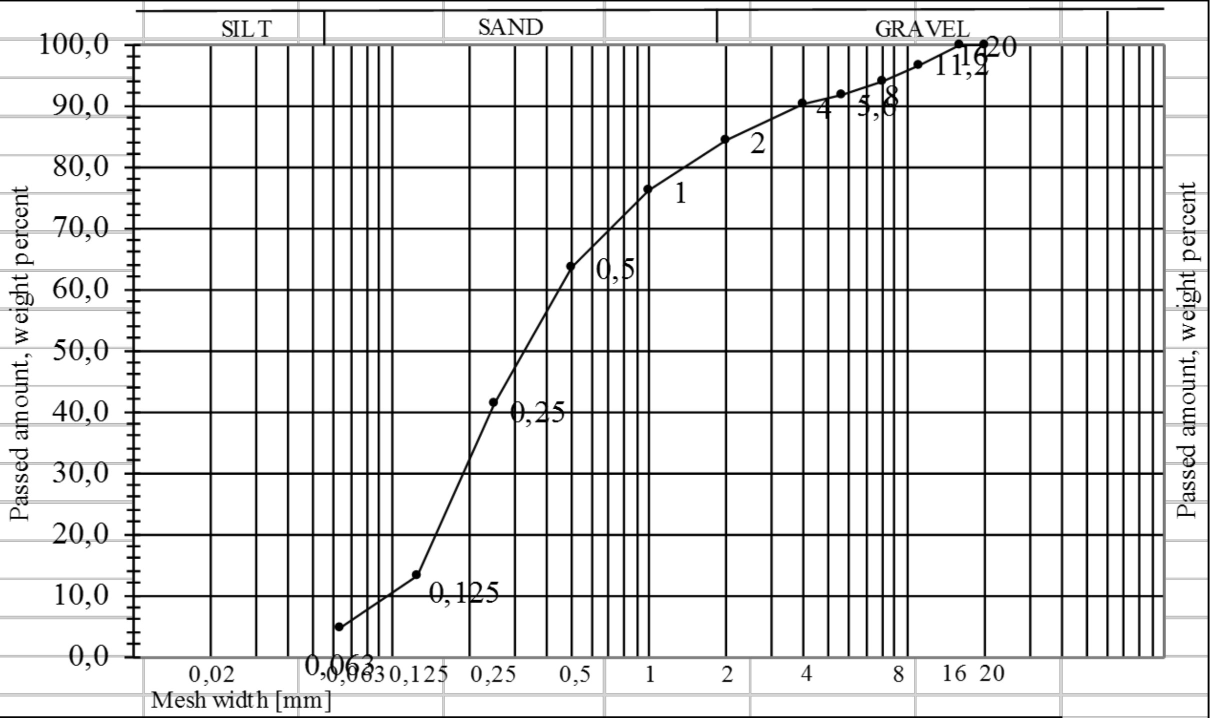
Bowl	
Before drying [g]	554,0
After drying [g]	498,8
Water [g]	55,2
Natural water ratio [%]	11

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	1%	96%	3%
fine	0%	40%	3%
medium	0%	43%	
coarse	0%	13%	
	100%		
	Medium sand		

Sieve analysis

Project	22	Total sample weight [g]	680,3	Depth [m]	0,55
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	22,6	3,7	96,3
8	15,7	2,6	93,7
5,6	12,0	2,0	91,8
4	10,1	1,7	90,1
2	36,7	6,0	84,1
1	49,0	8,0	76,1
0,5	76,6	12,5	63,6
0,25	137,1	22,4	41,2
0,125	170,4	27,9	13,3
0,063	52,2	8,5	4,8
Rest	29,2	4,8	
Sum	611,6	100,0	

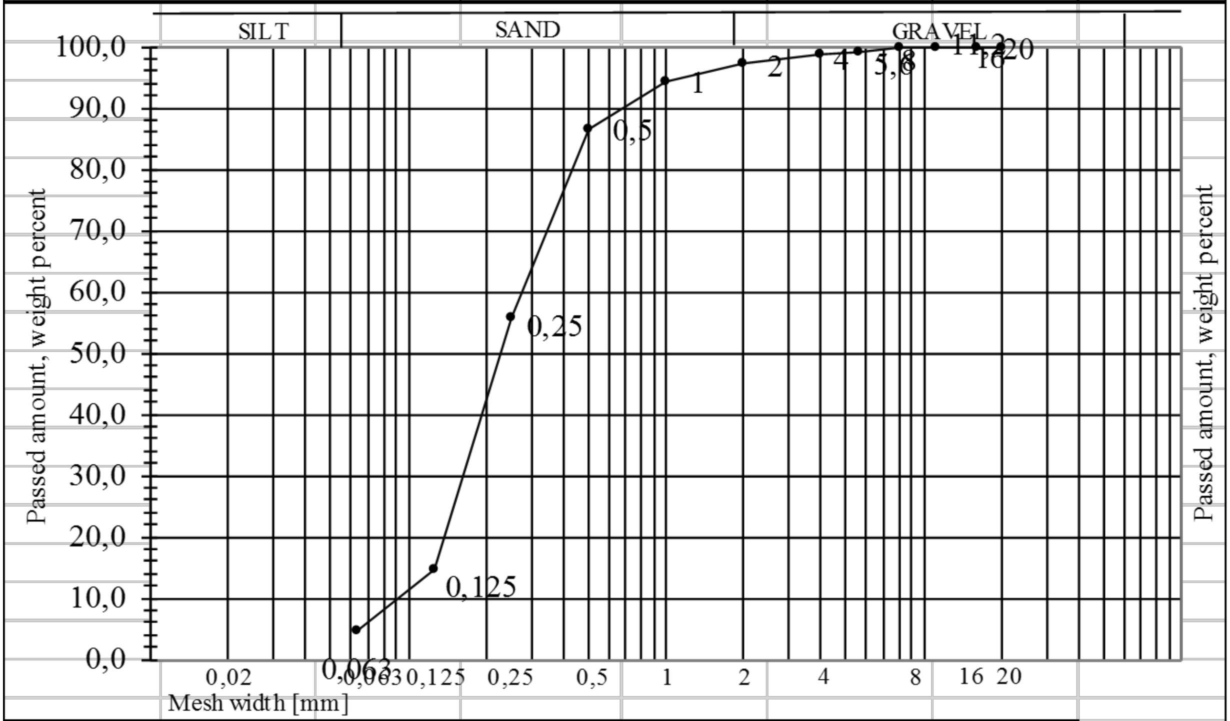
Bowl	
Before drying [g]	680,3
After drying [g]	612,1
Water [g]	68,2
Natural water ratio [%]	11

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	16%	79%	5%
fine	8%	36%	5%
medium	8%	22%	
coarse	0%	21%	
	100%		
	Fine sand		

Sieve analysis

Project	23	Total sample weight [g]	678,6	Depth [m]	0,55
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	0,0	0,0	100,0
5,6	6,6	1,1	98,9
4	2,1	0,3	98,6
2	9,3	1,5	97,1
1	16,8	2,7	94,4
0,5	48,5	7,8	86,7
0,25	192,8	30,9	55,8
0,125	256,4	41,1	14,7
0,063	62,2	10,0	4,7
Rest	29,6	4,7	
Sum	624,3	100,0	

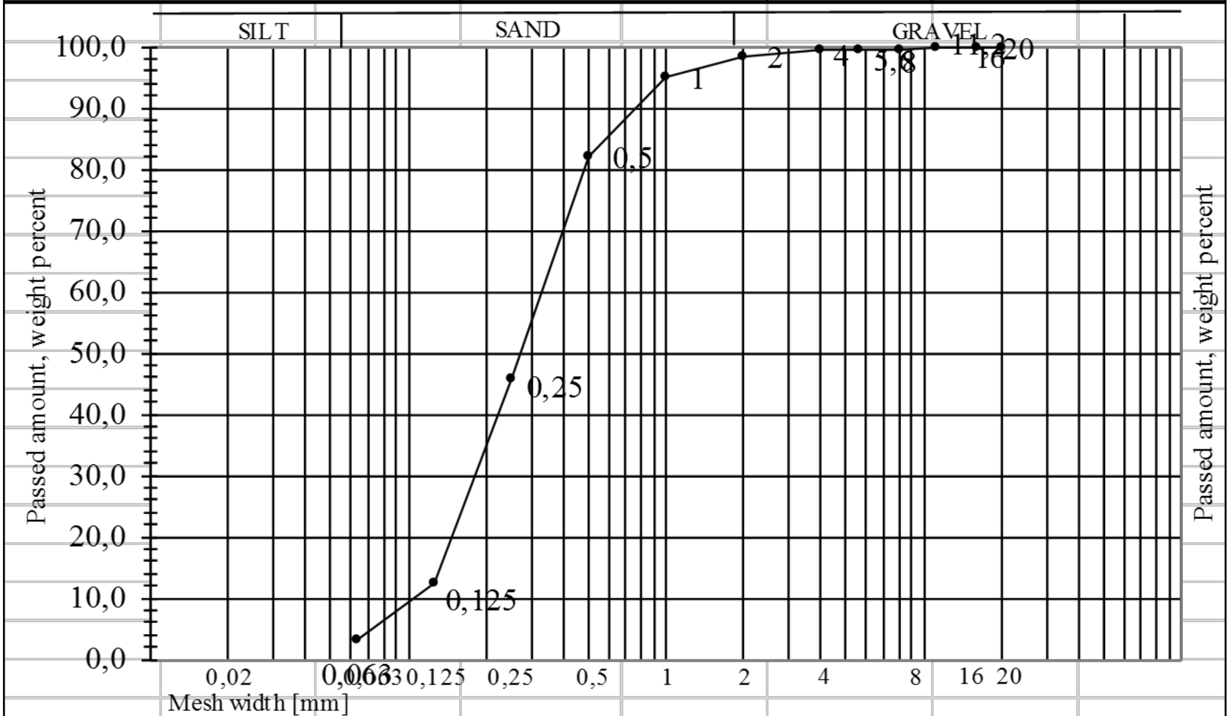
Bowl	
Before drying [g]	678,6
After drying [g]	622,9
Water [g]	55,7
Natural water ratio [%]	9

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	3%	92%	5%
fine	2%	51%	5%
medium	1%	31%	
coarse	0%	10%	
	100%		
	Fine sand		

Sieve analysis

Project	24	Total sample weight [g]	538,6	Depth [m]	0,55
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	0,0	0,0	100,0
8	1,8	0,4	99,6
5,6	0,3	0,1	99,5
4	1,0	0,2	99,3
2	3,4	0,8	98,5
1	15,3	3,5	95,0
0,5	56,5	12,9	82,1
0,25	158,3	36,3	45,8
0,125	145,2	33,3	12,5
0,063	40,8	9,3	3,2
Rest	13,8	3,2	
Sum	436,4	100,0	

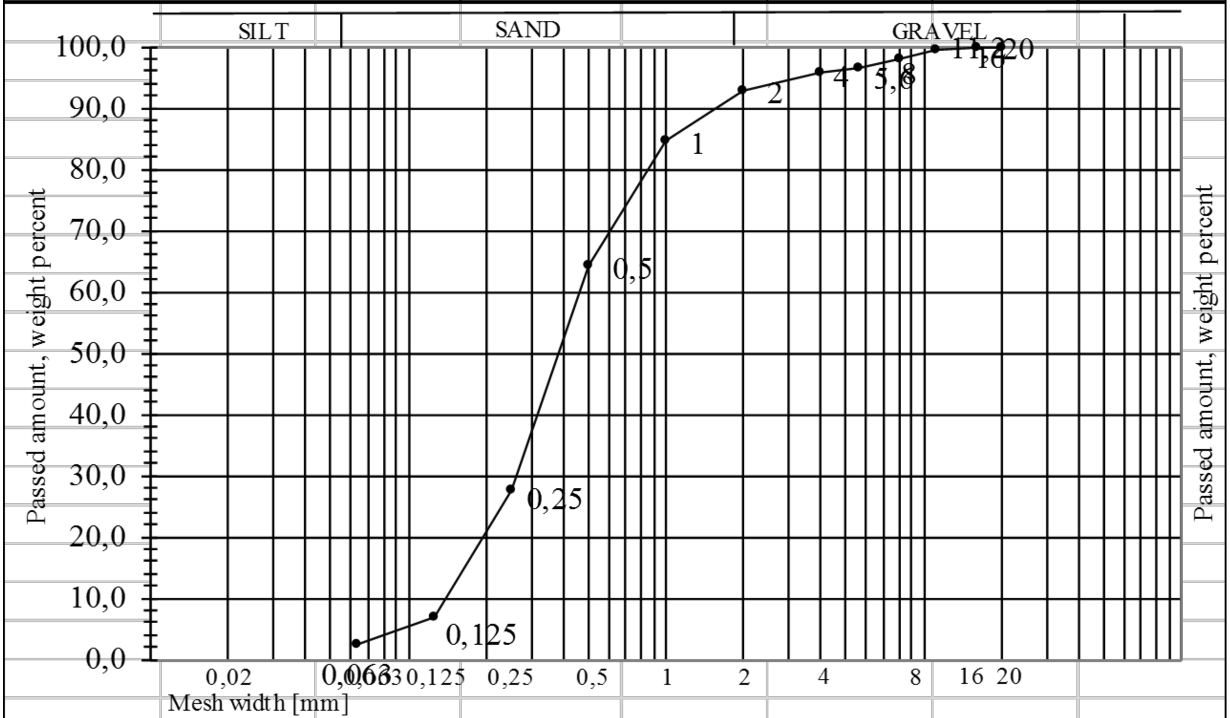
Bowl	
Before drying [g]	538,6
After drying [g]	436,0
Water [g]	102,6
Natural water ratio [%]	24

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	1%	95%	3%
fine	1%	43%	3%
medium	0%	36%	
coarse	0%	16%	
	100%		
	Fine sand		

Sieve analysis

Project	25	Total sample weight [g]	759,3	Depth [m]	
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	Retained aggregate [%]	Total passed weight [%]
20	0,0	0,0	100,0
16	0,0	0,0	100,0
11,2	4,3	0,6	99,4
8	10,8	1,6	97,8
5,6	8,3	1,2	96,6
4	5,0	0,7	95,9
2	21,7	3,2	92,7
1	56,1	8,2	84,5
0,5	140,0	20,4	64,1
0,25	251,9	36,7	27,4
0,125	140,2	20,4	7,0
0,063	31,2	4,5	2,5
Rest	16,9	2,5	
Sum	686,4	100,0	

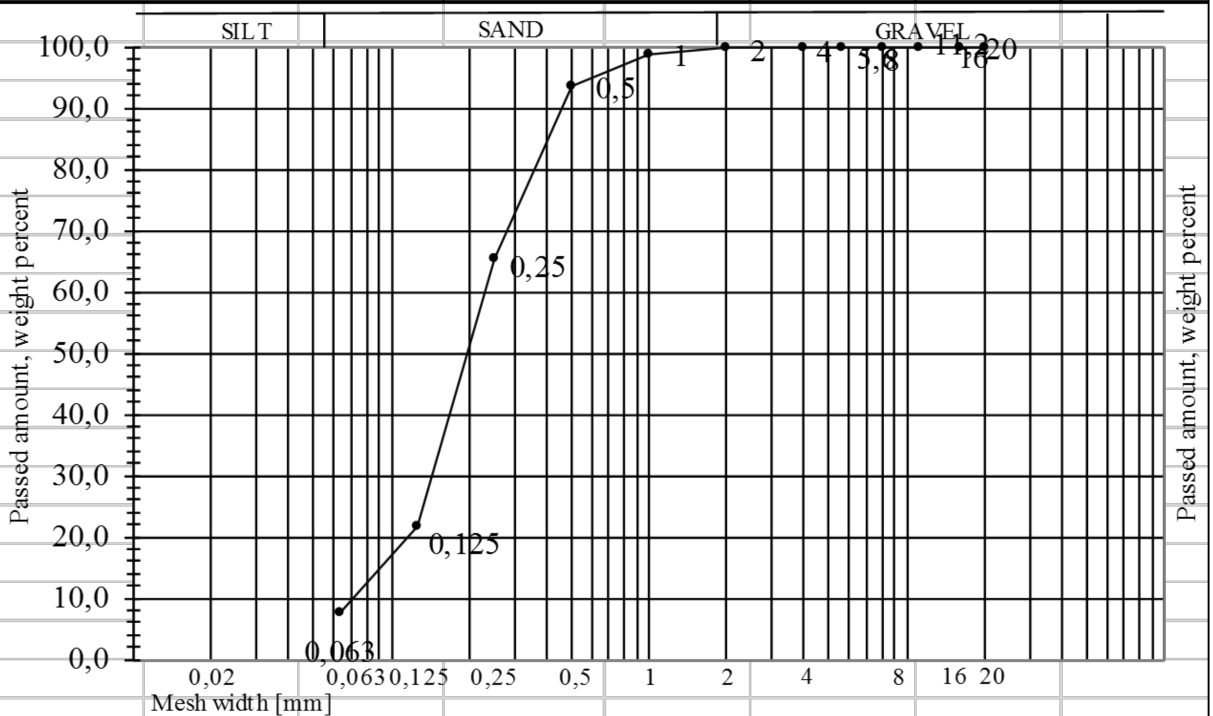
Bowl	
Before drying [g]	759,3
After drying [g]	686,8
Water [g]	72,5
Natural water ratio [%]	11

Analysis performed
by J. Utas, A. Lilliestierna
on 2015-04-14

	gravel	sand	silt/clay
total	7%	90%	2%
fine	4%	25%	2%
medium	3%	37%	
coarse	0%	29%	
	100%		
	Medium sand		

Sieve analysis

Project	26	Total sample weight [g]	688,3	Depth [m]	0,55
		Weight >20mm [g]	0,0	Shake time	7min



Sieve mesh width [mm]	Retained aggregate [g]	[%]	Total passed weight [%]	Bowl	
20	0,0	0,0	100,0	Before drying [g]	688,3
16	0,0	0,0	100,0	After drying [g]	631,9
11,2	0,0	0,0	100,0	Water [g]	56,4
8	0,0	0,0	100,0	Natural water ratio [%]	9
5,6	0,8	0,1	99,9	Analysis performed by	J. Utas, A. Lilliestierna
4	0,4	0,1	99,8	on	2015-04-14
2	1,0	0,2	99,7		
1	5,2	0,8	98,8		
0,5	33,4	5,3	93,5		
0,25	177,5	28,1	65,4		
0,125	276,2	43,7	21,7		
0,063	90,0	14,3	7,4		
Rest	46,9	7,4			
Sum	631,4	100,0			

	gravel	sand	silt/clay
total	0%	92%	7%
fine	0%	58%	7%
medium	0%	28%	
coarse	0%	6%	
	100%		
	Fine sand		