**South West Link - Feedback of experience from thermal design**

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# Contents

# 1 Introduction

The purpose of this feedback of experience is to gain further knowledge and develop the design and performance within the field of thermal issues regarding ground installed high voltage cables.

The thermal resistivity of natural soil and backfill affects the cable temperature and thereby also the dimensioning of the whole cable trench. A high thermal resistivity results in a much higher cable temperature compared to low thermal resistivity at a given energy loss in transfer.

There are many parameters that affect the thermal resistivity around cables in this type of installations. It is not the mean that will be dimensioning, instead it is the highest thermal resistivity. A very small part of the total stretch, the weakest link, will be dimensioning and this part is on the scale of 1-5 m which corresponds to 0.005 % for a cable stretch of 100 km.

# 2 Methodology

In order to evaluate and optimize the thermal design a couple of questions regarding thermal issues were stated:

- Did the construction documents regarding ground conditions match reality?
- What was possible to achieve regarding construction documents and requirements, especially concerning thermal backfill (thermal sand surrounding cables)?
- To what extent was active design a part of the implementation?

Through self-monitoring, control samples and interviews with involved persons, the final construction was set in relation to pre-design, design and construction documents. Following cable stretches were selected for evaluation 309-312, 332-333, 505-507, 529-533 and at 12 joint bays of the cable within these stretches. Theses stretches were in a construction phase that suited well in time for taking control samples, beside that they were randomly selected.

Temperature measurements on power cables with fiber optic cables (DTS) can, when power is switched on, be used as a further step to evaluate and verify the dimensioning properties.

# 3 Basis for thermal design

## 3.1 Natural soil

The initial design was conducted with a thermal resistivity of 1 m·K/W for all friction soils surrounding the cables, the upper soil which was perceived to be dryer was assessed to have a thermal resistivity of 1.4 m·K/W. After the start of pre-design, the question regarding thermal issues in ground was raised. A thorough ground investigation was then conducted by Sundberg (2011) in order to act as a basis for geothermal design. The results were then also used in order to set relevant requirements for cable sand properties. The investigation contained field measurements, statistical analysis and modelling and simulation of water content in time. Some of the results are presented in Figure 1 and Table 1. Observe that results are presented as thermal conductivity in Figure 1 (the inverse of thermal resistivity).

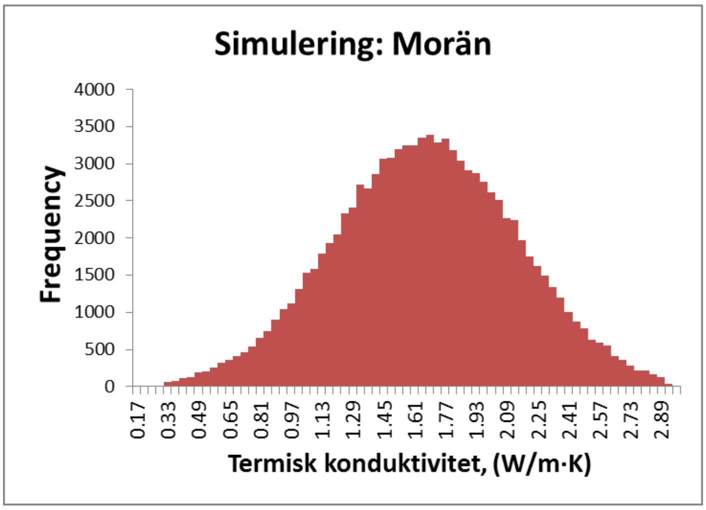



Figure 1 Monte Carlo simulation of thermal conductivity (W/(m·K)) for till (Sundberg et al, 2011).

Table 1 Results from Monte Carlo simulations of thermal resistivity ((m·K )/ W) for different soil types (Sundberg et al, 2011).

| **Soil type** | **1-percentile, ((m·K)/W)** | **5-percentile, ((m·K)/W)** | **Mean ((m·K)/W)** |
|---|---|---|---|
| Group A field | 0.93 | 0.77 | 0.53 |
| Group A laboratory | 0.89 | 0.79 | 0.64 |
| Group B field | 2.17 | 1.27 | 0.70 |
| Group B laboratory | 2.27 | 1.54 | 0.83 |

Following soils was classified into different types due to relatively large differences in thermal resistivity (Sundberg et al, 2011).

- Type A. Normal soil, clay, silt, clayey- silty- and sandy till independent of groundwater level, which assumes to keep normal ground moisture all year around.

- Type B. Dry soil. Cohesion or friction soil, sand, gravelly sand, gravel- and blocky till, which have a groundwater level deeper than 1.5 m.

- Type C. Normal moist organic soil. Moist or wet peat, mire or other organic soil with a groundwater level shallower than 1.5 m in mean.

- Type D. Dry organic soil. Dry peat and other organic soil with a groundwater level deeper than 1.5 m in mean

- Type E. Very wet organic soil. Very wet peat and mire with a groundwater level shallower than 0.5 m all year around.

## 3.2 Design of cable trench and cable dimensions

The thermal design of the cable was initially made on the assumption of a thermal resistivity of 1 (m·K)/W in surrounding natural soil. More precise geothermal design was incorporated in a later stage in 2011 and was based on the investigation made by Sundberg et al (2011), see chapter 3.1. During design, the dimensions of the cables were increased in two steps. In 2012 the cable dimensions were changed to better and coarser dimensions, 2010 mm$^2$ and 2590 mm$^2$ both of aluminium, which to some extent should compensate for ground conditions with high thermal resistivity, e.g. type B soils. Previous dimensions were 1600 mm$^2$ copper and 1800 mm$^2$ aluminium. Final design for dry soils (type B) was performed with a highest acceptable thermal resistivity of 1.5 m·K/W which can be compared to the measured 5-percentile from investigations made by Sundberg et al (2011). An important part in the design was that geothermal active design would be performed for cable dimension 2010 mm$^2$, if these cables were placed in trench with ground conditions consisting of soil type B with thermal resistivity of 1.5 (m·K)/W or higher (Emme, 2012).

Thermal soil type is one out of several affecting parameters that governs the resulting temperature in cables. Other parameters that affect the cable temperature are cable depth, amount of cables, separation distance between cables, cable dimensions, electrical load in cables, natural undisturbed soil temperature and variations. This together with additional cases due to for example road crossings resulted in 74 different design cases of cable trenches (sub groups included). An illustration of a case is presented in Figure 2.

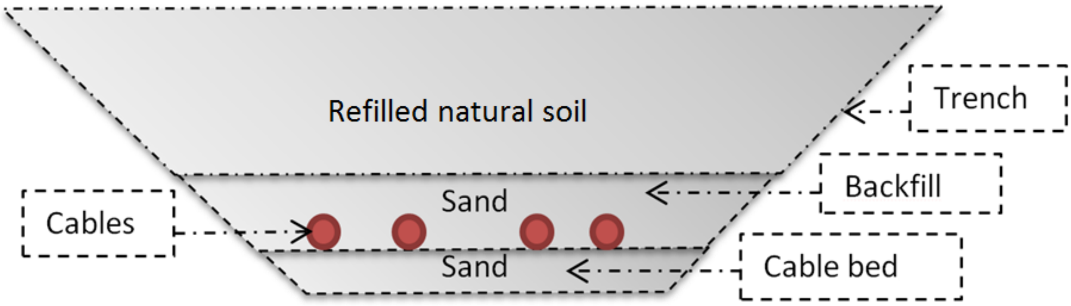



Figure 2. Illustration of cable trench, the geometry and materials differs between the 74 design cases.

## 3.3 Thermal sand in cable bed and backfill

As a basis for requirements regarding thermal material for cable bed and backfill an investigation was conducted by Sundberg and Sundberg (2012). 14 different fractions of sand from 7 different suppliers were evaluated in order to find suitable requirements for degree of compaction, densities, water retention capacity, moisture content etc. with the purpose of achieving good thermal backfills that could meet the requirements connected to limitations in cable temperature.

Several soil fractions with varying mineral content were analysed regarding thermal resistivity. The different fractions were mixed with different moisture content and compared with each other, with respect to thermal resistivity. Since there are several properties such as degree of compaction, quartz content and moisture content that affects the thermal resistivity rather than the material itself, the requirements are based on both material and implementation (Sundberg and Sundberg, 2012).

Where to use different sand types mainly depend on natural soil types and their thermal resistivity established by Sundberg and Wrafter (2011). A soil type with high thermal resistivity needs to be compensated by a cable bed and backfill with low thermal resistivity. Thermal sand type A (low thermal resistivity) should be matched with soil type A. Thermal sand type B (very low thermal resistivity) should be matched with soil types B-E.

# 4 Technical requirements regarding thermal sand

The technical requirements for material and implementation for cable sand, Garin and Sundberg (2013) was mainly based on different parameters governing thermal properties in cable sands evaluated by Sundberg and Sundberg (2012). The purpose of the document was to state requirements for sand material and implementation within the cable trench.

The requirement differs in two types of material. Sand type A and sand type B as mentioned in chapter 3.2. In following tables some of the important requirements are highlighted regarding material and implementation.

Samples of cable sand shall be taken before and after delivery, which shall fulfil the material requirements stated in Table 2 and Figure 3 below.

Table 2 Requirements for material and compaction (Garin and Sundberg, 2013).

| **Material requirements** | Sand type A | Sand type B |
|---|---|---|
| Quartz content | ≥ 30% | >85% |
| Material fraction 0/4 [mm] | Yes | Yes, or 0/2 if fine soil ≤ 15% |
| Optimal dry density at heavy compaction or corresponding modified proctor compaction | ≥ 1950 kg/m$^3$ | ≥ 1950 kg/m$^3$ |

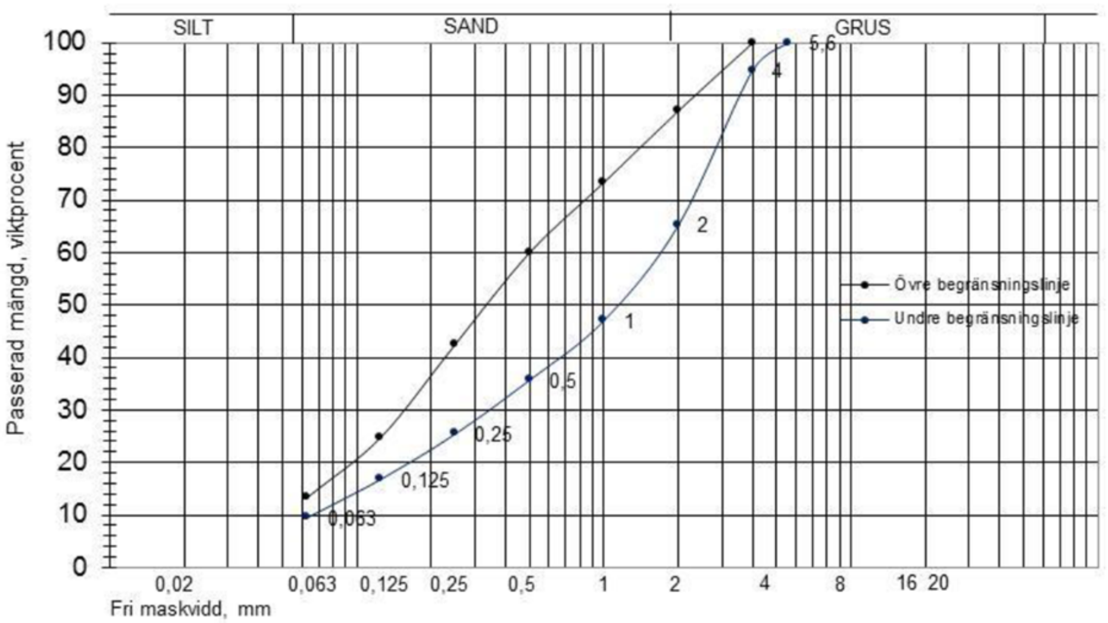



Figure 3 Particle size distribution curve for 0/4 material. Only material between lower and upper limitation curve is accepted. The lower limitation curve can be neglected for 0/2 material but fine soil need to be ≤ 15% (Garin and Sundberg, 2013).

Supplier shall deliver compaction curves (at heavy compaction or corresponding modified proctor compaction) with sieve test for at least 600g (with pre wash), optimal dry density, determine water content. Test should be performed on 10 samples from different spots in each quarry (5 sub samples/sample). In addition to this, mineral content should be determined at lab with certified methods for three samples.

Table 3 Requirements for compaction of sand in trench (Garin and Sundberg, 2013).

| **Requirements for compaction in trench** | Sand type A and B |
|---|---|
| Dry density during compaction | ≥ 1850 kg/$m^3$ |
| Moisture content during compaction (weight of water divided with weight of dry material) | ≥ 5% |
| Minimum compaction for single measurement in regard to heavy compaction or modified proctor compaction. Minimum compaction for mean values for each control object within parentheses. | 85 % (90%) |

Moisture content should also be determined for each control object.

## 4.1 Requirement on control of compacted material

For sand surrounding cables (backfill), density of compacted material should be controlled with nuclear density gauge, backscatter to 100 mm depth. Measurements on cable bed and sand filling with no nearby cables can be made with direct transmission (with extended rod). Deviations in measurements shall be less than 5 kg/m3, which is govern by the measuring time, BS 4 minutes and DT 1 minute. The required control for compacted material can be found in Table 4. An illustration of the function of a nuclear density gauge can be seen in Figure 4.

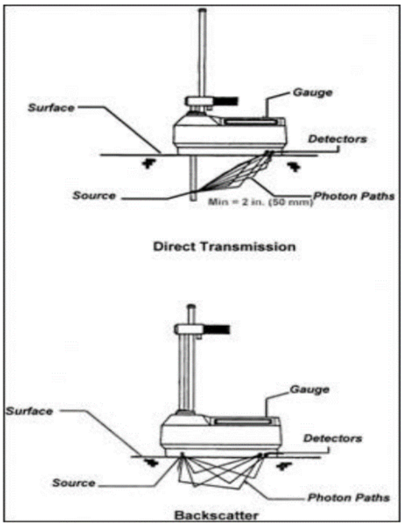



Figure 4. Nuclear density gauge (www.dot.state.oh.us)

Table 4 Required control measurements on cable sand (Garin and Sundberg, 2013).

| **Material control** | Frequency along cable stretch [m] | Area of control/ control object | Testing points |
|---|---|---|---|
| Cable bed | 500 | Measure points equally spread along 100m | 5 |
| Backfill (cable sand surrounding cables) | 500 | Measure points equally spread within 10 $m^2$ | 5 |
| Cable bed | Every second joint bay | Outside of cable package but within trench. | 10 (5 with backscatter + 5 with direct transmission) |

# 5 Calibration of compaction control

During contract time the method for measuring the degree of compaction, dry density, moisture content etc. needed to be changed from direct transmission (DT 0.3m) to backscatter (BS) and DT 0.1m in order to not damage the cables. This changed the conditions for evaluating measurements with technical requirements, which were based on DT 0.3m. Due to deviations in results regarding degree of compaction during measurements at joint bay 210 in late summer 2013, a calibration program was set up in order to look at deviations between the two methods, BS and DT. Deviations were expected to some extent but deviations in mean values between the methods were though larger than predicted; therefore a rather comprehensive investigation was performed at joint bay 522 in order to compare the two methods and to find ways in dealing with uncertainties from measuring methods.

The analysed area at joint bay 522 was approximately 6 $m^2$ and contained totally 180 measurements at four different depths in cable bed, surface, 0.1 m, 0.2 m and 0.3 m. 11 rubber balloon measurements were also carried out for comparison with densities and moisture contents measured with BS and DT. A rubber balloon measurement is carried out by digging a hole, collect the sand from the hole in a container, weigh it before and after drying in an oven. Fill the hole with a rubber balloon through pressure, connected to a cylinder with water to receive the volume in the hole. Densities and moisture content of the sand can then be calculated and thereby also the degree of compaction by comparing it to optimal proctor density. Figure 5 below illustrates the large deviation between methods and measurements.

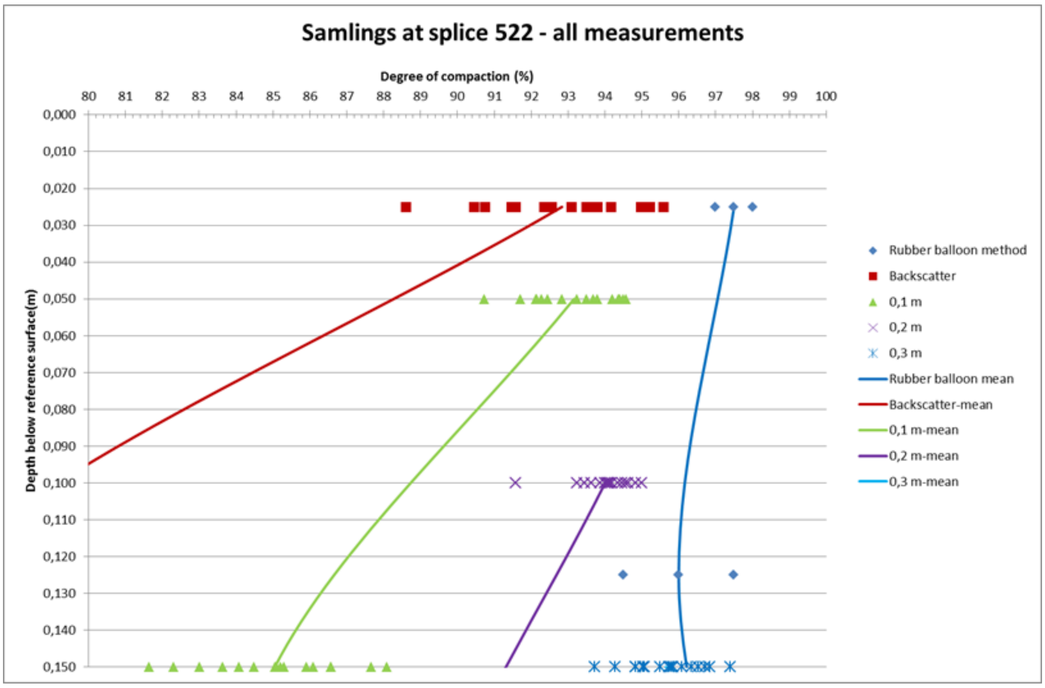



Figure 5 Measurements for calibration, deviations in results compared to rubber balloon results (Garin, 2014).

With respect to the result in this investigation, the conclusion and recommendation below were given, based on mean values (Garin, 2014).

If no separate determination on moisture content is performed in lab, measuring values regarding degree of compaction shall be adjusted with following percentage units:

- Backscatter adds 4.5 %-units
- Direct transmission, rod extended 0.1m adds 2,5%-units
- Direct transmission, rod extended 0.2m adds 1,5 %-units
- Direct transmission, rod extended 0.3m adds 0%-units

Even though the recommended adjusted values were given, a large deviation existed between measurements with density gauge and what has been analysed with rubber balloon method.  Figure 6 illustrates single measurements at joint bay 522 for BS and DT 0.1m, DT 0.2 and DT 0.3 measurements compared to rubber balloon measurements performed at the same location. The figure shows that measurements with the nuclear density gauge have a large uncertainty and results in a much lower degree of compaction than what is analysed with rubber balloon. As in Figure 5 above most inaccurate measurements are from backscatter, in some cases with a deviation of 15 % compared to rubber balloon measurements (lab). Best results are achieved with DT 0.3m but still with a deviation up to 6%, see Figure 6.

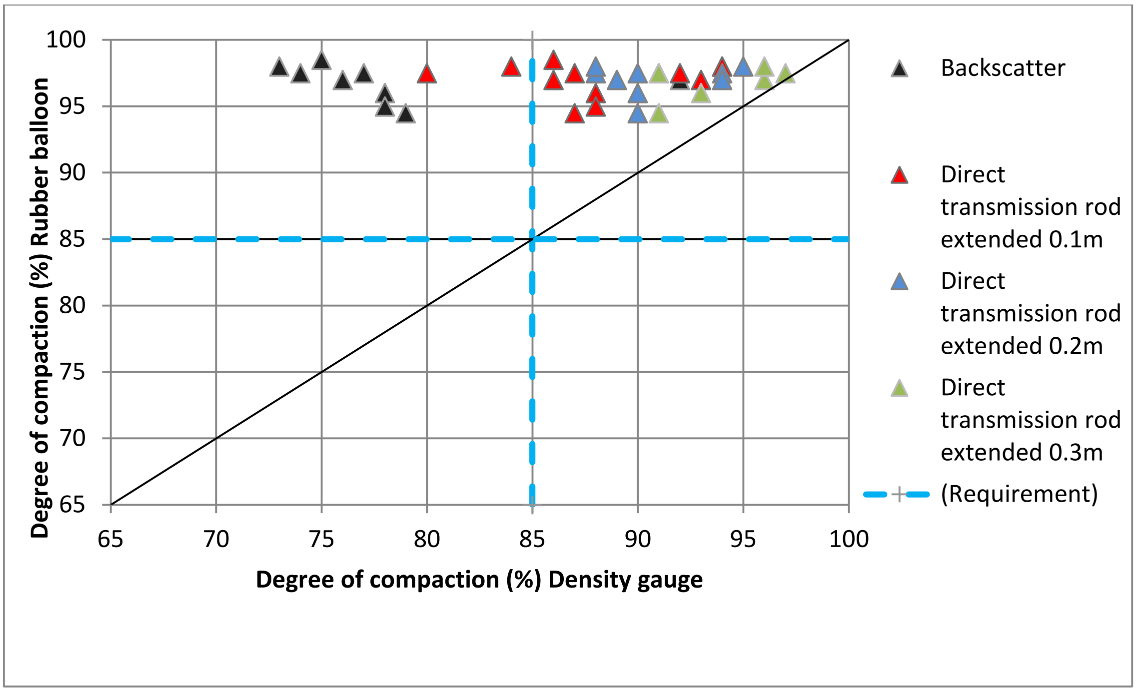



Figure 6 Measurements in field with density gauge vs rubber balloon measurements for joint bay 522. Rubber balloon results are assessed to be the true degree of compaction. Blue dashed line symbolizes the requirement regarding degree of compaction.

# 6 Self-monitoring during implementation

The following stretches were randomly selected for investigation in this feedback of experience; 309-312, 332-333, 505-507, 529-533 and at 12 joint bays within these stretches. In order to verify that the implementation and control have been properly performed, a check has been done in this feedback of experience, final construction documents vs self-monitoring. Relevant information from final construction documents regarding sand type A and B are:

- The Cable beds shall always consist of sand type A when cables are placed directly on top of cable bed. Thickness of at least 150 mm on stretches and at least 500 mm at joint bays

- The backfill shall consist of either sand type A or B, all depending on natural soil type which is divided into soil type A-E, see chapter 3.1. Sand type A is placed were Soil type A exists and sand type B is placed were soil types B-E exists.

- Backfill at joint bays always consist of sand type B, regardless soil type.

## 6.1 Material properties

Out of the 15 stretches, a big difference was observed regarding documents reported to the client. Documents for stretches 309-312 and 332-333 contained low or no information regarding sand types in cable beds and backfills, quartz content, lab reports from proctor tests and no information about the quarry from which the sand material derives from. Some particle size distribution curves exist but they only confirms that 0/4 material have been used and are within limitation lines. Due to lack of reported documents from 7 of the 15 investigated stretches, it cannot be verified that the requirements have been fulfilled, nor can the opposite be stated.

For cable stretches 505-507 and 529-533 all documentation exist and confirms that almost all requirements are fulfilled and implementation have been correctly performed. Only one question mark can be found for stretch 529 section 580/100 were sand type B has been placed as backfill. According to construction documents sand type A should have been used as backfill. As long as type B has been used instead of type A it is no problem, due to better thermal properties. On the other hand, the fact that this has occurred testifies that misplacement with type A instead of Type B more likely may exist. That would result in a thermally inferior section.

## 6.2 Measurements during execution

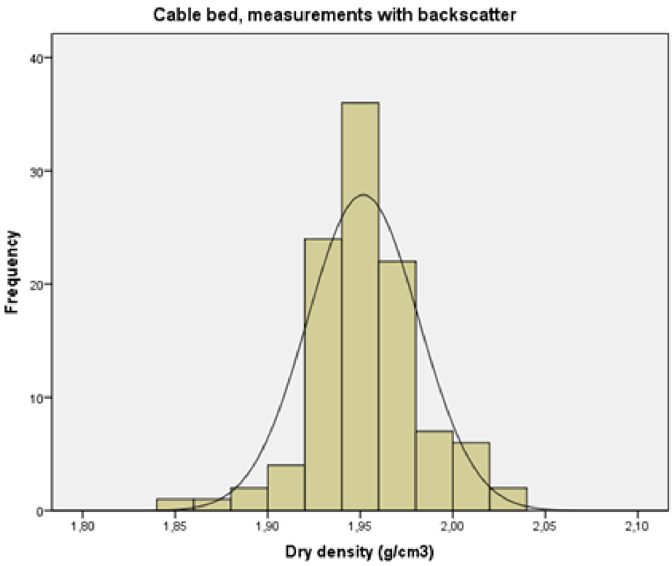
The contractor has performed control measurements with nuclear density gauges during their execution. Measuring results includes bulk density, dry density, moisture content, degree of compaction and amount of water (g/cm$^3$).

The measurements have been performed with BS- method on backfill. At joint bays and cable bed both BS- and DT-methods have been used. The results that are presented in this chapter are adjusted according to chapter 5. With adjustment it means that additional percentages are added to the result in order to compensate for errors in measurements with nuclear density meter. Data in Figure 7 is assessed to be normally distributed, data in Figure 8 and Figure 9 are expected to diverge from that distribution. Note that the histograms presented in Appendix 1 are not adjusted according to chapter 4.

There are many parameters that affect the thermal resistivity around cables in this type of installations. A very small part of the total stretch will be dimensioning and this part is on the scale of 1-5 m which corresponds to 0.005 % of the total stretch in this project (Sundberg et al, 2012). This means that e.g. all minimum values from measurements for the different parameters should be included in the evaluation against requirements because they represent 0.5-2 % of all measurements. This is on the other hand only true if these minimum values can be assessed to be 100 % correct, which of course is impossible to guarantee due to potential instrument and handling errors. In this investigation results are treated as 100% correct since the minimum values are too important to dismiss without an obvious reason.

## 6.3 Measurements on cable bed

This chapter highlights the measurements with backscatter method on cable bed, measurements with direct transmission are presented in Appendix 1 together with measurements on backfill. In histograms below 105 BS-measurements are presented. Measurements have been correctly performed according to requirements regarding measuring frequency and the degree of compaction is fulfilled, after adjustment with addition of around 4.5 %-units (results for dry density and degree of compaction are multiplied with 1.05). Measurements with the BS-method have only been for 2 minutes instead of required 4, this affects the precision of density determination. How much this has affected the total result is hard to say but a larger spreading in the population is expected. Measurements of moister content are difficult with a nuclear density gauge and the spreading in results confirms that, see Appendix 1. Even though a large spreading can be seen, the requirement of 5 % moisture content is fulfilled.



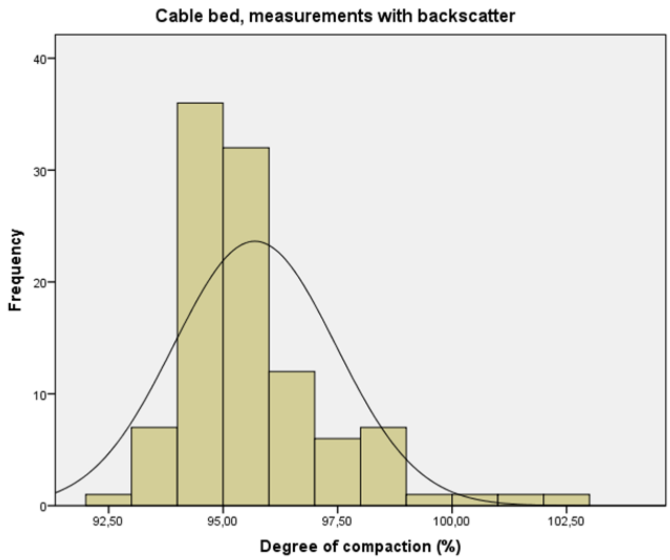

**Statistics**

Dry density (g/cm3)

| | | |
|---|---|---|
| N | Valid | 105 |
| | Missing | 0 |
| Mean | | 1,9516 |
| Median | | 1,9488 |
| Std. Deviation | | ,03004 |
| Minimum | | 1,85 |
| Maximum | | 2,04 |
| Percentiles | 5 | 1,9008 |

Figure 7 Dry density from measurements with backscatter, values are adjusted according to chapter 5.

Figure 7 shows a plot of dry density measured with backscatter at cable bed and with adjusted measuring values. The required 1.85 g/cm$^3$ is fulfilled for the whole population and the mean value is 1.95 g/cm$^3$.



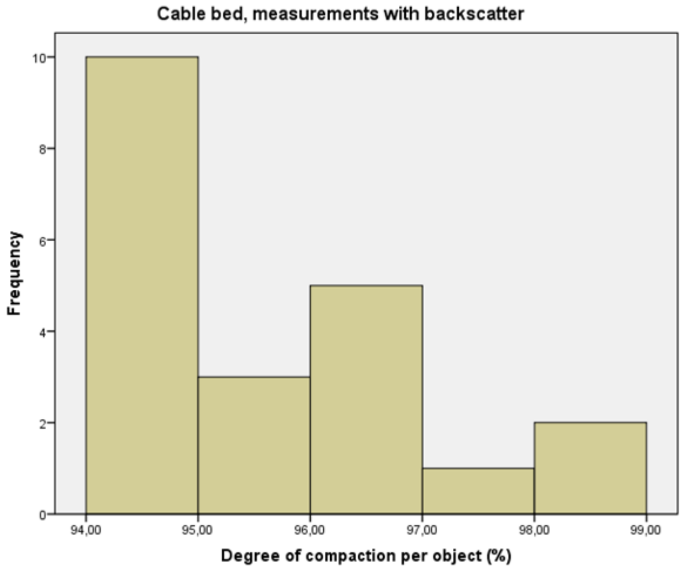

**Statistics**

Degree of compaction (%)

| | | |
|---|---|---|
| N | Valid | 105 |
| | Missing | 0 |
| Mean | | 95,6900 |
| Median | | 95,5500 |
| Std. Deviation | | 1,77181 |
| Minimum | | 92,40 |
| Maximum | | 102,90 |
| Percentiles | 5 | 93,4500 |

Figure 8 Degree of compaction from single measurements with backscatter, values are adjusted according to chapter 5

Figure 8 above shows all single measurements with backscatter at cable bed after adjustment of measuring values. Required value was 85 % which is fulfilled with a large margin.




**Statistics**

Degree of compaction per object (%)

| | | |
|---|---|---|
| N | Valid | 21 |
| | Missing | 84 |
| Mean | | 95,7000 |
| Median | | 95,5500 |
| Std. Deviation | | 1,41986 |
| Minimum | | 94,50 |
| Maximum | | 98,70 |
| Percentiles | 5 | 94,5000 |

Figure 9 Degree of compaction per object from measurements with backscatter, values are adjusted according to chapter 5

Compared to single measurements the mean for the degree of compaction per object are presented in Figure 9. This means that the mean of 5 single measurements within a stretch of 100 m are analysed as an object. The result shows that the required degree of compaction of 90 % is fulfilled.

## 6.4 Measurements on backfill and joint bays

Measurements on backfill and joint bays showed to fulfil the requirements regarding frequency and degree of compaction when adjusted values are used, both with BS- and DT-method. No abnormal trends can be seen compared to measurements on cable bed but results regarding dry density, degree of compaction and moisture content are lower and would not fulfil requirements without adjustment. Results are presented in Appendix 1.

# 7 Chalmers control samples

In April 2014 Chalmers were at site and took additional samples from cable bed at stretches 332, 333, 506 and 507 for analysis in lab. Following parameters were investigated and presented in diagrams:

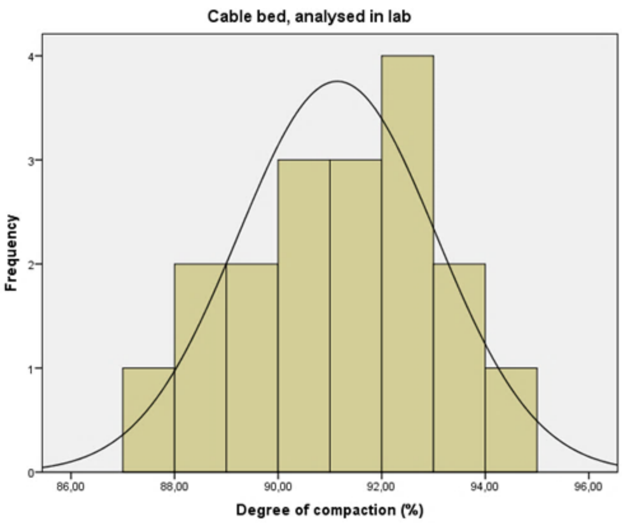
- Thermal resistivity (m·K/W)
- Dry density (kg/m$^3$)
- Degree of compaction (%) dry density in relation to Proctor.
- Moisture content % (weight of water divided with weight of dry material)
- Volumetric water content (%)
- Degree of saturation (%)

In contrast to measuring results with BS and DT-method from self-monitoring, these samples are analysed in lab. This means that these results can be compared to requirements without adjustments. According to construction documents, all samples are of sand type A. 9 of 18 samples derives from cable stretch 506 and 507. For these two stretches it can be verified through self-monitoring documents that cable bed consist of sand type A (Dalby 0/4). Material type for the other 9 samples from stretches 332 and 333 is according to construction documents sand type A but it cannot be verified through self-monitored documents (quarry is also unknown), see Table 5 below. According to Sabel (2014), no overall documentation exists or has been created by the contractors regarding placement of sand types, except from construction documents. According to Ingelson (2014) the documentation that has been provided to this feedback of experience is all that can be found.

Table 5 Samples taken by Chalmers in April 2014

| Sample | Sand type at cable bed according to construction documents | Quarry/material according to self-monitoring | Cable stretch | Section |
|---|---|---|---|---|
| H54 | A | Unknown | 332 | 381/760 |
| H7 | A | Unknown | 332 | 381/780 |
| H69 | A | Unknown | 332 | 381/880 |
| H62 | A | Unknown | 332 | 381/980 |
| H72 | A | Unknown | 332 | 382/100 |
| H73 | A | Unknown | 332 | 382/180 |
| H71 | A | Unknown | 333 | 383/080 |
| H56 | A | Unknown | 333 | 383/180 |
| H48 | A | Unknown | 333 | 383/300 |
| H35 | A (verified) | Dalby 0/4 | 506 | 521/012 |
| H11 | A (verified) | Dalby 0/4 | 506 | 521/160 |
| H24 | A (verified) | Dalby 0/4 | 506 | 521/322 |
| H29 | A (verified) | Dalby 0/4 | 506 | 521/351 |
| H46 | A (verified) | Dalby 0/4 | 506 | 521/708 |
| H5 | A (verified) | Dalby 0/4 | 506 | 521/140 |
| H59 | A (verified) | Dalby 0/4 | 506 | 521/012 |
| H13 | A (verified) | Dalby 0/4 | 507 | 521/749 |
| H51 | A (verified) | Dalby 0/4 | 507 | 521/749 |

Maximal densities from Proctor test derives from self-monitored documents reported to the client (2050 kg/m$^3$), it cannot be verified that these values relates to the actual sand that has been sampled. If not correct, they are assessed to be conservative, which means that results regarding degree of compaction probably are slightly higher. According to the requirements, lowest value for degree of compaction is 85 % (single measurement). In Figure 10 below these results are presented and verifies that requirements are fulfilled and somewhat surprisingly similar to self-monitored values, without adjustments.



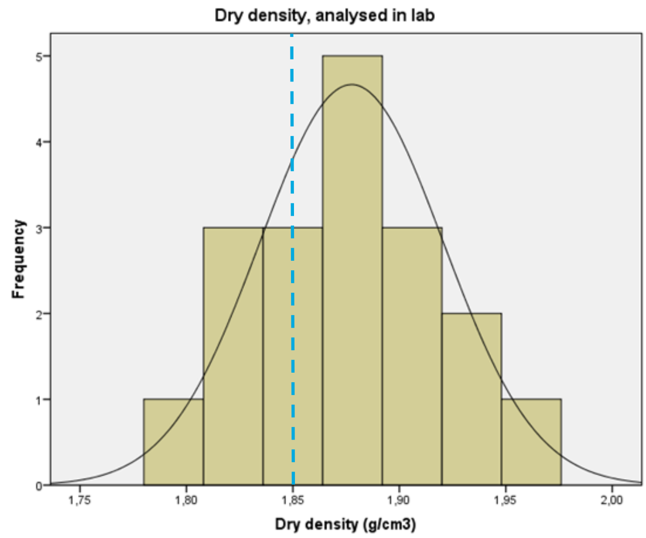

**Statistics**

Degree of compaction

| | | |
|---|---|---|
| N | Valid | 18 |
| | Missing | 0 |
| Mean | | 91,1422 |
| Median | | 91,3600 |
| Minimum | | 87,37 |
| Maximum | | 94,64 |
| Percentiles | 5 | 87,3700 |

Figure 10 Degree of compaction analysed in lab (dry density in relation to Proctor values from self-monitoring documents, 2050 and 2070 kg/m$^3$). Population is assessed to be normally distributed.

The dry density shows to be lower than required, the required dry density of 1850 kg/m$^3$ is not fulfilled for 20-25 % of the population. Figure 11 below shows the distribution of analysed samples. Consequences in thermal resistivity of not fulfilling the requirement of densities are illustrated in chapter 7.1 and Figure 15.




**Statistics**

Dry density (g/cm3)

| | | |
|---|---|---|
| N | Valid | 18 |
| | Missing | 0 |
| Mean | | 1,8776 |
| Median | | 1,8770 |
| Minimum | | 1,79 |
| Maximum | | 1,96 |
| Percentiles | 5 | 1,7910 |

Figure 11 Distribution of dry density analysed in lab. Population is assessed to be normally distributed. Blue dashed line symbolizes the requirement 1850 kg/$m^3$.

## 7.1 Measurements of thermal resistivity

Measurements of the thermal resistivity have been performed at three different times on the same 18 undisturbed samples mentioned above, first with natural moisture content at sampling occasion, at dry conditions after drying in oven and finally at saturated conditions. These three measurements are presented in diagrams below in relation to volumetric water content, degree of saturation, moisture content, dry density and degree of compaction.

In Figure 12 thermal resistivity is plotted against volumetric water content. A clear decrease in thermal resistivity can be seen when the volumetric water content raises from 0 to about 15 %, thereafter thermal resistivity seems to be stabilized. Compared to measurements made by Sundberg and Sundberg (2012), slightly lower thermal resistivity can be observed in samples taken by Chalmers in 2014.

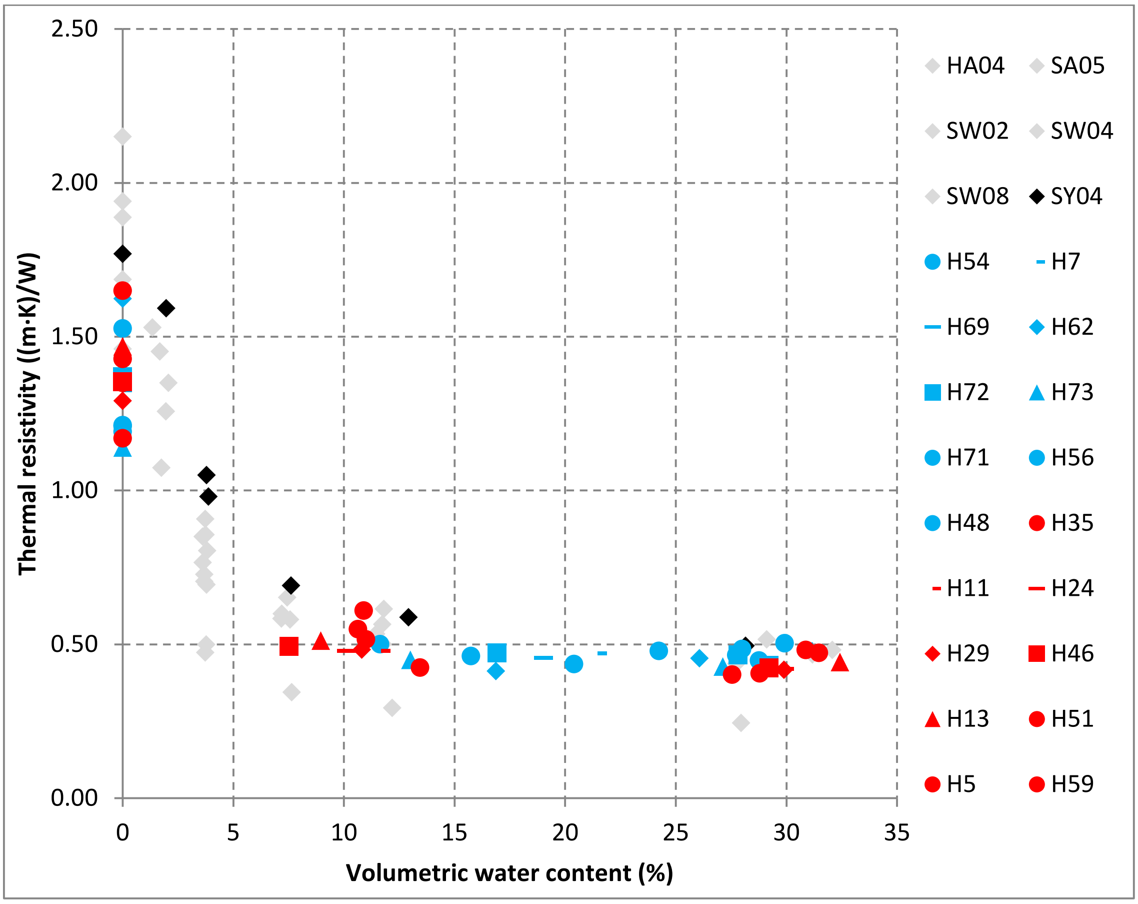



Figure 12 Thermal resistivity vs volumetric water content. Grey and black values belong to the investigation performed by Sundberg and Sundberg (2012). The black dots Sy04 = Dalby 0/4, same material as the red markings H5, H11, H13, H24, 29, H35, H46, H51 and H59, all from stretch 506 and 507. Blue markings are from stretch 332 and 333.

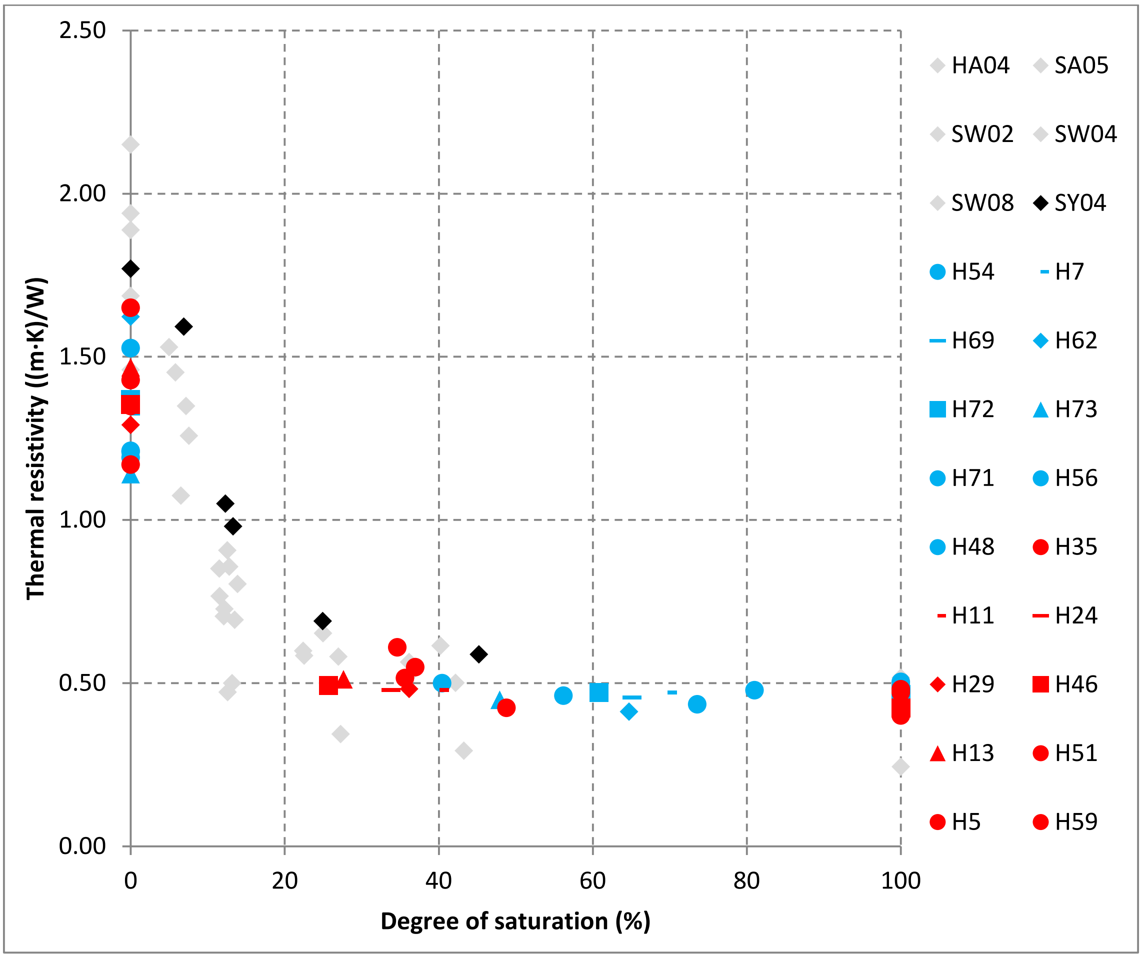



Figure 13 Thermal resistivity vs Degree of saturation. Grey and black values belong to the investigation performed by Sundberg and Sundberg (2012). The black dots Sy04 = Dalby 0/4, same material as the red markings H5, H11, H13, H24, 29, H35, H46, H51 and H59, all from stretch 506 and 507. Blue markings are from stretch 332 and 333.

In Figure 13 above thermal resistivity is plotted against degree of saturation. The trend is the same as in Figure 12.

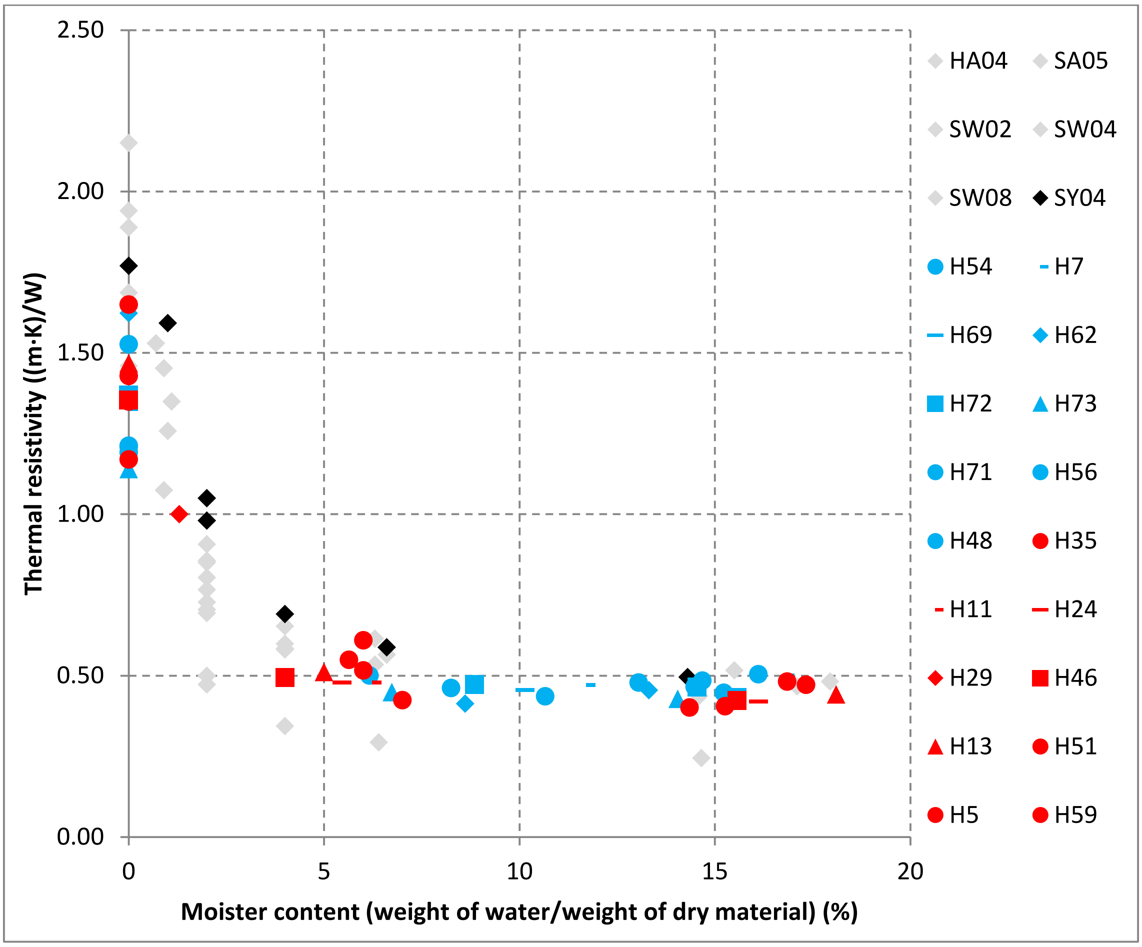



Figure 14 Thermal resistivity vs moisture content. Grey values belong to the investigation performed by Sundberg and Sundberg (2012). The black dots Sy04 = Dalby 0/4, same material as the red markings H5, H11, H13, H24, 29, H35, H46, H51 and H59, all from stretch 506 and 507. Blue markings are from stretch 332 and 333.

In Figure 14 above thermal resistivity is plotted against moister content. The trend is the same as in Figure 12 and Figure 13 above.

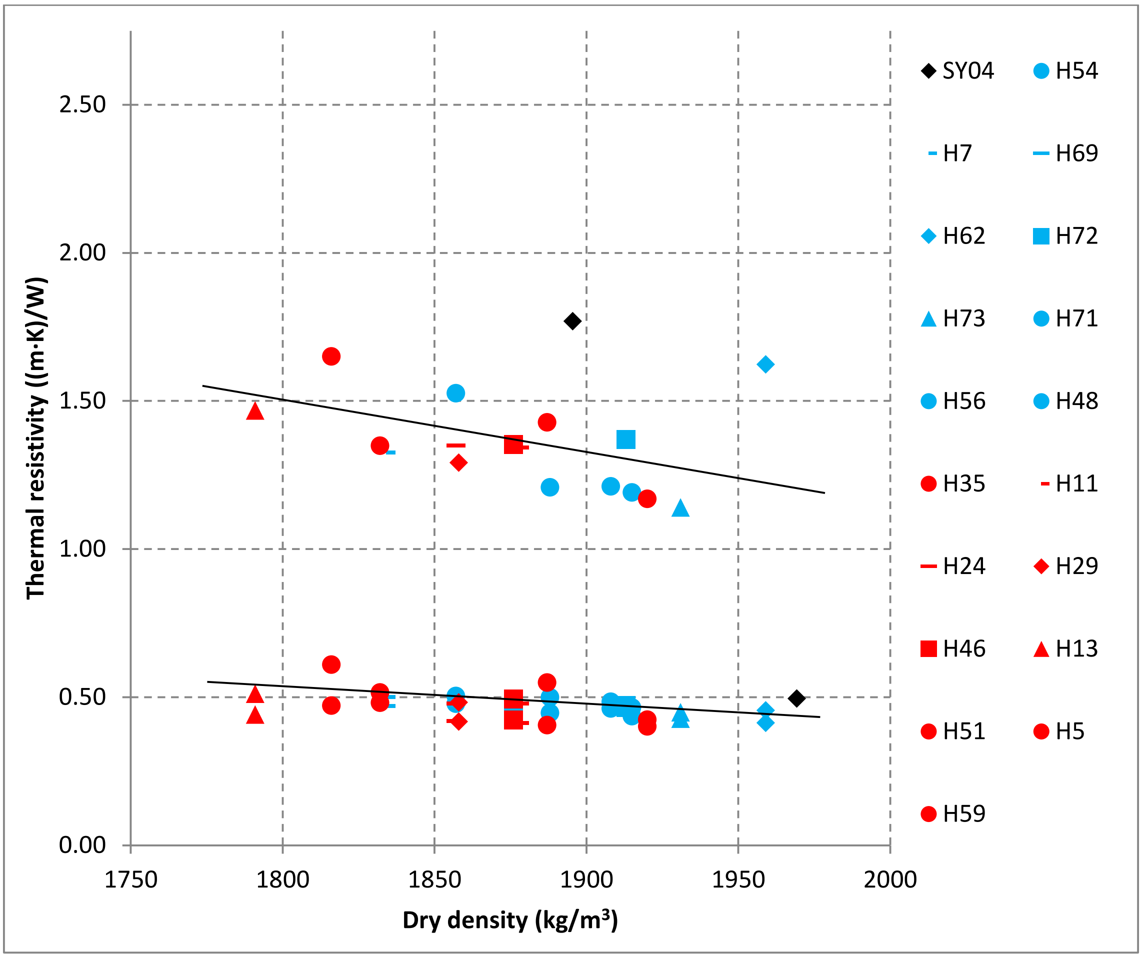



Figure 15 Thermal resistivity vs dry density. For each sample three measurements have been performed regarding thermal resistivity, one with zero water content (highest value in the figure), one with natural water content (middle value) and one at saturated conditions (value with lowest thermal resistivity). Black dots belong to the investigation performed by Sundberg and Sundberg (2012), dry and saturated. The black dots Sy04 = Dalby 0/4, same material as the red markings H5, H11, H13, H24, 29, H35, H46, H51 and H59, all from stretch 506 and 507. Blue markings are from stretch 332 and 333.

In Figure 15 thermal resistivity is plotted against dry density. A trend can be seen regarding decrease in thermal resistivity with increase in dry density, see black lines. The dry samples are represented by the upper black line which has a steeper slope than the two below (coincide with each other) which represents samples that contain water.

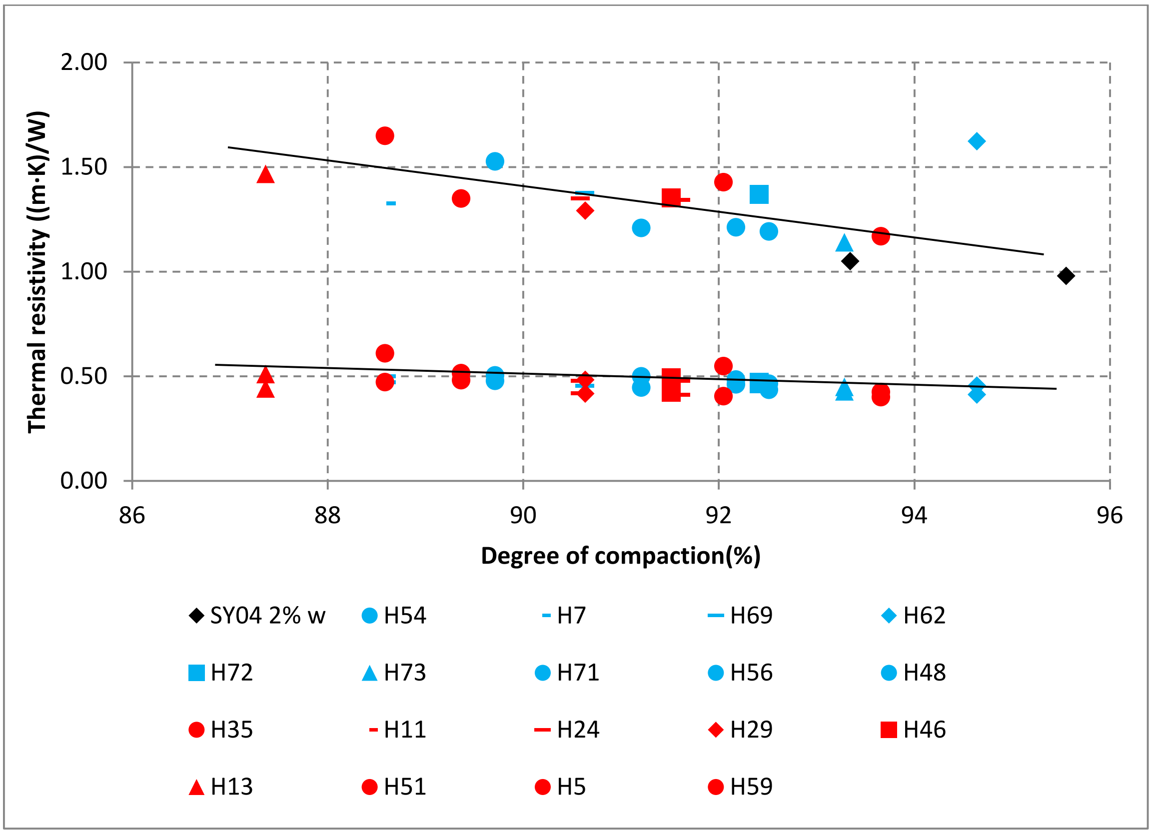



Figure 16 thermal resistivity is plotted against degree of compaction. The same trend can be seen as in Figure 15. The lines illustrate the decrease in thermal resistivity when the degree of compaction is raised. For each sample three measurements have been performed regarding thermal resistivity, one with zero water content (highest value in the figure), one with natural water content (middle value) and one at saturated conditions (value with lowest thermal resistivity). Black dots belong to the investigation performed by Sundberg and Sundberg (2012), dry and saturated. The black dots Sy04 = Dalby 0/4, same material as the red dots H5, H11, H13, H24, 29, H35, H46, H51 and H59, all from stretch 506 and 507.

The black lines in Figure 16 shows that the degree of compaction is even more important regarding thermal resistivity if the material gets dry. For example, by increasing the degree of compaction from 90 to 95 %, the thermal resistivity decreases with approximately 30 % if the samples are dry (upper black line in Figure 16). The lower black lines are overlapping each other, making it look like one line.

# 8 Evaluation of design based on previous reports and modelling

In the design the natural soil was divided into different types, e.g. A for thermally good soils and B for soils with higher thermal resistivity. A coarser cable area was therefore chosen in type B soils. The match of natural soil types together with correct cable dimensions is a difficult task since the geology is uncertain and the cable area and length can only be changed at the joint bays. The boundaries between different soil types is hard to know in advance, therefore the geothermal active design was intended to be incorporated as a solution at places were pre-knowledge did not correlate to reality. This process demands geological expertise during excavation. Since this process not was performed as intended there are places where the smaller cable area also is installed in type B soils, but as well places where the coarser cable is installed in type A soils.

The investigation conducted by Sundberg et al (2011) shows that in type B soils, the thermal resistivity can reach 2.22 m·K/W by looking at the 1-percentile and 1.54 m·K/W for the 5-percentile (statistical analyse and assessment). Since the parameters that governs the thermal resistivity in soil vary a lot, the geology always consist of uncertainties.  An infinite amount of field measurements would be needed to cover all possible values of thermal resistivity in soil, which of course is impossible, but the ones that are performed can work as a basis for statistical analyse. This is the best way of finding the values that not is found through field measurements. Min and max values of thermal resistivity can though be set because water content, grain size, mineral types etc. in soils are limited due to their individual properties regarding thermal resistivity but the distribution and variation for the whole population cannot be determined without a statistical analyse. In Table 6 Group B equals soil type B and consist of sandy till, gravelly till and gravelly sand.

Table 6 Results from Monte Carlo simulations of thermal resistivity ((m·K)/W) for different soil types (Sundberg et al, 2011).

| **Soil type** | **1-percentile, ((m·K)/W)** | **5-percentile, ((m·K)/W)** | **Mean ((m·K)/W)** |
|---|---|---|---|
| Group A field | 0.93 | 0.77 | 0.53 |
| Group A laboratory | 0.89 | 0.79 | 0.64 |
| Group B field | 2.17 | 1.27 | 0.70 |
| Grupp B laboratory | 2.27 | 1.54 | 0.83 |

Where the smaller cable dimension 2010 mm$^2$ is installed in type B soils and the thermal resistivity is higher than 1.5 m·K/W according to Table 6 above, high thermal resistivity stretches may occur. Figure 17 below shows one of the problematic stretches, type B soil with the smaller cable dimension. It is located in a topographically higher area which may result in dryer soils during dry seasons.

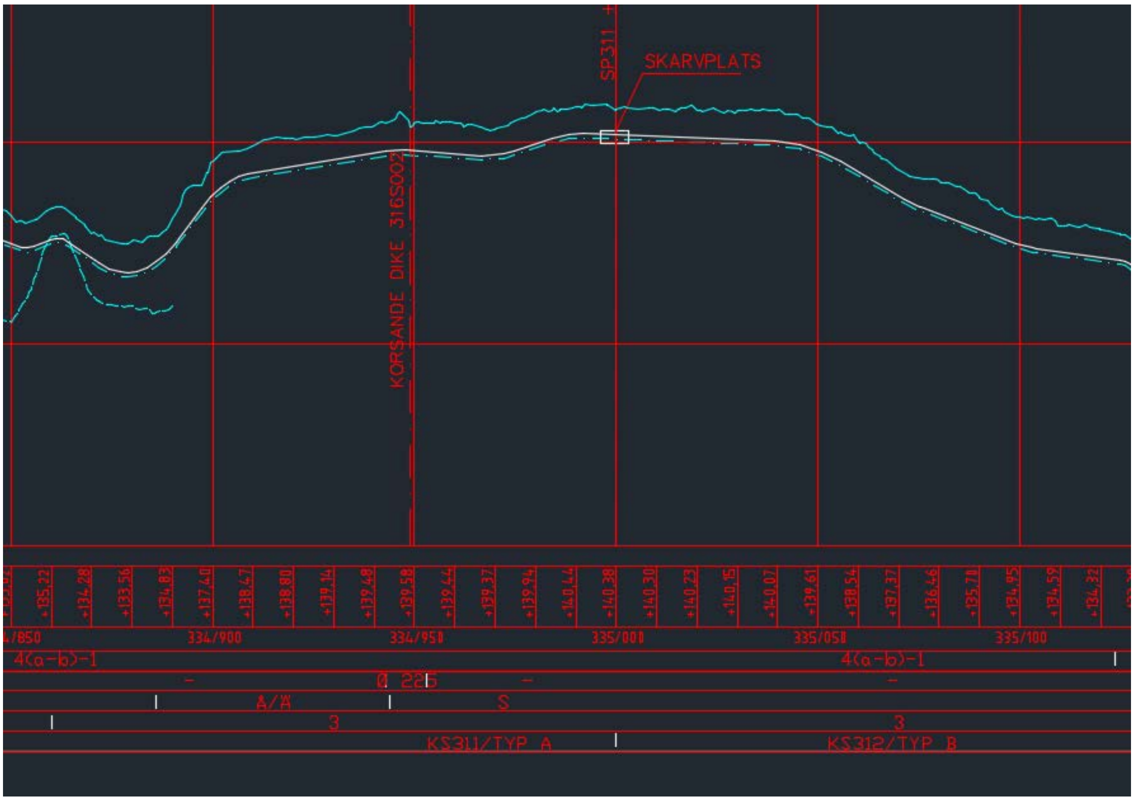



Figure 17 profile drawing from design documents, parts of the cable stretches 311 and 312. Cable joint in soil type B (design case 4 (a-b)-1). Smaller cable dimension type A located in type B soil.

The stretch in Figure 17 can be problematic if the thermal properties of the soil tends to be as the 5-percentile or lower. In order to illustrate these conditions the software Comsol Multiphysics has been used and the following results were obtained. See Figure 18 - Figure 20.

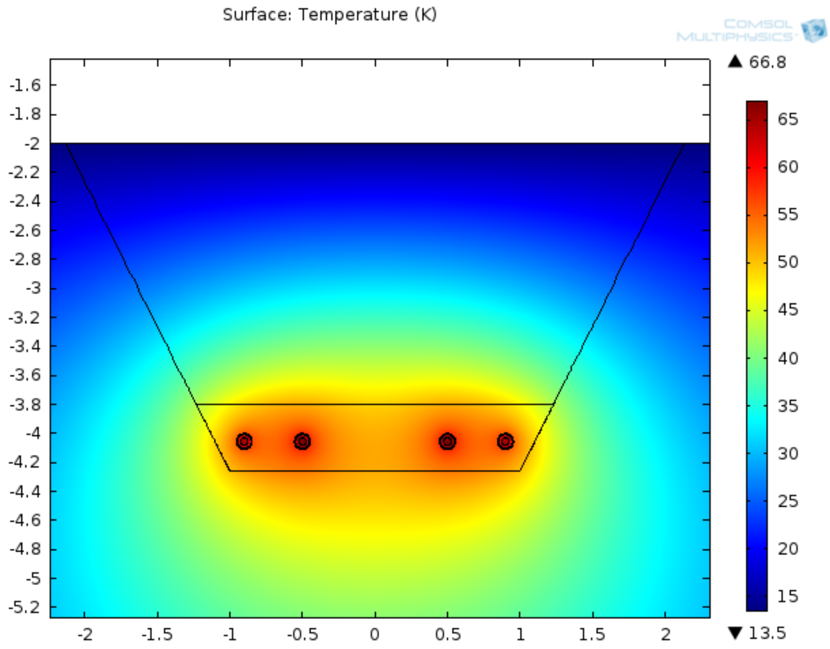



Figure 18. Design case 4a. With cable dimension 2010 mm$^2$ and a thermal resistivity for the surrounding soil type B according to the 5-percentile (1.54 m·K/W), thermal sand (1.0 m·K/W). At steady state the maximum temperature reaches 66.8 degrees. Stationary conditions is reached after approximately 10 years.

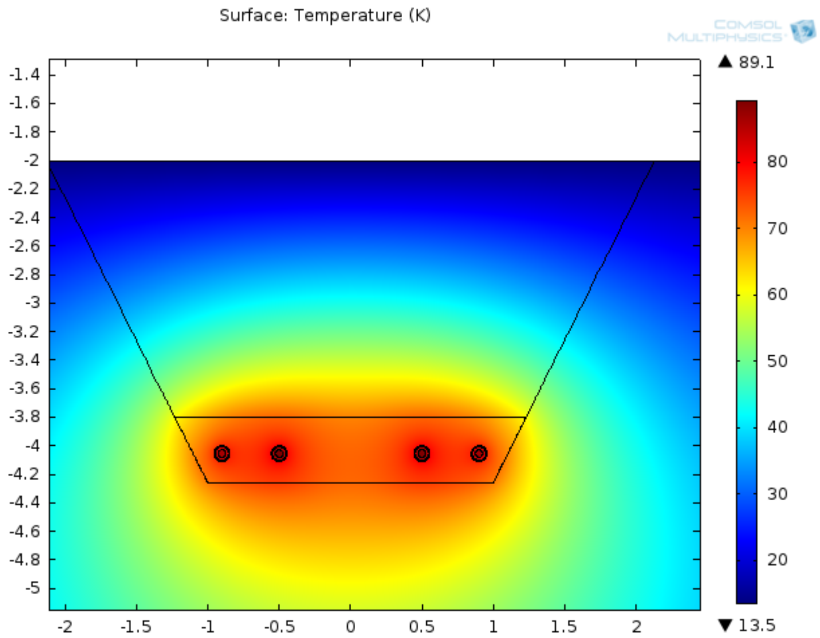



Figure 19 Design case 4a. With cable dimension 2010 mm$^2$ and a thermal resistivity for the surrounding soil type B according to the 1-percentile (2.22 m·K/W), thermal sand (1.0 m·K/W). At stationary conditions the maximum temperature reaches 89.1 degrees. Stationary conditions is reached after approximately 10 years.

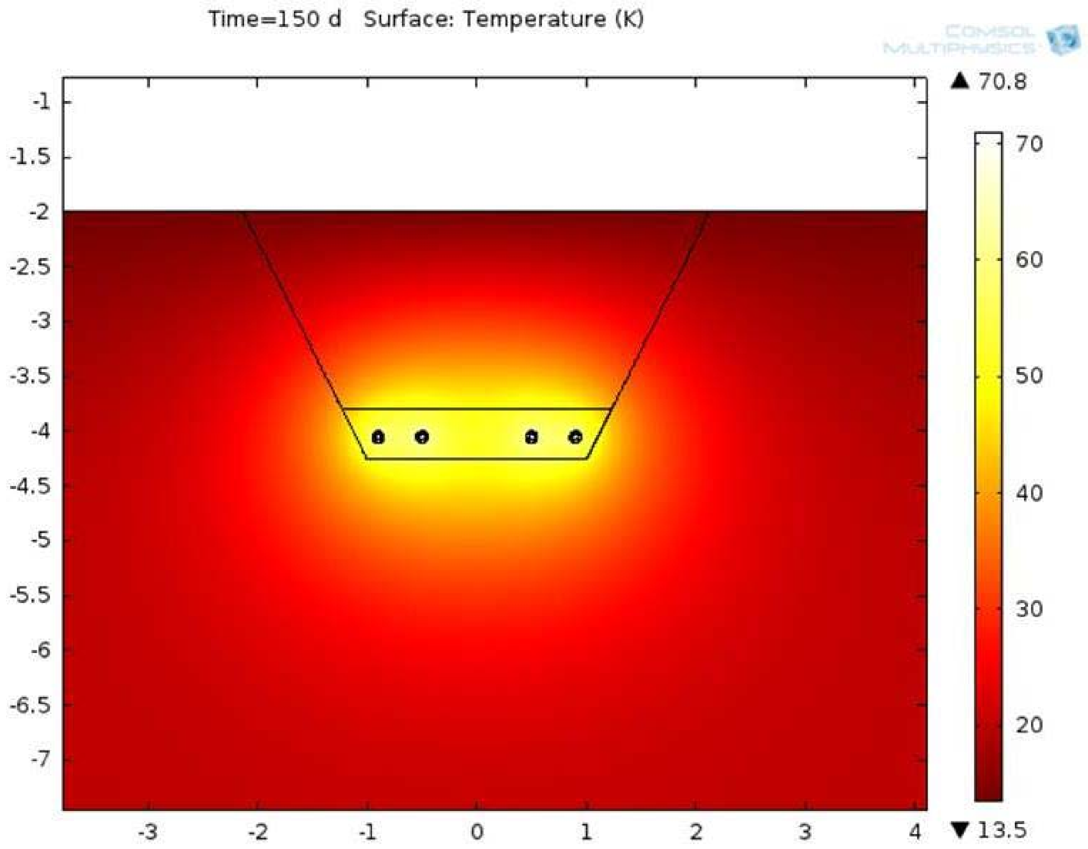



Figure 20 Design case 4a. With cable dimension 2010 mm$^2$ and a thermal resistivity for the surrounding soil type B according to the 1-percentile (2.22 m·K/W), thermal sand (1.0 m·K/W). Under non stationary conditions the temperature reach 70.8 degrees after 150 days.

# 9 Bentonite filled PE-pipes

At several places along the stretch of south west link the HVDC-cables are placed in protection pipes out of polyethylene (PE-pipes). The pipes have the dimension of 225 mm in diameter and are used and implemented in different ways. Both in deeper areas with a predrilled method but also laid in trench. The drilled method is used at for example road crossings and under environmentally sensitive areas such as peat bogs. When the cables are placed inside PE-pipes they do not fill out the total volume inside the pipe. Therefore there is a need of filling the residual volume with a thermally good material, instead of letting the cables be surrounded by air inside the pipe (poor thermal conditions assuming conduction only). During design it was decided that the pipes were supposed to be filled with a special type of bentonite clay with a thermal resistivity of approximately 1.0 m·K/W.

During quality control by the cable supplier regarding the bentonite filled pipes, it was concluded that at several height points the pipes were insufficient filled with bentonite clay. Due to this it was noticed that there was a risk for thermal hot spots along the stretch, especially at height points. This resulted in an investigation performed by Svenska kraftnät and the cable supplier. During the investigation, 213 height points were considered to pose a risk for future hot spots. A test stretch was established for 6 height points (24 pipes) and unfilled pipes were refilled. Svenska kraftnät and the cable supplier did then evaluate the 213 critical spots by analysing parameters that affects the thermal conditions, such as cable depth, cable separation and thermal properties of the surrounding ground (different resistivity for different soil types). All spots were analysed individually by the numerical software Comsol Multiphysics including calculation of thermal radiation. Convection was excluded in order to create easier and faster models but with slightly higher temperatures as a result. Based on these analyses together with knowledge from the test stretch, only 4 points remained to pose a risk. The pipes at these spots where then open and refilled. In total have 11 height points (44 pipes) been opened, controlled and refilled. Beside this investigation, ABB performed an investigation regarding temperature difference in the conductor due to different amount of filled bentonite in the PE-pipe. The conclusion was that it only differs 4 degrees between an unfilled and filled pipe when both convection and radiation were included. It was also concluded that it only differ 1 degree between a 100% filled bentonite pipe compared to one with 30% filling (Nääs and Lindström, 2015).

# 10 Questionnaire survey

As a part of the feedback of experience a questionnaire survey has been conducted for the South West Link. The survey was handed out to relevant persons involved in the project such as design engineers, the project group, construction managers, foremen, SWL management and other experts connected to the project.

## 10.1 Design

Some deficiencies have arisen due to the fact that the thermal aspects were highlighted far too late into the design. Even though most of the shortcomings were handled in a good way and finally resulted in relatively good documents they could have been treated and avoided in an earlier stage. Some of the things that have been perceived to cause difficulties are: pre-knowledge of water content in the peat, late information regarding action that where needed in soil with high thermal resistivity and the knowledge of other cables and pipes that exist in the ground.

Design and dimensioning of cable sand and filling were performed by an external expert and the overall opinion is that this has worked out well. Late changes in the preconditions for design did though lead to unnecessary stress.

There has been a large engagement from all participants in order to solve difficulties that have arisen during both the design and implementation phase. Knowledge about the importance of thermal consequences leads to better implementation but can also render in delays and inevitable compromises if the information not is clearly stated at an early stage.

It was a late decision to not let the cable supplier be responsible of the thermal dimensioning and an opinion was that it caused unnecessary stress with risk of miscalculations. It is a crucial part that may render in problematic scenarios if not correctly performed. An opinion was that a greater support regarding thermal dimensioning throughout design and implementation with a following quality control would probably have caused fewer problems during the project time and secured the quality.

As a consequence of uncertainties in geology and hydrogeology, design errors have occurred. Groundwater stand pipes were neglected in the beginning but later installed, this showed to be a critical factor that later had a significant impact on the design. A more thorough pre design and ground investigation could though have led to fewer errors, even if the ones that occurred were manageable. The tender contract could have been clearer regarding how to perform the geological survey. Surveying staff, hydrogeologists and geologist from the designers walked the stretch but with different approach. The best result was achieved by localizing borders between hard rock and peat; instead of registering the ground conditions at fixed cc with 50 meters but both methods had advantages.

In order to make sure that the design constitutes to a good construction document, it needs to be clearly stated in an early stage what sorts of requirements that will govern the design regarding the cable and its surrounding material. Otherwise it will lead to confusion in a big organization and things may be done differently by the parties or forgotten, which results in forced work at the end.  An open dialog and frequent contacts among persons involved in thermal issues would have saved a lot of time and resulted in an even better construction document.

Revisions regarding the preconditions have led to many retakes during the design in this project. A smaller and more united organization in the design phase may be preferable. Furthermore unpleasant surprises could also be reduced by letting environmental authorities take part in early discussions.

## 10.2 Construction document

The construction documents were not found as unambiguous as needed and could have been better. A mismatch has occurred between ground plan and standard sections. There has been poor correlation between quantity list and drawings. Likewise there were deficiencies between administrative directions and contracts. The newly created codes that were incorporated into the quantity list were not sufficiently explained and have led to interpretation rights for the contractors. Technical requirements and quantity list were in some cases needed to complement the drawings. The consultant had deficiencies in their control, inaccuracies discovered in design documents were not updated in the final construction document. The variation in tenders with factor 2.5 reflects the ambiguities in documents.

Deficiencies in the documents have and will probably always occur as a consequence when tight deadlines arise. People with low pre knowledge need to be used and error may follow. Some of the deficiencies in the project were;

- In some cases only information about cable type existed and not soil type.
- Flow-defining filling materials were misplaced or missing, this caused insecurity.
- Boundaries between materials and depth have not been optimal but expected with such a long stretch and few pre investigations.
- Information about how resistant the cable is when it comes to packing and filling material has been insufficient.
- It has been hard to know what packing tools that are accepted.
- Ambiguities concerning minimum coverage of filling material.

The construction documents was perceived to have a surprisingly good match to reality regarding soil type A and B, but to some extent the division of stretches had to be changed in order to achieve a better match.

## 10.3 Construction management

The block division in the construction contract has worked out well, the division between cable contract and ground contract did not turn out well due to weaknesses in the boundary, this could have worked better through more synchronized contracts. A performance contract like this is probably still to prefer rather than a prime contract since it would have required a detailed tender document, with information that is hard to predict.

The excavation contractor did not really realize the complexity in the project. As a result they were initially shorthanded and could not instruct field staff sufficiently in order to get the work correctly performed.

The construction documents have not been considered difficult. However less installation cases would have made implementation simpler and would have facilitated the work for contractors and construction managers. The contractors seemed to have some problems with the large number of cases. To some extent unpredicted additional work was needed dependent on many cases. The large amount of normal sections caused an overload for the surveying staff and the different soil types caused logistical problems with soil masses.

Geothermal active design has only partly been implemented in areas with geological uncertainties. Some parts have been handled in corporation between designers, geotechnical and thermal expertise. Regular active design (not thermal) has also been regarded to result in additional work and not as smooth as desired. A higher proactivity would have led to less incorrect performances from contractors, for example trench slopes and groundwater issues. There have also been unrealistic deadlines, where excavation, groundwater lowering and packing of cable sand were planned to be performed within a day.

## 10.4 Construction

Difficulties that arose during implementation were partly caused by deviations between design and the ground conditions in reality. Ground water was considered to be a difficult task to handle. The tender contract was not clear enough regarding groundwater lowering and slope angles, discussions between the client and one of the contractors caused delays and problems with too much water in the trench as a result. The construction of roads above the trench caused issues and discussions. The interaction between excavation contractors and the cable supplier did not work due to deficiencies in contract interface. One problematic part was that the trenches needed to be open for longer periods since the joint contacts not were approved. This caused problems with water in trench but also with masses for the temporary roads, that could not be moved and reused until trench was refilled.

Packing of cable sand and filling material were a bit problematic at some locations. Depending on normal sections and its natural material, the overpasses that were needed varied. But in general it was achieved with 6 overpasses which is rather time consuming. If the degree of compaction would be raised to 95 % according to proctor it would be difficult, especially if the underlying soil type for example consists of peat. When it reaches a certain degree of compaction the material bounces on top of the underlying material, without achieving increased compaction.

During implementation defects in workmanship has occurred but probably not more than normal, sometimes it has been considered that the contractors had the approach of solving problems when they arise rather than planning to avoid them. At some locations cables were laid in pipes in order to not disturb environmental areas and road crossings, cable supplier did not manage to completely fill the pipes with the required amount of bentonite.

Construction documents had to be redone for some areas to achieve a good implementation, but after being redone the implementation worked well.

## 10.5 Control and follow up

The control documents have been slightly unclear and the monitoring frequency has been regarded to be too high. Self-monitoring is not deemed to have worked as it would and documents were not conclusive. Construction managers also needed to act as inspectors. If monitoring moments instead would have been incorporated into the contract it would have been easier to implement. A requirement on direct refilling after cable laying for instance, something that may have been easier with a prime contractor. Then monitoring could have been performed continuously rather than by each contractor at different occasions.

The requirement of compaction to fulfill desired density on cable bed was hard to achieve due to varying undelaying material; however this has later been fulfilled through compaction of overlying filling material. In areas with underlying friction soil the compaction has been easier to achieve.

The requirements on quartz content in cable sand has not been hard to fulfill but has caused long distance transports since only a few quarries could provide the type of material.

The location of where to perform measurements in the cable bed regarding degree of compaction was not clearly stated. It was found inappropriate to use the equipment rod near the cables. Initially this caused a stop in the sampling and should have been clarified earlier.

## 10.6 Additional comments

Working relationship and corporation between all parties have been regarded as very good and overall the project has been seen as interesting and pleasant. Basis and documents regarding thermal dimensioning was considered to be of great support during the design. Parts of the active design with protective pipes through peat after revision of normal sections were lifted by the contractors as something that worked well.

Another opinion is that instead of placing cables with varying dimension it would have been better to choose a coarser cable along the whole stretch. This would have made the implementation easier and time schedule would have been kept better which also may have saved money.

Compared to the tender sum the final sum has risen to the double, caused by additional work but also by large legal costs.

# 11 Discussion

## 11.1 Early and final design – natural soil, trench and cables

Potential problems regarding geothermal issues need to be identified early in the project, something that not has been thoroughly performed for this project. Experts from the different areas need to, in an early stage discuss and identify geothermal problems that may arise during project planning and implementation. Implementations that seem trivial for one group of people may be unrealistic for another. Through an early identification and with a clear strategy for forecasting thermal properties, other better options can be chosen that e.g. cause less thermal design cases with higher certainty. Since crucial requirements, such as the geothermal, were incorporated in a late stage it caused problems further into the project. Revisions were needed in the design and inaccuracies arose in documents, with defects in workmanship as a result. Additionally more thorough pre investigation regarding geological conditions would have rendered in fewer unwanted surprises.

The overall thermal design was changed two times due to upgrade in cable dimensions. In the last document regarding design conditions, geothermal active design was integrated as a way of dealing with type B soils that had a higher thermal resistivity than 1.5 m·K/W, when a smaller cable dimension (2010 $mm^2$) had to be used. There were also a lot of thermal design cases in the design documents, which made it a bit unclear and harder to handle. Instructions regarding how to perform the geothermal active design were not included in the instructions for design cases, something that would have been needed. The intention was to use geothermal active design as a complement to the thermal design cases at difficult and geologically uncertain places. In areas with peat and road crossings there was a geothermal active design but not in type B soils where the geological boundaries may have been unclear and a smaller cable dimension is installed, see chapter 8. It has resulted in under-dimensioned parts of some stretches. It would have been preferable to have a geological and hydrogeological expert studying the open trench along the stretch in order to classify the natural soils and their groundwater levels. This to make sure that active design took place if the smaller cable dimension was installed in type B soils.

In Appendix 2 actual parts of the cable route with the combination of type B soil and 2010 $mm^2$ cable are listed. In total 5%, 9575 m, of the total length have this combination.

At places where drilling/placement of PE-pipes have occurred, e.g. under peat bogs and below road crossings, the cables were installed in bentonite filled PE-pipes. The filling process did not work as planned and air pockets arose in the pipes and refilling was needed, especially at height points. This is a problematic part since the pipes at some locations are placed in soils with high thermal resistivity. Svenska kraftnät and the cable supplier made an investigation which were followed by measures and concluded that after the refilling there was no longer a risk for hot spots due to insufficient bentonite filled pipes (temperatures in the models did not exceed 70 degrees). There is still a large amount of pipes that not are filled to the top with bentonite clay. As long as the surrounding soil have the thermal resistivity such as the assumed during temperature modeling, it might not be a problem. The resistivity for soils that were used during numerical modelling for the 213 locations, were the same as previously used in the project and presented in Emme (2012). As mentioned above, 1.5 m·K/W is probably not a conservative value for type B soils. Therefore these parts are under dimensioned even without involving the knowledge about insufficient bentonite filling. The insufficiently filled pipes would then contribute to an even higher risks of hot spots when they appear on the same location as type B soils or as most common below the peat bogs with 2010 $mm^2$ cable dimension. According to the investigation performed by ABB, regarding temperature difference between filled and unfilled pipes, there was a small temperature difference, only 4 degrees. The radiation seems to play a major role in the temperature modelling and the high temperature and the used emissivity factor for PE-pipes of 0.95 seems to be the reasons.

## 11.2 Cable bed and backfill

The technical requirements for implementation of thermal backfill need to be clear regarding what documents that should be reported back to the client after implementation, which simplifies the follow up. There have been deficiencies in several parts of self-monitoring in relation to requirements. Inadequate documentation for some stretches regarding placement of sand type A and B but also information regarding sand properties analysed in lab, such as mineral content and proctor curves. For the stretches 505-507 and 529-533 this documentation has been rather clear and adequate. For stretches 309-312 and 329-333 the lack of information is high, especially lab reports regarding mineral content and maximal density during heavy compaction. Some samples have been taken and analysed to ensure that the material are within limitation lines for particle size distribution, but the origin of the sample cannot be stated. Since this relevant information is missing, it is impossible to verify neither if the work has been properly performed nor if right material has been used.

Documents from contractors have also been very unstructured and hard to draw conclusions from. A requirement of reporting an overall document, including the documentation mentioned above, would give a clearer view of how well the construction has met the demands.  Requirements may also need to be modified regarding methods for measuring moisture content and densities.

The method of using a nuclear density gauge seems to work rather well if the rod with 0.3m extension is used, but probably not good enough. The intention was to use it but it would have required a cable bed of at least 0.3m, the double of what was actually used. Conditions were changed during the project and the backscatter method was used instead. For this purpose this method showed to render in very uncertain and incorrect results. The equipment only measures the top surface of the material, approximately 1 cm and not deeper into the material which was the intention, see Figure 6. Rubber balloon measurements are therefore a much more accurate method.

The self-monitoring documents do not express if additional compaction has been performed when the degree of compaction has not fulfilled the requirements. According to the questionnaire survey, it seems like some of the contractors thought this problem would take care of itself when the natural backfill is placed on top of the thermal backfill. This will though not change the degree of compaction in the cable sand.

It has been noticed that for one location, type B sand has been used instead of type A that was supposed to be used according to construction documents. Since sand type B has lower thermal resistivity it is not a problem as long as this sand purposely have been used. Otherwise it testifies that construction documents are wrong or misplacement has occurred. At one stretch, macadam had been laid around cables in order to solve water problems; it was discovered by a construction manager and was corrected but could have been missed, with severe consequences as a result.

The project had clearly stated contracts for excavation contractors and cable supplier but a much better synchronization between them was though desired. One of the problems related to this is the installation of cables after compaction of cable bed. The trench remained open for longer periods after the compaction of cable bed was performed. Groundwater and rain softened up the compacted sand material, which increases the thermal resistivity.

## 11.3 Control samples – cable bed

In addition to self-monitoring the following cable stretches were investigated with additional control samples 309-312, 329-333, 505-507 and 529-533. By comparing self-monitoring results with control samples it becomes clearer that the backscatter method not is trustworthy for this purpose. According to self-monitoring values with adjustment all requirements are fulfilled for cable bed, but in reality approximately 20 percent of the samples had lower dry density than required, when control samples were analysed in lab. The errors produced by backscatter method seems to be the reason. Since requirements of densities not has been fulfilled it may have an impact on the thermal resistivity.

Measurements regarding thermal resistivity for samples consisting of material Dalby 0/4 seems to be lower than for the ones measured by Sundberg and Sundberg (2012). It should be noted that the samples that were taken for thermal analysis do not represent the whole cable stretch. It should also be mentioned that water retention is not measured, which have a rather significant impact on the water content which in turn is affecting the thermal resistivity.

Measurements on control samples confirms that low water content in sand strongly contributes to an increase in thermal resistivity, especially if moisture content undergoes 6-7% and becomes a real problem if it approaches 0 %. Moisture content is also the parameter that is the hardest to control over a long period of time due to variables such as e.g. precipitation.

## 11.4 Geological and geotechnical investigations and technical description

The thermal investigations were made at a late stage of the design phase. However, the geotechnical and geological investigations held high quality and made it possible to perform the thermal design in a successful way. Appendix 3 provides an overview of geo-related investigations and technical description for Sydvästlänken.

# 12 Conclusions and recommendations

## 12.1 Overall conclusions

- It is crucial that the client has a responsible person that guaranties that thermal issues becomes a part of the whole process, from early pre-investigations to final construction and control.

- The thermal design was to a large extent well thought out and conservatively performed but did not reach the whole way since the intended active design regarding thermal issues not was performed during construction phase.

- Parts of the stretch that consist of type B soil with the smaller 2010 $mm^2$ cable dimension may be strongly under powered (see Appendix 2 for locations).

- The large number of engineering cases (at least 74 cases) made the implement-tation complicated and put great demands on the site organization and the contractor.

## 12.2 Other conclusions

- The method of using a nuclear density gauge at cable bed and backfill is not to recommend. Rubber balloon measurements are to prefer in order to measure densities and moisture content. It provides more accurate results but takes a couple of minutes more per measurement to perform, compared to a nuclear density gauge.

- The documentation of type and placement of cable sand and backfill has been inadequate, at some stretches it is impossible to verify neither if the work has been properly performed nor if right material has been used.

- The contract between excavation contractors and cable supplier were unsynchronized, resulting in trenches remaining open for longer periods which among others affected the compaction of cable bed at several stretches.

- 20 percent of Chalmers control samples at cable bed had lower densities than required which may affect the thermal resistivity in a negative way.

- Over a longer period of time, the natural soil surrounding the trench is expected to be the dimensioning factor for the south west link. Stretches with smaller cable dimension in soils with high thermal resistivity would be of interest for future DTS measurements, in order to verify previously assessed properties of cable sand and natural soil.

- Measurements of the actual temperature development around cables during operation are essential in order to gain knowledge about how well the implementation has been carried out. It may also lead to an understanding of where and why thermal hot spots may appear in South west link. The numerical models that have been used can also be adjusted and further developed through comparison with measured temperatures, as a help for future similar HVDC projects.

## 12.3 Recommendations

The intention in this project was to analyze the time course of the temperature rise by DTS measurements in the optical cables attached to the two inner power cables. Through these measurements the intention was to analyze the thermal resistivity for cable sand and its possible variation over time. This has not been possible to perform due to delays in cable operation.

It is strongly recommended that DTS measurements are performed during operation of the cable. Important parts like soils with high thermal resistivity and with potential of causing hot spots, e.g. dry soils and soils consisting of peat where the smaller 2010 $mm^2$ cable dimension has been installed. Beside the temperature development due to resistive natural soils, it is also recommended that measurements shall take place where different design cases has been used, in order to evaluate how the temperature is affected by cable depth and separation. This entails repetitive analyzes during a long period of time.

It is important that the electrical load and temperature development is measured and stored continually from test operation and forward. It is further recommended that a try-out is performed directly after test operation, in order to evaluate and ensure that data are measured and stored in a good way.

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CHALMERS
UNIVERSITY OF TECHNOLOGY

# Appendix 1

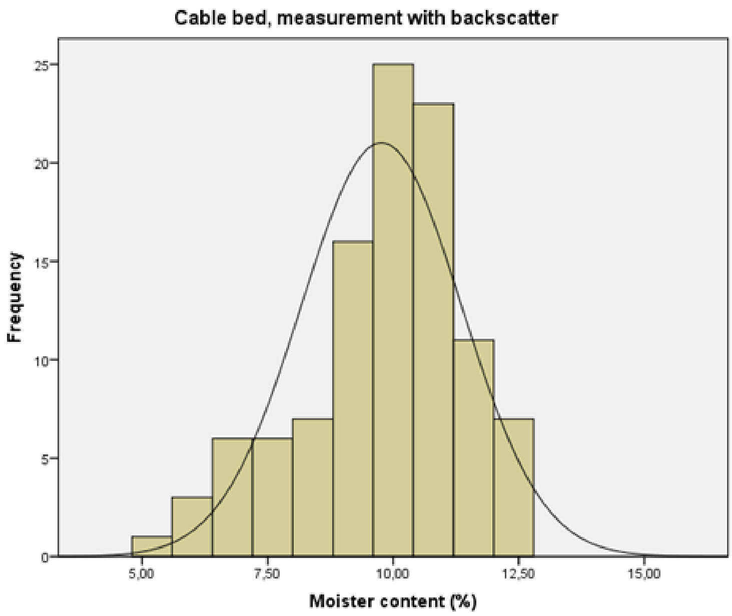
Department of Civil and Environmental Engineering
*Division of GeoEngineering*
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Report 2016:6

# Appendix 1. Self-monitoring of compaction, measurements with nuclear density gauge at cable bed, backfill and joint bays

## Measurements on cable bed, BS-method

Table 7 Measurements performed with backscatter method on cable bed, stretches 505-507 and 529-533. Red numbers symbolize requirements that are not fulfilled.

| **Cable bed** Method: Backscatter | Readout moisture content (%) | Dry density, single measurement (kg/m$^3$). Adjusted values within parenthesis | Degree of compaction, single measurement (%). Adjusted values within parenthesis | Degree of compaction mean/object (%). Adjusted values within parenthesis |
|---|---|---|---|---|
| Measurements | 105 | 105 | 105 | 21 objects |
| Median | 9.87 | 1856 **(1949)** | 91 **(95.5)** | 91 **(95,5)** |
| Min value | 5.23 | 1760 **(1848)** | 88 **(92.5)** | 90 **(94.5)** |
| Max value | 12.61 | 1939 **(2036)** | 98 **(100)** | 94 **(98.5)** |
| CV (%) | 16.2 % | 1.5 % | 1.8 % | 1.4 % |

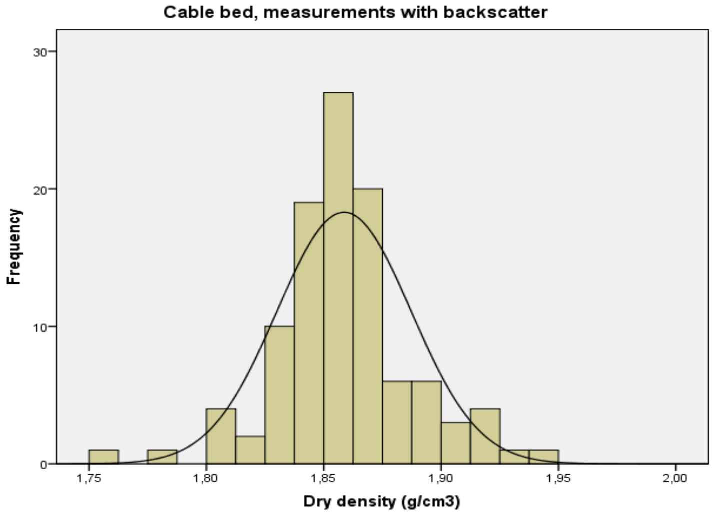



**Statistics**

Moister content (%)

| | | |
|---|---|---|
| N | Valid | 105 |
| | Missing | 75 |
| Mean | | 9,7645 |
| Median | | 9,8700 |
| Minimum | | 5,23 |
| Maximum | | 12,61 |
| Percentiles | 5 | 6,5690 |
| | 25 | 8,9950 |
| | 50 | 9,8700 |
| | 75 | 10,8050 |
| | 95 | 12,2220 |

Figure 21 Measurements and statistics for moisture content at cable bed with BS-method, raw data without adjustment.

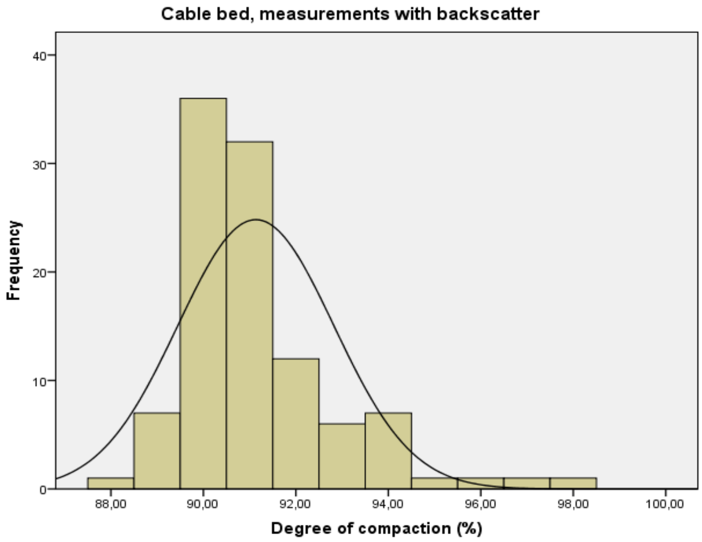



**Statistics**

Dry density (g/cm3

| | | |
|---|---|---|
| N | Valid | 105 |
| | Missing | 0 |
| Mean | | 1,8586 |
| Median | | 1,8560 |
| Minimum | | 1,76 |
| Maximum | | 1,94 |
| Percentiles | 5 | 1,8103 |
| | 25 | 1,8440 |
| | 50 | 1,8560 |
| | 75 | 1,8715 |
| | 95 | 1,9151 |

Figure 22 Measurements and statistics for dry density at cable bed with BS-method, raw data without adjustment.




**Statistics**

Degree of compaction (%)

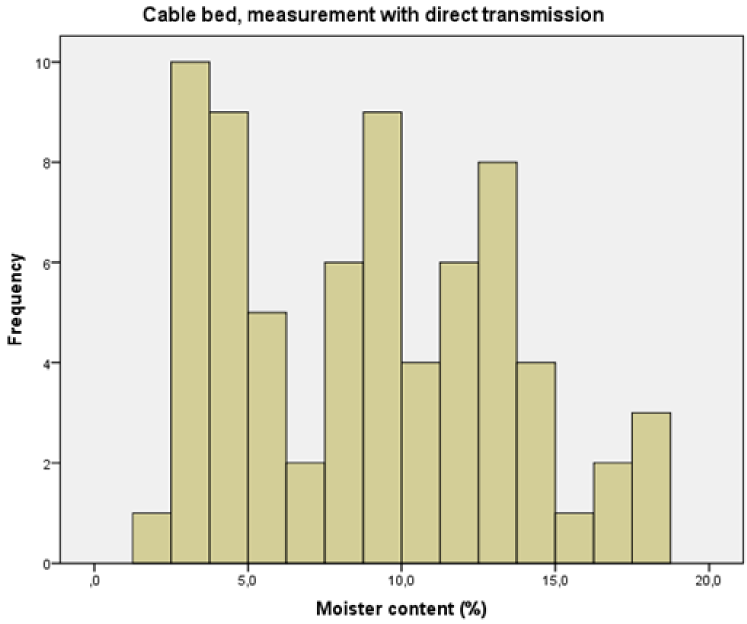
| | | |
|---|---|---|
| N | Valid | 105 |
| | Missing | 0 |
| Mean | | 91,1333 |
| Median | | 91,0000 |
| Minimum | | 88,00 |
| Maximum | | 98,00 |
| Percentiles | 5 | 89,0000 |
| | 25 | 90,0000 |
| | 50 | 91,0000 |
| | 75 | 92,0000 |
| | 95 | 94,0000 |

Figure 23 Measurements and statistics for degree of compaction at cable bed with BS-method, raw data without adjustment.

## Measurements on cable bed, DT-method

Table 8 Measurements performed with direct transmission method on cable bed, stretches 309-312 and 332-333. Red numbers symbolize requirements that are not fulfilled.

| **Cable bed** Method: Direct transmission rod extended 0,1m | Bulk Density (kg/m$^3$) | Readout moisture content (%) | Dry density, single measurement (kg/m$^3$). Adjusted values within parenthesis | Degree of compaction, single measurement (%). Adjusted values within parenthesis | Degree of compaction mean/object (%). Adjusted values within parenthesis |
|---|---|---|---|---|---|
| Measurements | 70 | 70 | 70 | 70 | 14 objects |
| Median | 2023 | 9.15 | 1829 **(1920)** | 90 **(92.5)** | 90 **(92.5)** |
| Min value | 1765 | 2.1 | 1711 **(1796)** | 87 **(89.5)** | 90 **(92.5)** |
| Max value | 2098 | 18.1 | 1910 **(2006)** | 96 **(98.5)** | 93 **(95.5)** |
| CV (%) | 4.8 % | 50 % | 2.6 % | 2.0 % | 1.0 % |

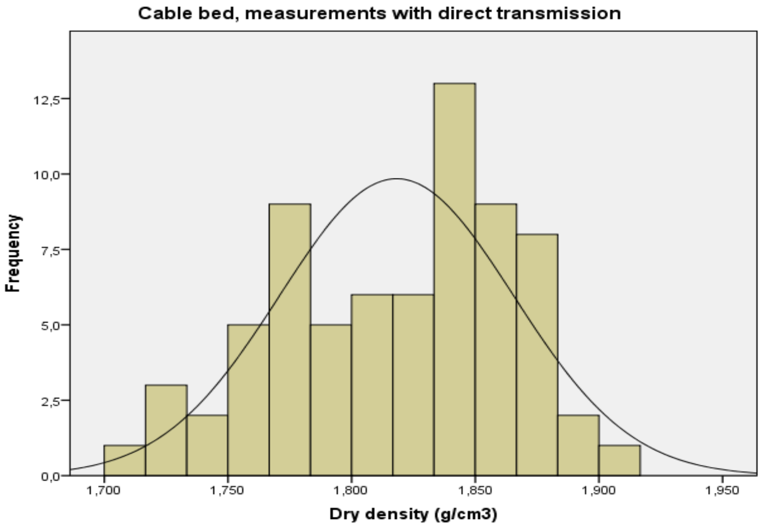



**Statistics**

Moister content (%)

| | | |
|---|---|---|
| N | Valid | 70 |
| | Missing | 110 |
| Mean | | 8,860 |
| Median | | 9,150 |
| Minimum | | 2,1 |
| Maximum | | 18,1 |
| Percentiles | 5 | 2,700 |
| | 25 | 4,725 |
| | 50 | 9,150 |
| | 75 | 12,525 |
| | 95 | 17,215 |

Figure 24 Measurements and statistics for moisture content in cable bed with DT-method, rod extended 0.1m, raw data without adjustment.

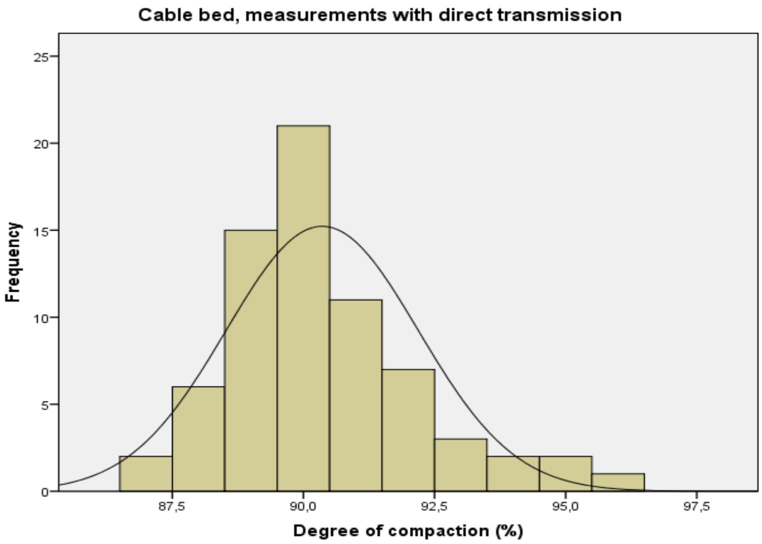



**Statistics**

Dry density (g/cm3)

| | | |
|---|---|---|
| N | Valid | 70 |
| | Missing | 0 |
| Mean | | 1,81816 |
| Median | | 1,82900 |
| Minimum | | 1,711 |
| Maximum | | 1,910 |
| Percentiles | 5 | 1,72830 |
| | 25 | 1,78250 |
| | 50 | 1,82900 |
| | 75 | 1,85700 |
| | 95 | 1,88180 |

Figure 25. Measurements and statistics for dry density at cable bed with DT-method, rod extended 0.1m, raw data without adjustment.




**Statistics**

Degree of compaction (%)

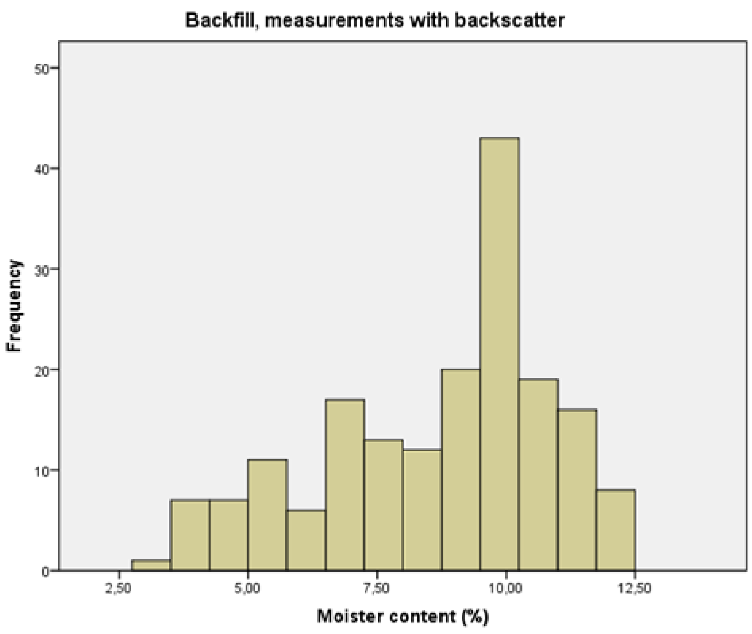
| | | |
|---|---|---|
| N | Valid | 70 |
| | Missing | 0 |
| Mean | | 90,36 |
| Median | | 90,00 |
| Minimum | | 87 |
| Maximum | | 96 |
| Percentiles | 5 | 88,00 |
| | 25 | 89,00 |
| | 50 | 90,00 |
| | 75 | 91,00 |
| | 95 | 94,45 |

Figure 26. Measurements and statistics for degree of compaction at cable bed DT-method, rod extended 0.1m. Raw data without adjustment.

## Measurements on backfill

Table 9. Measurements performed with backscatter method on backfill, stretches 309-312, 332-333, 505-507 and 529-533. Red numbers symbolize requirements that are not fulfilled.

| **Backfill** Method: Backscatter | Bulk Density (kg/m$^3$) | Readout moisture content (%) | Dry density, single measurement (kg/m$^3$). Adjusted values within parenthesis | Degree of compaction, single measurement (%). Adjusted values within parenthesis | Degree of compaction mean/object (%). Adjusted values within parenthesis |
|---|---|---|---|---|---|
| Measurements | 180 | 180 | 180 | 180 | 36 objects |
| Median | 2020 | 9.27 | 1843 **(1935)** | 91 **(95.5)** | 90.5 **(95.0)** |
| Min value | 1767 | 3.4 | 1681 **(1765)** | 83 **(87.5)** | 87 **(91.5)** |
| Max value | 2154 | 12.3 | 1923 **(2019)** | 94 **(98.5)** | 93 **(97.5)** |
| CV (%) | 4.0 % | 25.6 % | 2.4 % | 1.8 % | 1.4 % |

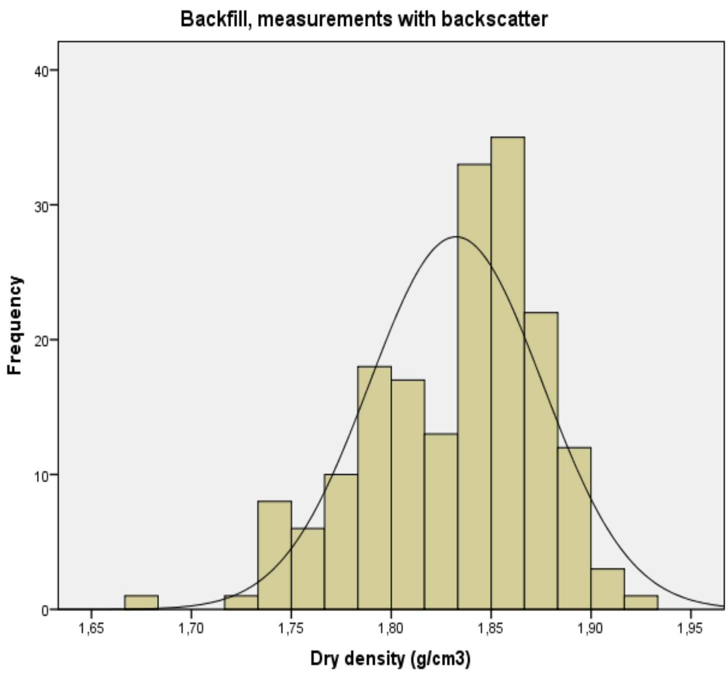



**Statistics**

Moister content (%)

| | | |
|---|---|---|
| N | Valid | 180 |
| | Missing | 0 |
| Mean | | 8,6568 |
| Median | | 9,2700 |
| Minimum | | 3,40 |
| Maximum | | 12,30 |
| Percentiles | 5 | 4,6000 |
| | 25 | 7,0000 |
| | 50 | 9,2700 |
| | 75 | 10,2075 |
| | 95 | 11,6985 |

Figure 27. Measurements and statistics for moisture content in backfill, BS-method, raw data without adjustment.

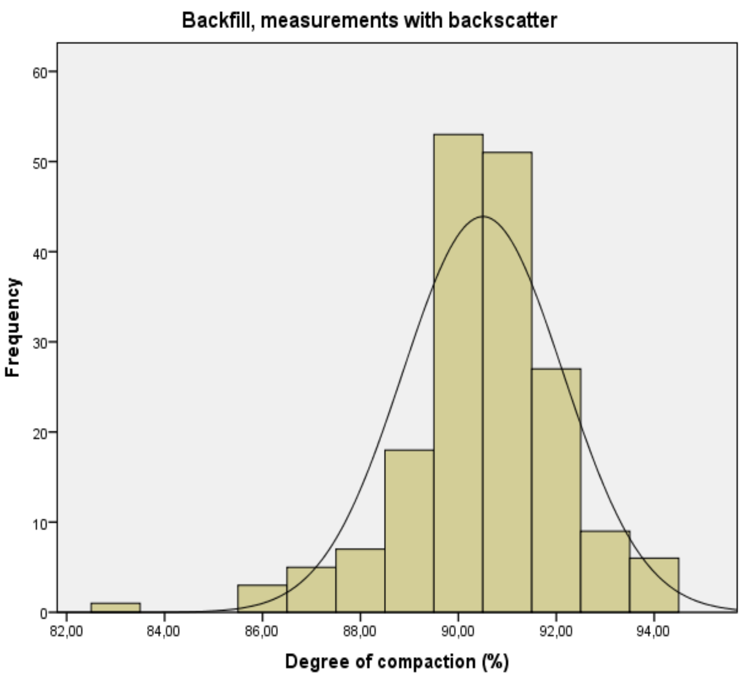



**Statistics**

Dry density (g/cm3)

| | | |
|---|---|---|
| N | Valid | 180 |
| | Missing | 0 |
| Mean | | 1,8324 |
| Median | | 1,8425 |
| Minimum | | 1,68 |
| Maximum | | 1,92 |
| Percentiles | 5 | 1,7481 |
| | 25 | 1,8015 |
| | 50 | 1,8425 |
| | 75 | 1,8630 |
| | 95 | 1,8910 |

Figure 28. Measurements and statistics for dry density at backfill with BS-method, raw data without adjustment.




**Statistics**

Degree of compaction (%)

| | | |
|---|---|---|
| N | Valid | 180 |
| | Missing | 0 |
| Mean | | 90,5000 |
| Median | | 91,0000 |
| Minimum | | 83,00 |
| Maximum | | 94,00 |
| Percentiles | 5 | 87,0500 |
| | 25 | 90,0000 |
| | 50 | 91,0000 |
| | 75 | 91,0000 |
| | 95 | 93,0000 |

Figure 29 Measurements and statistics for degree of compaction at backfill with BS-method , raw data without adjustment.

## Measurements at joint bays

Table 10. Measurements performed with backscatter method on cable bed at 12 joint bays between 309-312, 332-333, 505-507 and 529-533. Red numbers symbolize requirements that are not fulfilled but measurements are not adjusted.

| **Joint bays** Method: Backscatter | Bulk Density (kg/m$^3$) | Readout moisture content (%) | Dry density, single measurement (kg/m$^3$). Adjusted values within parenthesis | Degree of compaction, single measurement (%). Adjusted values within parenthesis | Degree of compaction mean/object (%). Adjusted values within parenthesis |
|---|---|---|---|---|---|
| Measurements | 60 | 60 | 60 | 60 | 12 objects |
| Median | 2025 | 8.9 | 1847 **(1939)** | 90 **(94.5)** | 90 **(94.5)** |
| Min value | 1723 | 2.39 | 1677 **(1761)** | 85 **(89.5)** | 86 **(90.5)** |
| Max value | 2116 | 12.47 | 1948 **(2045)** | 95 **(99.5)** | 93 **(97.5)** |
| CV (%) | 5.1 % | 29.7 % | 3.6 % | 2.7 % | 2.2 % |

Table 11. Measurements performed with direct transmission method on cable bed at 12 joint bays between 309-312, 332-333, 505-507 and 529-533. Red numbers symbolize requirements that are not fulfilled but measurements are not adjusted.

| **Joint bays** Method: Direct Transmission rod extended 0,1m | Bulk Density (kg/m$^3$) | Readout moisture content (%) | Dry density, single measurement (kg/m$^3$). Adjusted values within parenthesis | Degree of compaction, single measurement (%). Adjusted values within parenthesis | Degree of compaction mean/object (%). Adjusted values within parenthesis |
|---|---|---|---|---|---|
| Measurements | 60 | 60 | 60 | 60 | 12 objects |
| Median | 2063 | 9.4 | 1868 **(1961)** | 91 **(93.5)** | 91 **(93.5)** |
| Min value | 1768 | 2.40 | 1720 **(1806)** | 87 **(89.5)** | 90 **(92.5)** |
| Max value | 2132 | 12.40 | 1941 **(2038)** | 96 **(98.5)** | 94 **(96.5)** |
| CV (%) | 4.5 % | 32 % | 2.5 % | 1.8 % | 1.3 % |

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# Appendix 2

Department of Civil and Environmental Engineering
*Division of GeoEngineering*
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Report 2016:6

# Kabeltyp, längder och fördelning av jordarter, Sydvästlänken

Områden där den tunna kabeltypen (d=2010mm$^2$) är förlagd i jordtyp B kan vara underdimensionerad. De sträckor där detta inträffar har framtagits, och presenteras i detta dokument. Profilritningar från Sydvästlänken har använts för att ta fram data.

**Kabellängder– övergripande**

Total längd, andel, och några andra nyckeltal rörande de två kabeltyperna som är förlagda i Sydvästlänken visas i Tabell 1**.** Det kan konstateras att nästan 60 % av de 192 km består av den tunna 2010 mm$^2$ kabeln.

*Tabell 1. Nyckeltal över fördelning av 2010 och 2590 kabel i Sydvästlänken*

| **Kablar** | Tot | 2010mm2 | 2590mm2 | Kommentar |
|---|---|---|---|---|
| Längd [m] | 192003 | 114398 | 77605 | |
| % av total längd | 100% | 59.6% | 40.4% | |
| Antal längder | 144 | 76 | 68 | |
| Medellängd [m] | 1333 | 1505 | 1141 | |
| Kortaste kabel [m] | 8 | 8 | 8 | 1 Se fotnot |
| Längsta kabel [m] | 1825 | 1825 | 1340 | |

[1]De korta kabellängderna beror på att en kabel kan ha flera beteckningar i CAD. Den kortaste kabeln är ca 400m.

**Jordklasser - övergripande**

I Tabell 2 återfinns längdfördelningen av de olika jordklasserna längs med Sydvästlänken. Dessa är baserade på vilket förläggningsfall som är utfört. För en lista över förläggningsfall hänvisas till Tabell 3 på nästa sida.

*Tabell 2. Nyckeltal över fördelning av jordklass längs med sydvästlänken.*

| **Jordklass** | A | B | C | D | E | Ospecificerat | Total |
|---|---|---|---|---|---|---|---|
| Antal delsträckor | 573 | 163 | 272 | 34 | 26 | 69 | 1137 |
| Total längd [m] | 127891 | 24907 | 26205 | 2241 | 3551 | 7208 | 192003 |
| % av total | 67% | 13% | 14% | 1% | 2% | 4% | 100% |

*Tabell 3. Simpel lista över förläggningsfall. Det stora flertalet förläggningsfall har varianter för att hantera olika situationer.*

| Förläggningsfall | Marktyp | Beskrivning |
|---|---|---|
| 1 | a | Trench i normal jord (typ A) , djup 1.2 m – 4 m |
| 2 | a | Trench i normal jord (typ A), djup 4 m – 6 m |
| 3 | a | Trench i normal jord (typ A) med 1 m mulljord |
| 4 | b | Trench i torr jord (typ B) |
| 5 | e | Trench i dyig våtmark (typ E) |
| 6 | c | Trench genom grund normalfuktig torv (typ C) |
| 7 | d | Trench genom torr torv (typ D) – 2590 mm2 |
| 8 | c | PE-rör i friktionsjord under grund normalfuktig torv (typ C) |
| 9 | c | Täckta PE-rör på botten av grund normalfuktig torv (typ C) |
| 10 | e | Täckta PE-rör på botten av grund mycket våt torv (typ E) |
| 11 | c | PE-rör på grund nivå i normalfuktig torv (typ C) – 2590 mm2 |
| 12 | e | PE-rör på grund nivå i mycket våt torv (typ E) |
| 13 | c | Djup styrd borrning i normalfuktig torv (typ C) - 2590 mm2 |
| 14 | a | Mycket liten väg på A-jord (b=7 m, h=0 m) |
| 15 | b | Mycket liten väg på B-jord (b=7 m, h=0 m) |
| 16 | a | Liten väg på A-jord (b=12 m, h=0 m) |
| 17 | b | Liten väg på B-jord (b=12 m, h=0 m) |
| 18 | a | Liten upphöjd väg på A-jord (b=12 m, h=1 m) |
| 19 | b | Liten upphöjd väg på B-jord (b=12 m, h=1 m) |
| 20 | a | Liten väg med hög bank på A-jord (b=12 m, h=5 m) |
| 21 | b | Liten väg med hög bank på B-jord (b=12 m, h=5 m) |
| 22 | a | Liten väg med mycket hög bank på A-jord (b=12 m, h=8 m) |
| 23 | b | Liten väg med mycket hög bank på B-jord (b=12 m, h=8 m) |
| 24 | a | Normalstor väg på A-jord (b=20 m, h=2 m) |
| 25 | b | Normalstor väg på B-jord (b=20 m, h=2 m) |
| 26 | a | Stor väg på A-jord (b=¥, h=3 m) |
| 27 | b | Stor väg på B-jord (b=¥, h=3 m) |
| 28 | a | Mycket stor väg på A-jord (b=¥, h=6 m) |
| 29 | b | Mycket stor väg på B-jord (b=¥, h=6 m) |
| 30 | a | Djup styrd borrning i A-jord (maxdjup 6 m) |
| 31 | b | Djup styrd borrning i B-jord (maxdjup 6 m) |
| 32 | a | Styrd borrning i A-jord + liten väg med hög bank (b=12 m, h=5 m) |
| 33 | b | Styrd borrning i B-jord + liten väg med hög bank (b=12 m, h=5 m) |
| 34 | - | Instruktion för korsningar med andra kraftkablar |

**Standardfall – förläggningsfall 1**

Standardförläggning, det vill säga förläggningsfall 1 (se Tabell 3), är utförd på totalt 265 sträckor om en total längd av 90 151 m.

## B-jord i 2010mm2 kabel

Tabell 4 visar hur stor del av Sydvästlänken där 2010mm$^2$ kabel är förlagd i jordklass B. Eftersom 2010-kabeln är tänkt att vara förlagd i jord med termisk resistivitet på mindre än 1.5 mK/W finns risk att delar av dessa sträckor är underdimensionerade.

*Tabell 4. Överblick för delsträckor med tunn kabel i jordklass B.*

| | |
|---|---|
| Total längd tunn kabel i jordklass B [m] | 9575 |
| Andel av Sydvästlänken | 5 % |
| Medellängd för delsträcka med tunn kabel i jordklass B [m] | 121.2 |
| Antal delsträckor med tunn kabel i jordklass B | 79 |

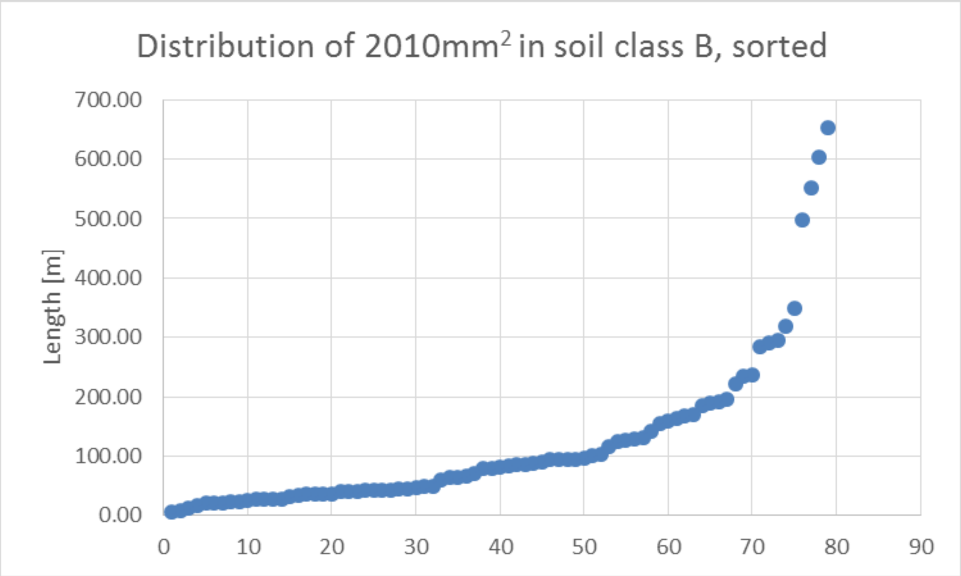
Tabell 5 visar en tabell över de sträckor där 2010 mm$^2$ kabel är förlagd i jordklass B.

*Tabell 5. Tabell över de sträckor där kabel med ledningsarea om 2010 mm² är förlagd i jordklass B. Kolumnerna för start och slut representerar avståndet från Sydvästlänkens start enligt plan och profilritningar.*

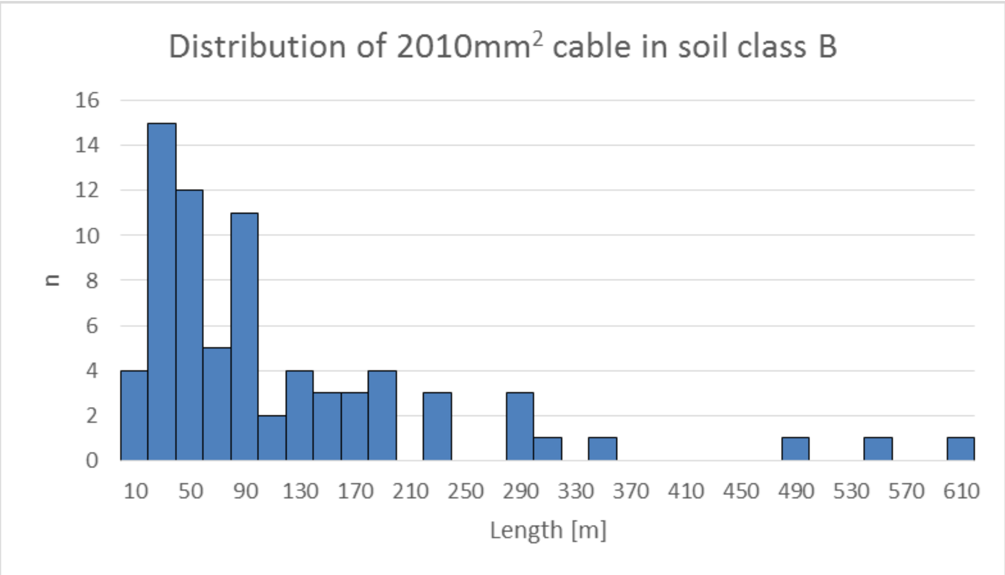
| Norra sträckan | | | | |
|---|---|---|---|---|
| Start | Slut | Längd | Förläggningsfall | Kommentar |
| 4770 | 4896 | 126 | 4(a-b)-1 | |
| 8698 | 8768 | 70 | 4(a-b)-1 | |
| 9647 | 9670 | 23 | 4(a-b)-1 | |
| **Södra sträckan** | | | | |
| Start | Slut | Längd | Förläggningsfall | Kommentar |
| 93 | 248 | 155 | 4(a-b)-1 | |
| 36123 | 36143 | 20 | 4(a-b)-1 | |
| 36202 | 36327 | 125 | 4(a-b)-1 | |
| 36474 | 36574 | 100 | 4(a-b)-1 | |
| **60175** | **60224** | **49** | **19** | **Oklart förläggningsfall** |
| **60224** | **60257** | **33** | **17** | **Oklart förläggningsfall** |
| 65506 | 65727 | 221 | 4(a-b)-1 | |
| 66005 | 66173 | 168 | 4(a-b)-1 | |
| 66173 | 66209 | 36 | 4(a-b)-1 | |
| 66209 | 66237 | 28 | 17b | |
| 66237 | 66788 | 551 | 4(a-b)-1 | |
| 66788 | 66820 | 32 | 17b | |
| 66820 | 67317 | 497 | 4(a-b)-1 | |
| 67317 | 67382 | 65 | 17b | |
| 67382 | 67673 | 291 | 4(a-b)-1 | |
| 68082 | 68316 | 234 | 4(a-b)-1 | |
| 69048 | 69075 | 27 | 4(a-b)-1 | |
| 69075 | 69084 | 9 | 15a | |
| 69084 | 69112 | 28 | 4(a-b)-1 | |
| 69398 | 69488 | 90 | 4(a-b)-2 | |
| 69488 | 69658 | 170 | 4(a-b)-1 | |
| 69911 | 70515 | 604 | 4(a-b)-1 | |
| 70515 | 70558 | 43 | 25a | |
| 70558 | 70601 | 43 | 4(a-b)-4 | |
| 70601 | 70645 | 44 | 4(a-b)-1 | |
| 70782 | 70832 | 50 | 4(a-b)-1 | |
| 70832 | 71182 | 350 | 4(a-b)-1 | |
| 72655 | 72840 | 185 | 4(a-b)-1 | |
| 73822 | 73902 | 80 | 4(a-b)-1 | |
| 73902 | 73927 | 25 | 4(a-b)-3 | |
| 73927 | 73994 | 67 | 4(a-b)-1 | |
| 74712 | 74753 | 41 | 4(a-b)-1 | |
| 74832 | 74911 | 79 | 4(a-b)-1 | |
| **84175** | **84180** | **5** | **4(a-b)-7** | **Förläggningsfallet avsett för 2590 mm²** |
| 84180 | 84197 | 17 | 4(a-b)-2 | |
| 84197 | 84360 | 163 | 4(a-b)-1 | |
| 84700 | 84890 | 190 | 4(a-b)-1 | |
| 85162 | 85256 | 94 | 4(a-b)-1 | |
| 85561 | 85752 | 191 | 4(a-b)-1 | |
| 93679 | 93762 | 83 | 4(a-b)-1 | |

| | | | | |
|---|---|---|---|---|
| 93848 | 94043 | 195 | 4(a-b)-1 | |
| 94143 | 94258 | 115 | 4(a-b)-1 | |
| 94948 | 94988 | 40 | 4(a-b)-1 | |
| 95600 | 95884 | 284 | 4(a-b)-1 | |
| 97012 | 97040 | 28 | 17b | |
| 97040 | 97076 | 36 | 4(a-b)-2 | |
| 97172 | 97267 | 95 | 4(a-b)-1 | |
| 97409 | 97568 | 159 | 4(a-b)-1 | |
| 97568 | 97603 | 35 | 17b | |
| 97603 | 97698 | 95 | 4(a-b)-1 | |
| 97752 | 97798 | 46 | 4(a-b)-1 | |
| 97833 | 98128 | 295 | 4(a-b)-1 | |
| 98128 | 98170 | 42 | 4(a-b)-2 | |
| 98170 | 98258 | 88 | 4(a-b)-1 | |
| 109099 | 109240 | 141 | 4(a-b)-1 | |
| 131820 | 131906 | 86 | 4(a-b)-1 | |
| 131906 | 131950 | 44 | 17b | |
| 133182 | 133500 | 318 | 4(a-b)-1 | |
| 133598 | 133619 | 21 | 4(a-b)-1 | |
| 133619 | 133748 | 129 | 4(a-b)-1 | |
| **133748** | **133850** | **102** | **31b** | **Förläggningsfallet avsett för 2590 $mm^2$** |
| 133850 | 134087 | 237 | 4(a-b)-1 | |
| 134130 | 134215 | 85 | 4(a-b)-1 | |
| 134268 | 134292 | 24 | 4(a-b)-1 | |
| 134692 | 134728 | 36 | 4(a-b)-1 | |
| 134856 | 134920 | 64 | 4(a-b)-1 | |
| 136604 | 137257 | 653 | 4(a-b)-1 | |
| 137257 | 137270 | 13 | 15a | |
| 137270 | 137365 | 95 | 4(a-b)-1 | |
| 137768 | 137865 | 97 | 4(a-b)-1 | |
| 137865 | 137906 | 41 | 17b | |
| 137906 | 137948 | 42 | 4(a-b)-1 | |
| **157357** | **157487** | **130** | **4a** | **Oklart förläggningsfall** |
| **176700** | **176759** | **59** | **4-a-2** | **Oklart förläggningsfall** |
| **177119** | **177140** | **21** | **4-a-2** | **Oklart förläggningsfall** |
| 179908 | 179990 | 82 | 21a | |

Figur 1 och Figur 2 visar hur längderna på de sträckor där 2010-kabel är förlagd i markklass B fördelar sig.




*Figur 1.* *Sorterad fördelning av längden på de sträckor där 2010-kabel är förlagd i markklass B.*




*Figur 2.* *Fördelnignsdiagram över längden på de sträckor där 2010-kabel är förlagd i markklass B. Varje stapel representerar ett intervall om 20 meter. (1-20m, 21-40 etc.)*

# Appendix 3

# Undersökningar och tekniskt underlag för Sydvästlänkens markarbeten - En översikt

## Inledning

Föreliggande beskrivning grundas på en presentation lämnad av Håkan Garin, projektansvarig geotekniker.

Arbetena omfattade en rad moment:

- ingenjörsgeologisk och geoteknisk kartering,
- geofysisk och geoteknisk undersökning,
- provgropsgrävning och provschakter,
- laboratorieundersökningar av jordprover – siktning m m
- fältmätning termiska egenskaper
- laboratorieundersökning av kabelsand – termiska egenskaper
- projektering inklusive termiska beräkningar
- upprättande av beskrivning med mängdförteckning

## Utredningsarbete

Undersökningarna genomfördes i olika faser:

- Ingenjörsgeologisk och geoteknisk skrivbordsstudie
- Ingenjörsgeologisk, geoteknisk och hydraulisk kartering i fält
- Geofysiska undersökningar i fält
- Geotekniska sonderingar och provtagningar samt geohydrologiska undersökningar
- Provschakt och provgropsgrävning
- Hydraulisk modellering av markvattenförhållanden utifrån topografi, vattendrag och avrinningsområden
- Tolkning, projektering och redovisning
- Teknisk beskrivning för förfrågningsunderlag

Kartering har skett i fält längs hela sträckan och bl.a. omfattat:

- Berg i dagen inom 25 m avstånd från planerad ledningsdragning
- Geologisk kartering och bedömning av jordlager längs planerad ledningsdragning. Provtagning med handhållen utrustning eller spade minst var 25:e meter.
    - Mulljordstjocklek
    - Bedömd jordart för schakt
    - Ytnära berg, d<0,25 m

De geofysiska undersökningarna, huvudsakligen georadar, syftade till att klarlägga bl.a. följande:

- Bergfrihet
- Blockighet i jordlager
- Fri grundvattenyta i friktionsjord
- Jordlagergränser
- Bottentopografi och förhållanden vid utförande på sjö/vattendrag

Uppdaterad tolkning och redovisning har skett efter utförda geotekniska och geohydrologiska undersökningar samt provschakter.

I ett sent skede genomfördes även fältundersökningar av termiska egenskaper med sondsmetod. På prover utfördes även laboratorieundersökningar.

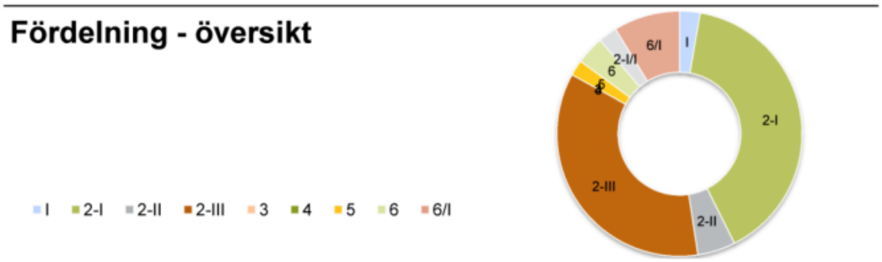
## Teknisk beskrivning

Sträckningen delades in i 5 block. I den tekniska beskrivningen för de 5 blocken använde man sig av markklasser och referensegenskaper för dessa, som underlag för entreprenörens schaktkapacitet. Markklasserna definierades efter prognosticerad mängd block (i olika storleksintervall), sten och kornstorleksfördelningen i övrigt. Dessa baserades på markundersökningar och provgropsgrävning, som inkluderade grovsiktning i fält. Sex markklasser infördes, med underklasser, som definierades och korrelerades mot materialtyp i AMA, se Tabell 1. Ett exempel på hur fördelning kunde se ut för ett avsnitt framgår av Tabell 2. Beskrivningar och illustrationer av de olika markklasserna utfördes, se exempel i Figur 1. Markklasserna lades också in på ritning, se Figur 2.

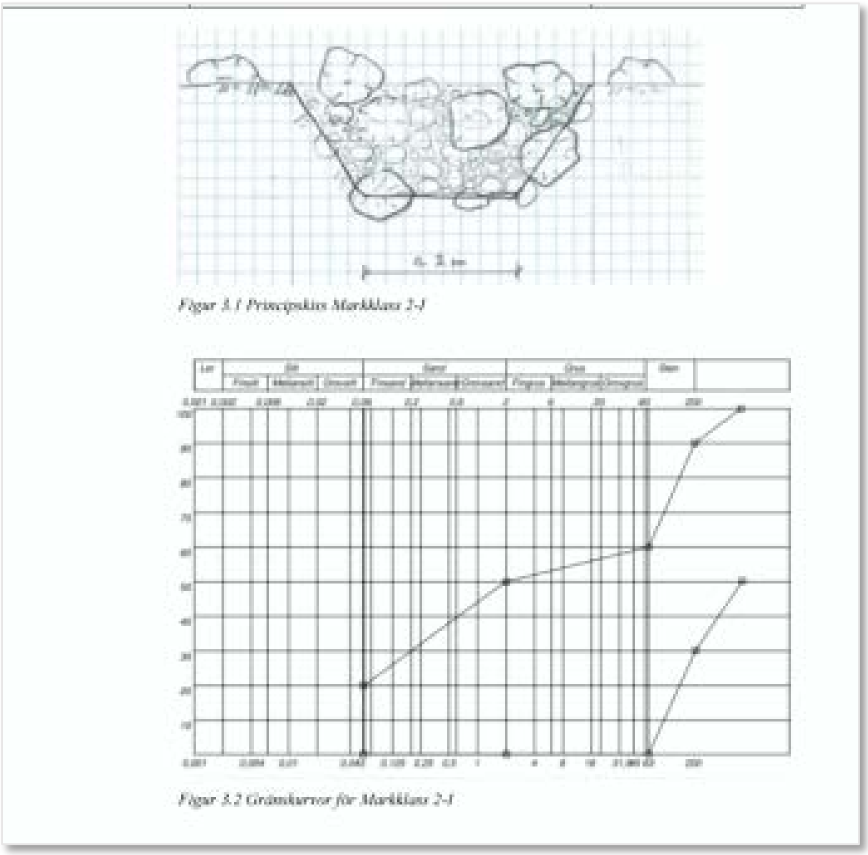
*Tabell 1 Markklasser*

| Markklass | Materialtyp, AMA | Finjordshalt* | Organisk halt | Sten- och blockhalt >63 mm | Blockhalt >200 mm | Blockhalt >630 mm | Beskrivning enligt 14688-2 |
|---|---|---|---|---|---|---|---|
| 1 | 1, 3A | | | | | | Berg |
| 2-I | 2, 3B | <30 | <2 | >40 | 10-70 | <50 | Block- och stenjord |
| 2-II | 2, 3B | <30 | <2 | 20-60 | <40 | <30 | Block- och stenjord |
| 2-III | 2, 3B, 4A | <40 | <2 | <40 | <20 | <10 | Blandkornig grov- och finjord |
| 3 | 2, 3B | <40 | <2 | <10 | <5 | | Blandkornig grov- och finjord |
| 4 | 2, 4A | <40 | <2 | | | | Blandkornig finjord, ensartad sand |
| 5 | 4B, 5A, 5B | ≥40 | ≤6 | | | | Finkornig jord |
| 6 | 6A, 6B | | >6 | | | | Organisk jord |

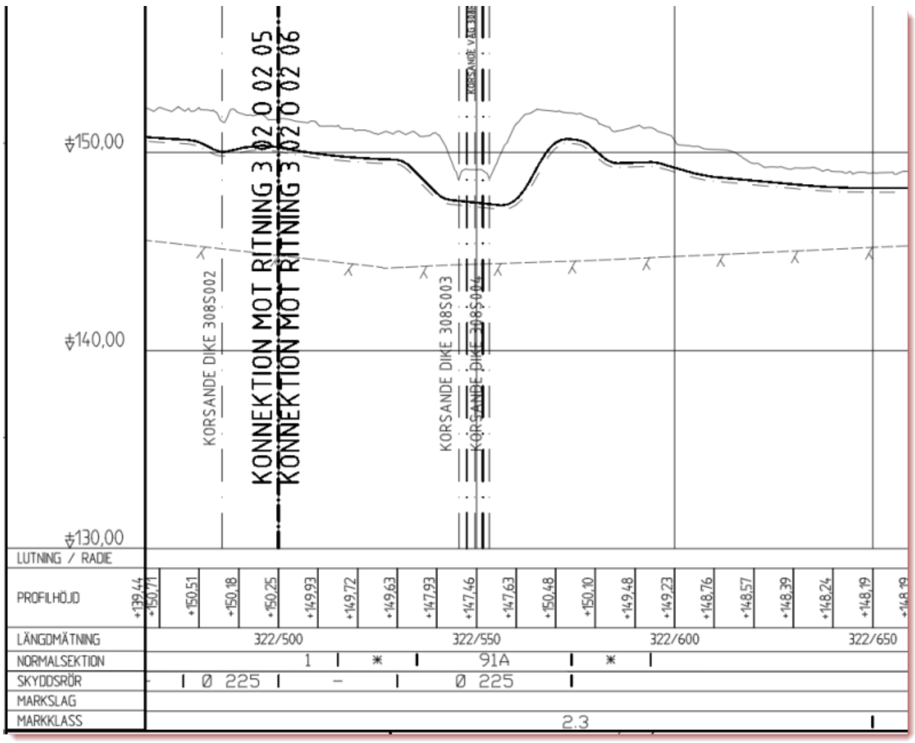
*Tabell 2 Exempel på fördelning av markklasser för en delsträcka.*




| Lagerföljd | Markklass | Prognos (m) | Prognos (%) | Variationsområde min (m) | Variationsområde max (m) | Anmärkning |
|---|---|---|---|---|---|---|
| Singulär jordlagerföljd | I | 65 | 3 | | | Bergschakt se CBC.329 |
| | 2-I | 958 | 40 | *800* | *1 150* | |
| | 2-II | 120 | 5 | *100* | *220* | |
| | 2-III | 850 | 35 | *760* | *990* | |
| | 3 | 0 | 0 | *0* | *150* | |
| | 4 | 0 | 0 | *0* | *0* | |
| | 5 | 50 | 2 | *20* | *100* | |
| | 6 | 90 | 4 | *65* | *150* | |
| Mix | 2-I/I | 59 | 2 | *45* | *100* | Bergschakt se CBC.329 |
| | 6/I | 210 | 9 | *170* | *250* | Bergschakt se CBC.329 |
| | Totalt | 2 402 m | 100 % | | | |




*Figur 1 Beskrivning och illustration av en markklass.*




*Figur 2 Illustration över markklass/referensegenskaper på ritning.*

I den tekniska beskrivningen indelades de olika blocken i delblock. För varje block gjorden en översiktlig beskrivning i textform.

## Tekniska egenskaper

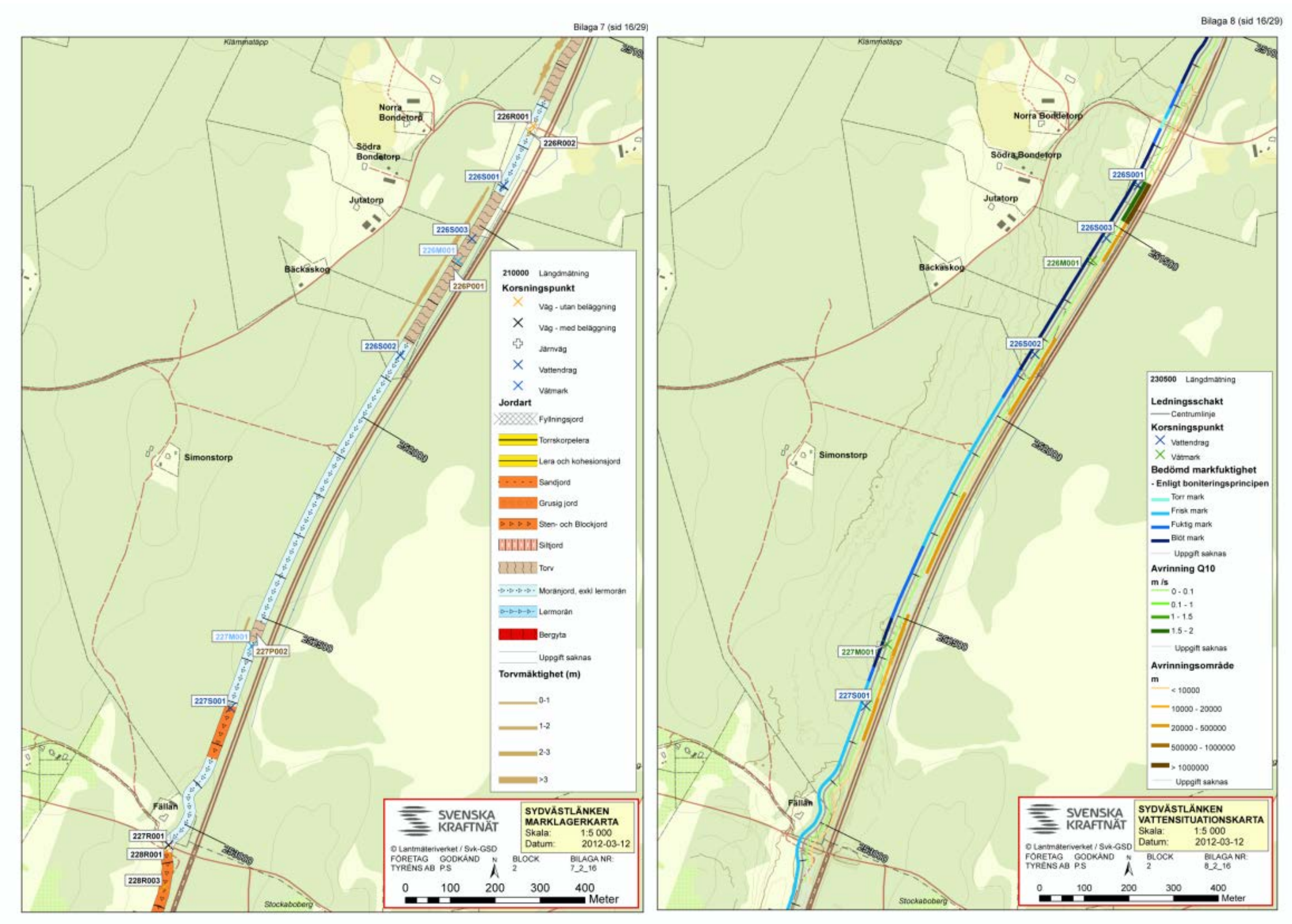
Fältundersökningar av termisk resistivitet genomfördes som grund för projektering av framförallt centrumavstånd för de två kabeltyperna.

En separat ATB togs fram för kabelsand. I den specificerade två typer av kabelsand, en för normal jord och en för jord med högre resistivitet. Krav på kornstorleksfördelning och kvartshalt ställdes, den senare för att säkerställa tillräckligt låg termisk resistivitet. Speciella krav ställdes på kabelsandens packning och densitet. Kavelsandens skulle packas till minst 90% proctor och därutöver med ett absolutkrav på torrdensitet större än 1850 kg/m$^3$.

Packningen skulle kontrolleras med kalibrerad nukleär densitetsmätare.

## GIS-underlag

Verktyg för genomförandet togs också fram i form av t.ex. marklager och vattensituations-kartor, se




*Figur 3 Kartor över marklager (tv) och vattensituationen (th).*