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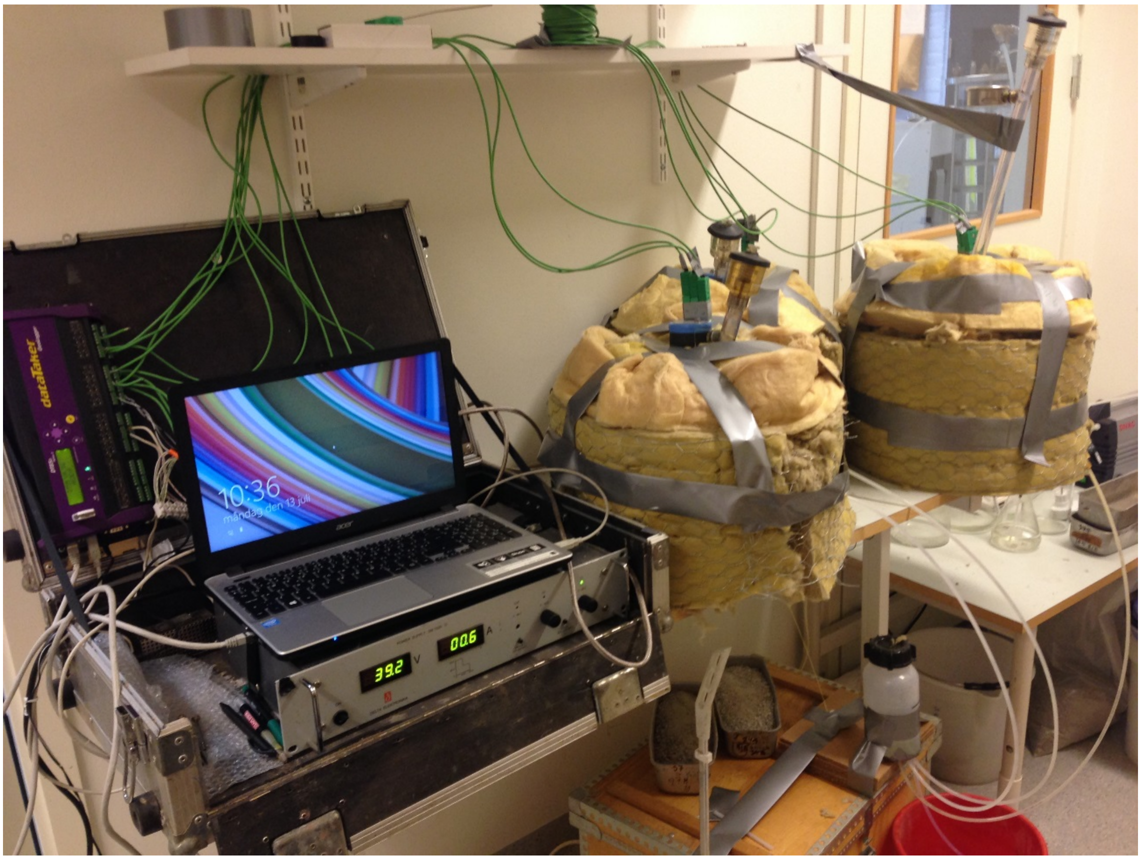
High temperature performance for high voltage underground cables in cable sand

Laboratory experiment

Peter Lidén, Jan Sundberg, Andreas Lilliestierna



Department of Civil and Environmental Engineering
Division of GeoEngineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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High temperature performance for high voltage underground cables in cable sand
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Sammanfattning

Vid en belastad markförlagd HVDC-kabel genereras värme p.g.a. kabelns elektriska motstånd, ett motstånd som även ökar med stigande temperaturer. Omgivande materials förmåga att leda bort värme har därmed stor betydelse för temperaturen i och runtomkring kabeln. En viktig parameter är vattenhalten i materialet. Vid en hög och långvarig belastning på kabeln kan det leda till att en uttorkning sker av kabelsanden närmast kabeln. Detta uppstår vid en kritisk punkt (temperaturnivå/flöde) och medför att en exponentiell temperaturökning sker som kan överstiga vad kabeln är dimensionerad för. Fenomenet orsakas av att ångdiffusionen, i temperaturgradientens riktning, inte längre är i balans med den kapillära återföringen i vätskefas. Hög vattenhållande förmåga för kabelsanden är därför väsentlig för att motverka uttorkning.

Det aktuella orienterande laboratorieförsöket har haft som syfte att studera om uttorkning sker i kabelsanden runt kabeln eller om ångdiffusionen kan betraktas som ett positivt tillskott till värmetransporten. Det finns motsägelsefull forskning i ämnet (se Sundberg, 2015). Den termiska resistiviteten i materialet tycks minska vid ökad temperatur under den kritiska punkten, på grund av tillskott till värmetransporten från ångdiffusion. Den termiska resistiviteten ökar sedan drastiskt när den kritiska punkten är nådd. Tidpunkten för den kritiska punkten beror i sin tur av flera faktorer, såsom t.ex. kabelsandens packningsgrad, mineralogi och vattenhalt, belastning på kabeln, kabeldimension mm, men har alla gemensamt att de påverkar den termiska resistiviteten.

Det orienterande laboratorieexperimentet innehöll tre olika kabelsandmaterial varav två användes vid Sydvästlänks-projektet, Sydsten Dalby och Södra Sandby. Utöver det så ingick sandmaterialet Hamneda. Vid experimentet packades värmesonder in i de tre olika materialen. Försöksuppbyggnaden utformades så att grundvattennivån kunde variera i anslutning till kabeln. Temperaturutvecklingen i sonderna och sanden, samt vattenhalten, studerades under försökets gång.

Det orienterande experimentet har varit framgångsrikt och gett indikativa svar på många av de uppställda frågeställningarna. Experimentet visar att så länge som vatten finns att tillgå genom kapillär upptransport från grundvattenytan sker ingen uttorkning runt kabeln. Detta trots att kabeln belastas med väldigt hög effekt, mycket högre än vad en markförlagd kabel utsätts för. Ångdiffusionen bidrar till den konduktiva värmetransporten.

Om den kapillära upptransporten av vatten bryts torkar kabelsanden däremot ut efter att vattnet migrerat genom ångdiffusion. Den termiska resistiviteten höjs med temperaturökning runt sonden som följd, eftersom luftfickor bildas i materialets porsystem. Effekten tenderar att leda till att vatten inte återgår till samma nivå i porsystemet som tidigare, trots återtransport av vatten.

För att kunna bekräfta resultaten från försöket samt för att bringa klarhet i vad som orsakar en bruten kapillär vattentransport rekommenderas att försöket skalas upp, värmetransporten, ångdiffusion och kondensation är förlopp som kräver en större volym för att kunna studeras och jämföras med verklig markinstallation. Eftersom det inte tycks ske någon uttorkning då det finns vatten att tillgå samt att den termiska resistiviteten tenderar att minska vid ökad ångdiffusion, skapas möjligheter för en enklare, kompaktare och mindre konservativ dimensionering.

Contents

1 Background and problem description

Heat is generated in operative underground HVDC-cables due to electric resistance in the conductor, a resistance that increases with increasing temperatures. The ability to lead away heat in the surrounding material (cable sand, also named as cable bed and backfill material) is therefore of great importance for the temperature in and around the cable. One of the prime parameters affecting this ability to transfer heat, is the water content in the material. During extended peak loads on the power throughput of the cable, the surrounding soil can suffer from local dry outs. This occurs at a critical combination of high temperature and low incoming capillary flow of groundwater and leads to exponential increase of temperature that can exceed the design values of the cable. This phenomena occurs when vapour diffusion in the direction of the temperature gradient no longer is in balance with the incoming capillary flow of water.

Anticipating the point of occurrence for this critical point is not trivial, neither is whether the build-up in temperature to this point is exclusively negative. The thermal resistivity in the material appears to decrease, due to vapour diffusion, when the temperature approaches critical levels, before rapidly increasing when this point is reached. This critical point is decided depending upon numerous factors, with the common denominator being that they affect thermal resistivity; the gradation and mineral composition of the backfill and cable bed material around the cable, its water content, cable dimension and the load applied, etc. By decreasing thermal resistivity in the cable and surrounding soil the risk of dehydration of the soil can be reduced. During installation of the cable in trenches surrounded by crystalline soil with favourable thermal properties, it is desirable to adequately compact the material in order to reduce the porous volume, thus increasing the materials ability to retain water above groundwater level. This leads to better heat transfer in the material since a lower total thermal resistivity is achieved when the porous system is water filled. If the material is allowed to dehydrate and produce pockets of air in the porous system, due to too much vapour diffusion, the thermal resistivity increases followed by increased temperature in and around the cable.

A literature study that has been carried out during this project covers some international research experiments being performed in this field of science (Sundberg, 2015). The general purpose of these studies has been to evaluate whether dehydration occurs around underground cables in a controlled laboratory environment. There where however differences regarding setup and geometry in these experiments, and the results where contradictory. Some of the experiments showed increased thermal resistivity at high temperature while others showed decreased thermal resistivity depending on experiment set-up and boundary conditions, see Sundberg, 2015.

2 Purpose and objectives

Since international research experiments give contradictory results, the purpose of this orienting laboratory experiment is to bring some clarity to what occurs around underground power cables for different temperatures and changed groundwater levels. The geometry and boundary conditions is set up to mimic real conditions better then aforementioned experiments. Three different sands are studied with applied electrical power, temperature and groundwater level, which are adjusted throughout the project.

The objectives of the experiments are to:

- Investigate whether dry out occurs around the cable
- Investigate the hypothesis that the vapour would condensate within the sand further away from the heat source and then flow back towards the heater due to unbalance in pressure.
- Investigate if there is a possibility to account for positive effects regarding heat transfer from vapour diffusion
- Investigate if temporary lowering of the groundwater table causes permanent decreases in water content and increased thermal resistivity in the soil, due to hysteresis
- Investigate how different degrees of compaction affects the heat transfer process.
- Investigate what effect the following parameters have on dry out of soil
    - Water retention properties
    - Pore pressure (groundwater level)
    - Magnitude of heat flow (applied electrical effect)
    - Temperature (from applied electrical effect and material properties)
    - Thermal properties of the material under regular circumstances (low temperatures)

3 Methodology

In an initial phase of the project the equipment is tested to make sure they are adequately functional and suitable for its purpose. If the equipment is on par with the requirements, the experiment continues according to the procedure in the following subchapter 3.1. A detailed numerical model of the setup is built in an early stage to establish the geometry and to create a basis that can be used for comparison and evaluation between the real experiment and the model. For this purpose, the numerical software Comsol Multiphysics is used.

3.1 Set-up and performance (Experiment 1)

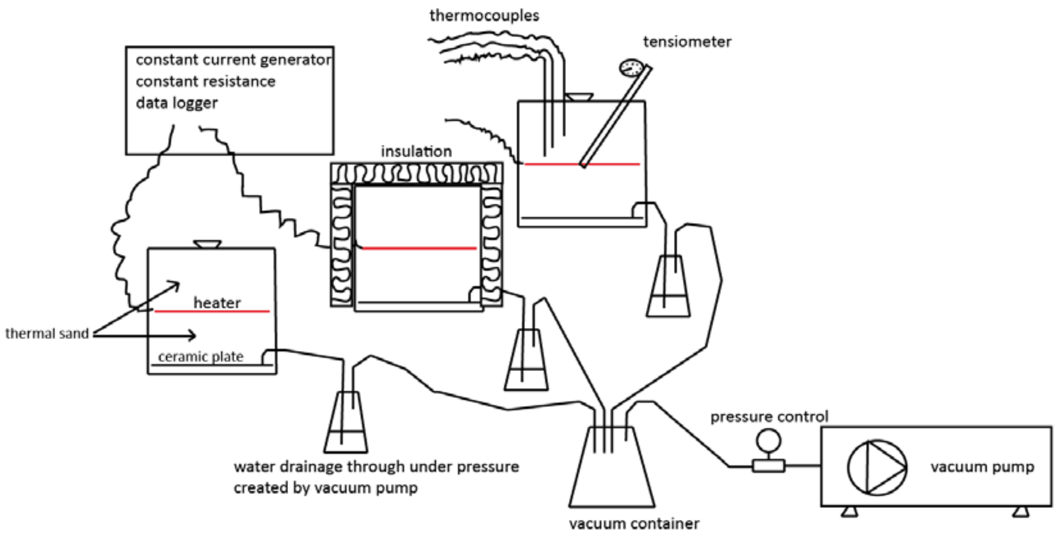

Figure 1. **Illustration of experiment 1. Three saucepans, all of them containing a heater, a ceramic plate, a tensiometer, thermocouples and outer insulation. The saucepans contains the three different sand materials that will be tested.**

Principal procedure of the experimental setup and performance for the initial experiment:

1. Ordering of necessary equipment such as porous ceramic plates, heating devices etc.

2. Obtaining cable sand (crushed rock material) from the three quarries (Hamneda 0-4 mm, Södra Sandby 0-5 mm, Sydsten Dalby 0-4 mm)

3. Analysis of water retention curves for the three cable sands. This gives information of water content versus different suction levels. Performed in the laboratory of Swedish University of Agricultural Sciences in Ultuna.

4. The experiment equipment is assembled in the laboratory of Geology in Chalmers. Three specially designed saucepans (normally used to determine soil retention curves) is connected to a vacuum pump. The ceramic plates is lowered to the bottom of the saucepans.

5. The sand is weighed in and mixed with water to reach a gravimetrical water content of 5%.

6. A thin layer of fine quartz powder is applied to the porous ceramic plates for better moisture contact with the cable sand before the cable sand is hand compacted (modified

proctor compaction) into the saucepans. Heaters, tensiometers and temperature sensors are installed during this procedure, wherefore extra care is taken when packing around these.

7. Total volume of the compacted sand is calculated.

8. Thermal resistivity is measured in the compacted sand. The sand is thereafter saturated with water and thermal resistivity is measured again.

9. The samples are drained to a moisture content equivalent to a groundwater level 0.5 meters below the heater. When the sand is drained to the correct level, insulation is applied on the sides and on top of the saucepans.

10. Parallel to the laboratory experiment, a model of the set-up is built in the software Comsol Multiphysics.

11. A known electric power is applied to the heater and after equilibrium temperature is reached, the power is increased in steps until the saucepans has reached ~70°C. The experiment is thereafter left untouched for at least 1 week.

12. The suction in the porous plate is increased to an equivalent negative pressure of 1.0 m at first and after pseudo steady state 2.0, 4.0 and 6.0 m of negative suction is applied (if the equipment allows stable conditions).

13. If the temperature in the heaters approaches extreme levels (close to 90-100°C) the applied power is to be decreased to a previous level.

14. When desired results have been obtained, the applied electric power is turned off and the experiment is deemed finished. When room temperature is reached, thermal resistivity is measured yet again, along with density and water content of the sands.

15. If necessary, complementary experiments with similar setup can be carried out in order to extract additional information due to experiences from the initial experiment or imperfections in the experiment.

3.2 Equipment

The equipment required for the setup is based on standardised equipment used when creating water retention curves for soil. In addition to this, equipment to simulate the heat from an electrical cable located in the centre of the saucepans is needed. In this case a heater placed in the cable sand that is exposed to a groundwater lowering.

The equipment used is standard equipment for constructing water retention curves including additional parts:

- Saucepan, specially designed with connections to fit porous ceramic plates.
- Porous ceramic plates, capable of withstanding a negative pressure of 1bar (equivalent to that of a -10 m groundwater level.)
- Glass containers and glass vacuum tank
- Valve for regulation of pressure
- Vacuum pump (Divac 1.4 HV3C)
- Vacumeter
- Insulation to encapsulate the saucepans (mineral wool d = 0.07m)
- Diffusion barrier for the lid of the saucepans

Equipment for measuring and heating:

- Thermal heaters with built-in thermocouples type J (Cartridge Heater Ø8x325mm 230V 300W, International Heating Products AB)
- Constant current generator (Delta Elektronika SM 7020-D)
- Logger (dataTaker DT85)
- Constant resistance 10mΩ for measurement of electric current
- Several thermocouples type K

For measuring thermal resistivity, a KD2-Pro device is utilised.

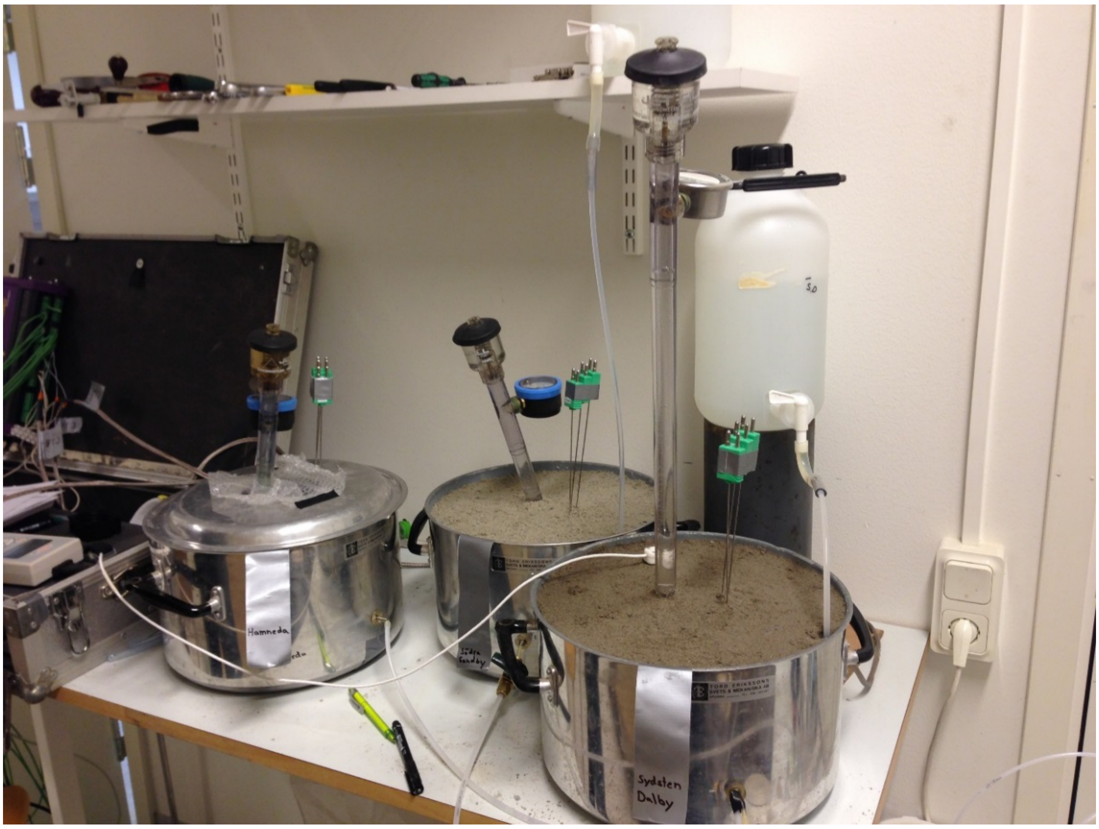

Figure 2. **Experimental setup after compaction with the sand exposed during measurement of thermal resistivity with a KD2-Pro device.**

Figure 2 shows how the tensiometers and thermocouples are installed in two of the saucepans, Sydsten Dalby and Södra Sandby. It also shows how the sand is saturated through a small pipe leading the water to the bottom of the pan. The sand in SS has a lighter colour than SD due to the high percentage of quarts.

The picture in Figure 3 shows the finished setup from experiment 1, right before application of insulation on the sides and on top. There is a diffusion barrier covering up the remainder of the hole in the lid to reduce the leakage of vapour.

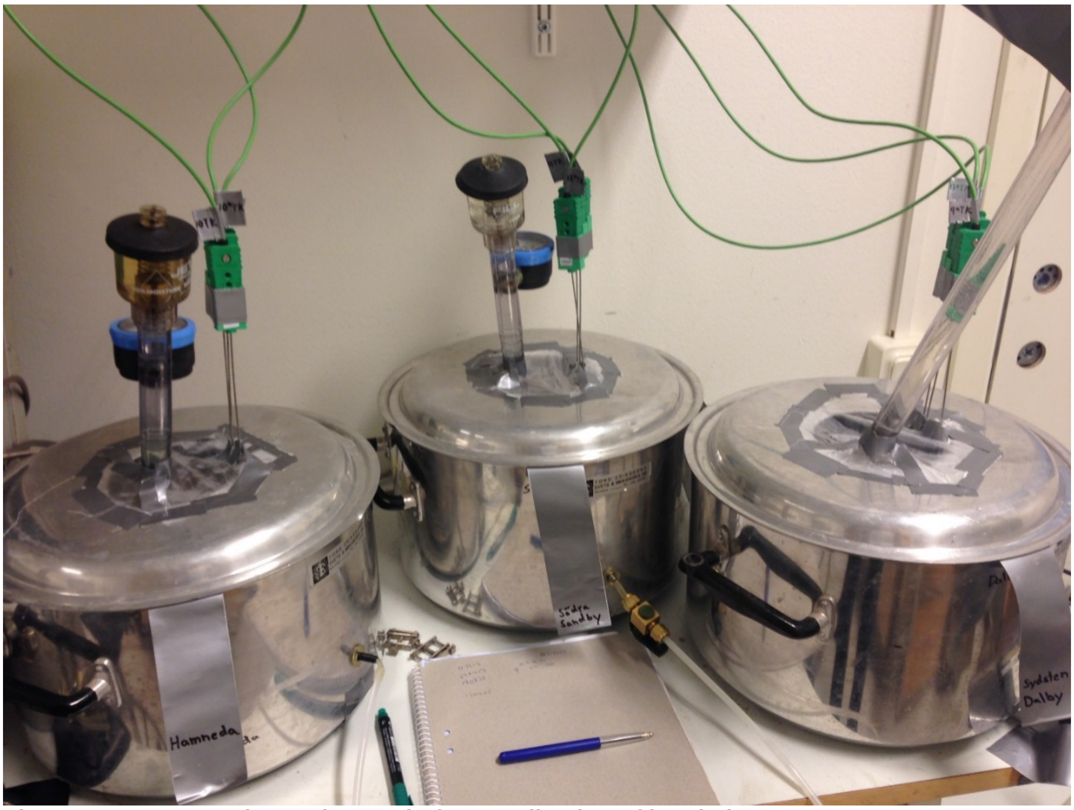

Figure 3. **Experimental setup before application of insulation.**

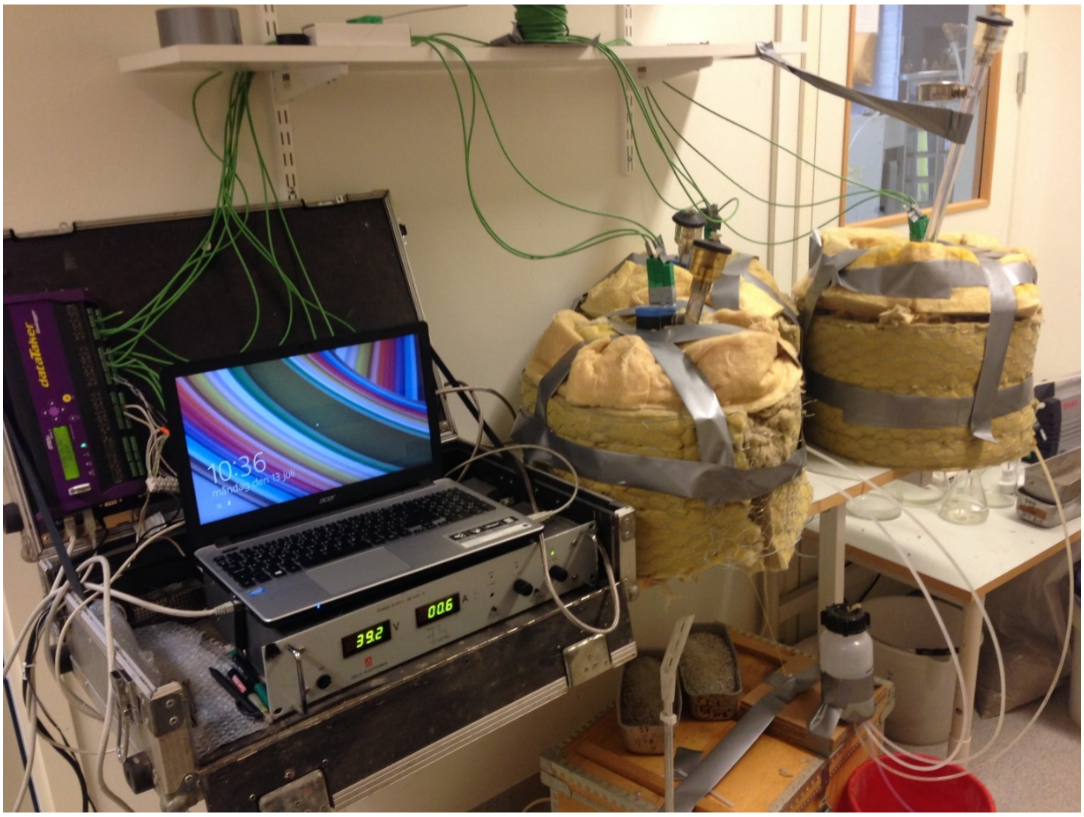

Figure 4. **The experimental setup including insulation. Note the logger and electrical unit on the left. The saucepans are connected to glass cylinders with plastic hoses, which in turn is connected to the vacuum pump.**

Power to the heaters was supplied by an electrical unit with a capacity of up to 20 Ampere and 70 Volt. The heaters were connected in parallel to allow enough voltage to produce adequate temperatures. For output data, the logger was set to record the temperatures every 15 seconds. The logger and the electrical power unit can be seen in Figure 4.

The finalised system for suction is visualised in Figure 5. The three porous ceramic plates in the saucepans are connected to their own glass cylinder with water, which in turn is connected to one larger glass vacuum tank. This vacuum tank is connected to the vacuum pump that can create suction equivalent of up to -1.0 Bar.

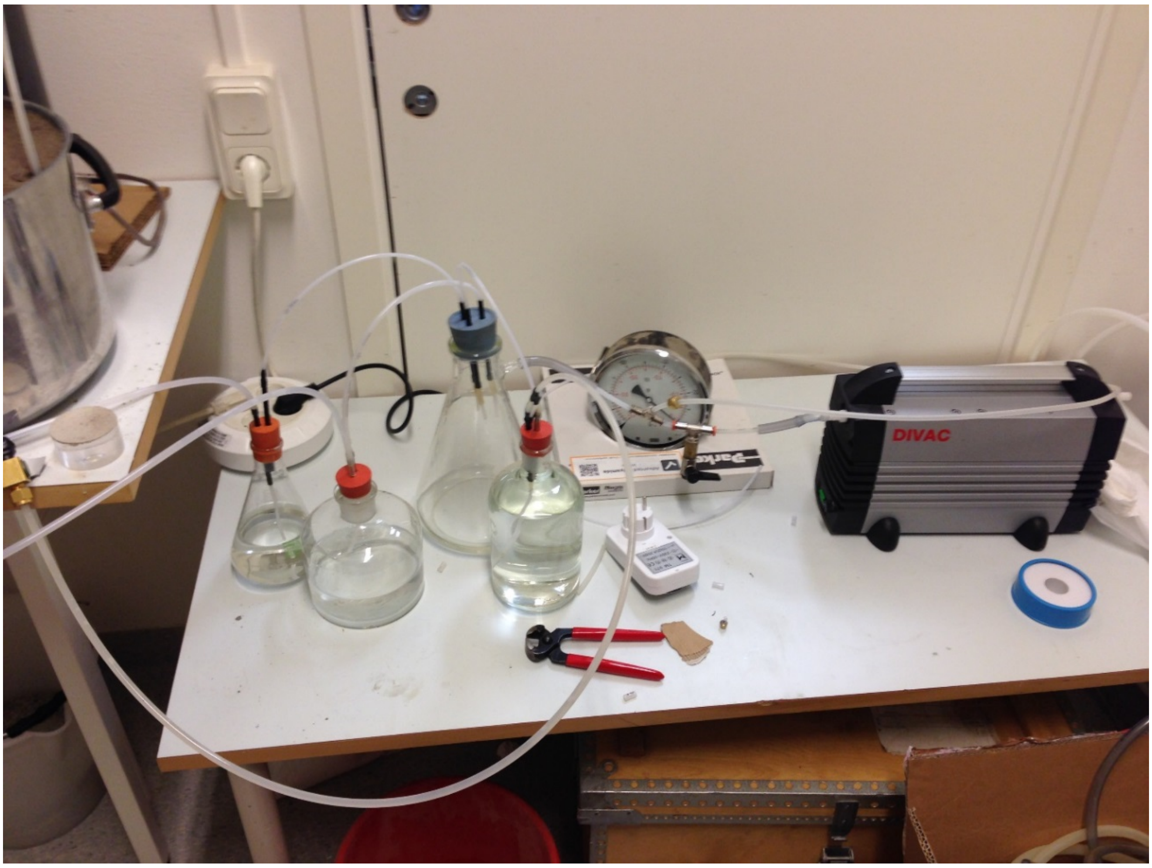

Figure 5. The pressurised system. A vacuum pump is connected to glass containers that retains drained water from the samples.

3.3 Complementary experiments, Experiment 2 and 3

Experiment 2 – Cable sand Sydsten Dalby (SD) and Södra Sandby (SS), repetition of experiment 1, without tensiometers, for the first ~500 hours of runtime. Same power input and negative pore pressures.

Experiment 3 – Cable sand SD, repetition of experiment 2, with no added compaction, for the first ~500 hours of runtime. The only compaction is due to natural compression caused by draining the water from the saucepan.

3.4 Numerical model in Comsol Multiphysics

This chapter aims to present and explicate the numerical model of the experiment, created in Comsol Multiphysics. A replica of the experiment was created in order to make parallel evaluation of the parameters involved and in order to analyse soil behaviour with different water content and temperatures. To save computation time, only one of the saucepans were built in the model and therefore the sands were evaluated in serial, not in parallel. The measured temperatures from the experiment is then compared to the computed temperatures in the model. The model can thereafter be altered until satisfactory fit have been reached.

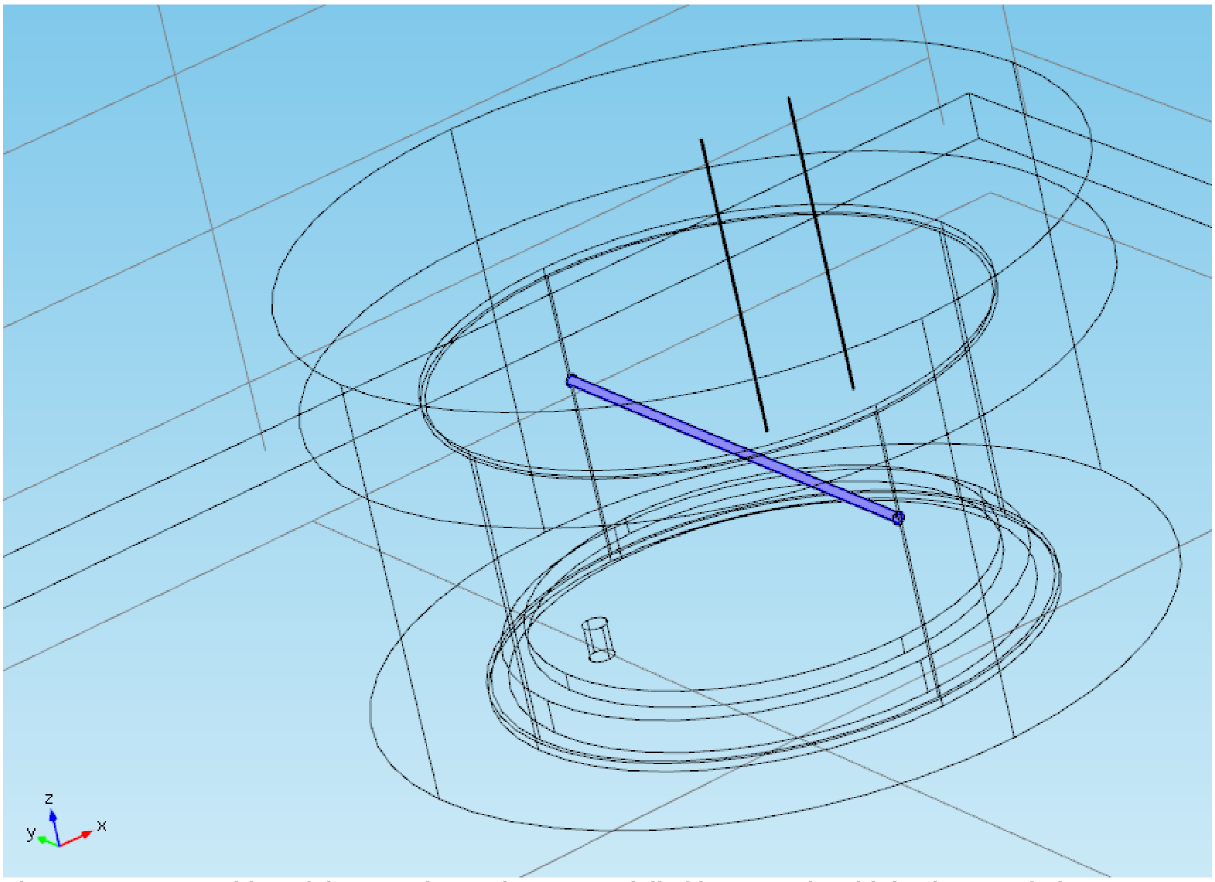

Figure 6. **Graphics of the experimental setup modelled in Comsol Multiphysics. Insulation, saucepan, sand within the saucepan, ceramic plate in the bottom of the saucepan and the heater in the centre of the saucepan.**

The model consists of the following elements:

- An air-filled room with boundary temperature (the real temperature of the room is logged and used as input in the model)
- A wooden table board on which the setup is built.
- Stainless steel saucepan with lid (r = 0.16 m, h = 0.175 m)
- Mineral wool insulation that encapsulates the saucepan (thickness = 0.07 m)
- Insulation on the bottom of the saucepan (thickness = 0.02 m)
- Porous ceramic plate on top of the bottom insulation (thickness = 0.01 m)
- Stainless steel thermocouples on various distances from the heater
- Heater in stainless steel, with magnesium oxide and ceramic core. Line heat source.

Boundary conditions includes room temperature and natural convection on all exposed areas, primarily on the insulation around the saucepan and the wooden table. In the solid materials heat is transferred with conduction only.

Most of the geometry and thermal properties were known, however there were certain parameters that needed further evaluation and calibration. This was done by fitting temperature curves in the model with the measured temperatures from the experiment. For instance, it became apparent that the tensiometers had a major impact on the temperature in the experiment, and to simulate this a simplification of the model was made where the value of thermal resistivity in the insulation was adjusted to include heat transfer through the tensiometer. However in the later stages experiment 2 and 3, the tensiometers were removed completely.

One of the major points of the project is to analyse how the thermal properties of the soil behave with different temperatures and water content, specifically to see if the thermal resistivity goes down when the temperature rises and when water content increase. This impact can be seen if a measured temperature curve anywhere in the sand during different applied effects and/or water content (mvp) is compared to a) constant thermal resistivity of the sand (measured) and b) variable thermal resistivity, dependent on temperature and water content.

The known inputs in the model are:

- Geometry
- Applied electric effect
- Thermal resistivity in
    - Stainless steel
    - Magnesium oxide
    - Mineral wool
    - Porous ceramic plate
    - Measured thermal resistivity of sand at 20°C

The uncertainties of the model are:

- The impact of the instrumentation in the saucepan
- Effective thermal resistivity in the insulation material
- Thermal resistivity of sand with increased temperature and variations in water content
- Potential vapour or water losses
- Heat loss through table

3.5 Analysis and evaluation

During and after the experiment an analysis and evaluation of the water retention properties and thermal properties will be performed. The results from the experiment will then be compared to the created model. A qualitative analysis is performed in order to study any deviations between the temperature curves in the experiment compared to the temperature curve in the model.

Through the aforementioned test procedure the length of the heater and the size of the sample sand will affect the temperature over time and will thus somewhat deviate from an infinitely long thermal source surrounded by sand. This is caused by 3D effects. In order to handle this, a detailed numerical Comsol Multiphysics model will be created based on purely conductive heat transfer. Based on this model, applied effect to reach certain temperatures can be predicted. A qualitative analysis of the temperature development and influence of vapour diffusion and dehydration should therefore be possible. Certain quantitative calculations could possibly also be performed.

4 Properties thermal sands

4.1 Material - thermal sand

Three cable sands (or thermal sands) were evaluated in the experiment, called SD (Sydsten Dalby), H (Hamneda) and SS (Södra Sandby), see Table 1. The difference between SD and H is the water retention properties. Type SD and SS has previously been used in the cable trenches of the Sydvästlänken project and is therefore interesting to analyse.

Table 1. Sand materials used in the experiment.

Material	Quarry	Grain size [mm]	Comment
SD	Sydsten Dalby	0-4	Analysed previously and used in the Sydvästlänken project. Relatively good water retention properties.
H	Hamneda	0-4	Analysed previously but not used in the Sydvästlänken project. Poorer water retention properties is to Expect.
SS	Ballast Södra Sandby	0-5	High quartz content. Previously analysed and sand with 0-2 mm grains used in the Sydvästlänken project (Sundberg, 2012). Lower thermal resistivity than the other two cable sands.

4.2 Summary table of properties for Experiment 1-3

After compaction of the sand, density and water content was calculated while thermal resistivity was measured. The same procedure was carried out after saturation and after the end of the experiment. Table 2 shows the results of the first run of the experiment, Table 3 shows data of the same parameters from Experiment 2 and Table 4 shows it for Experiment 3.

Table 2. Summary of measured parameters from Experiment 1.

Cable sand	Status	Density [kg/m^3]	Dry density [kg/m^3]	Gravimetric water content [m_w/m_{dry}]	Volumetric water content [V_w/V_{wet}]	Thermal conductivity [W/m·K]	Thermal resistivity [m·K/W]
H	After compaction	1896	1801	0.050	0.090	1.637	0.611
	After saturation	2019	1801	0.118	0.213	1.794	0.557
	End of experiment	1869	1822	0.025	0.046	1.113	0.898
SS	After compaction	2080	1976	0.050	0.099	2.147	0.466
	After saturation	2187	1976	0.105	0.207	3.143	0.318
	End of experiment	2111	2058	0.026	0.054	1.959	0.510
SD	After compaction	1908	1812	0.050	0.091	1.315	0.760
	After saturation	2055	1812	0.131	0.238	2.057	0.486
	End of experiment	1895	1839	0.030	0.056	1.263	0.792

Table 3. Summary of measured parameters from Experiment 2.

Cable sand	Status	Density [kg/m³]	Dry density [kg/m³]	Gravimetric water content [m_w/m_{dry}]	Volumetric water content [V_w/V_{wet}]	Thermal conductivity [W/m·K]	Thermal resistivity [m·K/W]
SS	After compaction	2041	1976	0.050	0.097	2.487	0.402
	After saturation	2151	1976	0.106	0.206	3.109	0.322
	End of experiment	2207	2118	0.042	0.09	2.246	0.445
SD	After compaction	1939	1842	0.050	0.092	1.461	0.685
	After saturation	2089	1842	0.131	0.242	2.216	0.451
	End of experiment	1829	1770	0.033	0.059	[1]	[1]

[1] not performed due to time limitations

Table 4. Summary of measured parameters from Experiment 3.

Sand	Status	Density [kg/m³]	Dry density [kg/m³]	Gravimetric water content [m_w/m_{dry}]	Volumetric water content [V_w/V_{wet}]	Thermal conductivity [W/m·K]	Thermal resistivity [m·K/W]
SD	After compaction	1436	1364	0.05	0.068	0.673	1.486
	After saturation	1869	1364	0.368	0.501	1.915	0.522
	End of experiment	1925	1794	0.073	0.131	1.915	0.522

4.3 Water retention capacity

Figure 7 and **Figure** 8 shows water retention curves for the three materials, plotted against degree of saturation and volumetric water content. The crosses represents water retention experimentally produced in 2012 by Vectura on materials from the same quarries as the ones evaluated in this experiments (Sundberg & Sundberg, 2012). The triangles shows the curves produced in 2015 in the laboratory of Swedish University of Agricultural Sciences in Ultuna while the diamonds symbolises an adjusted curve according to the porous volume calculated in this experiment.

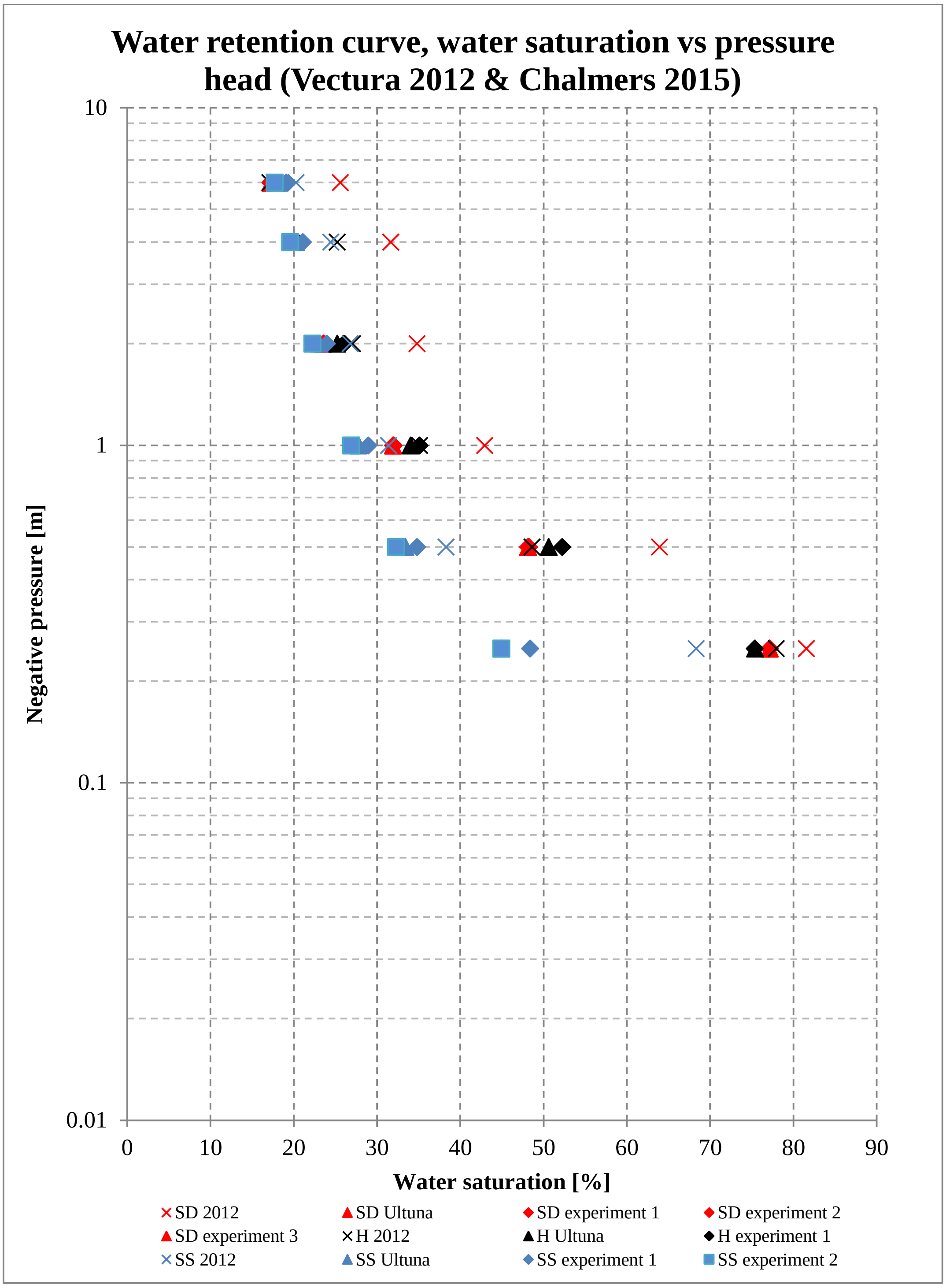

Figure 7 **Water retention curve for the three thermal sands, plotted against degree of saturation. Measured values from Vectura 2012 and new analysis in Ultuna from 2015. The experimental values are derived from Ultuna measurements adjusted with calculated porous volume.**

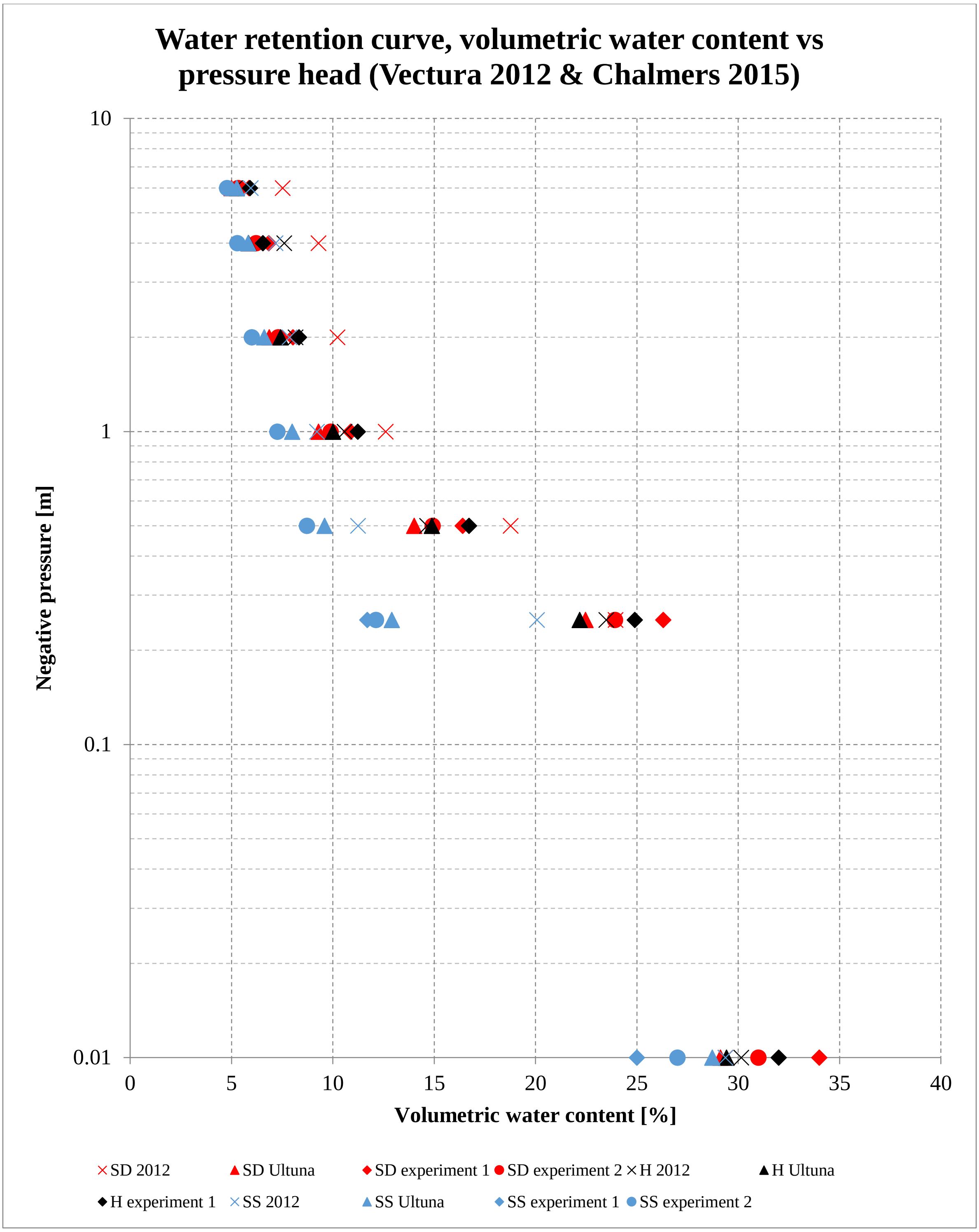

Figure 8 **Water retention curve for the three thermal sands, plotted against volumetric water content. Measured values from Vectura 2012 and new analysis in Ultuna from 2015. The experimental values are derived from Ultuna measurements adjusted with calculated porous volume.**

4.4 Thermal resistivity

4.4.1 Thermal resistivity vs volumetric water content

Figure 9 shows measured values of thermal resistivity plotted against volumetric water content. Crosses symbolises measured values by Vectura in 2012 while the diamonds represents values measured in 2015 at Chalmers.

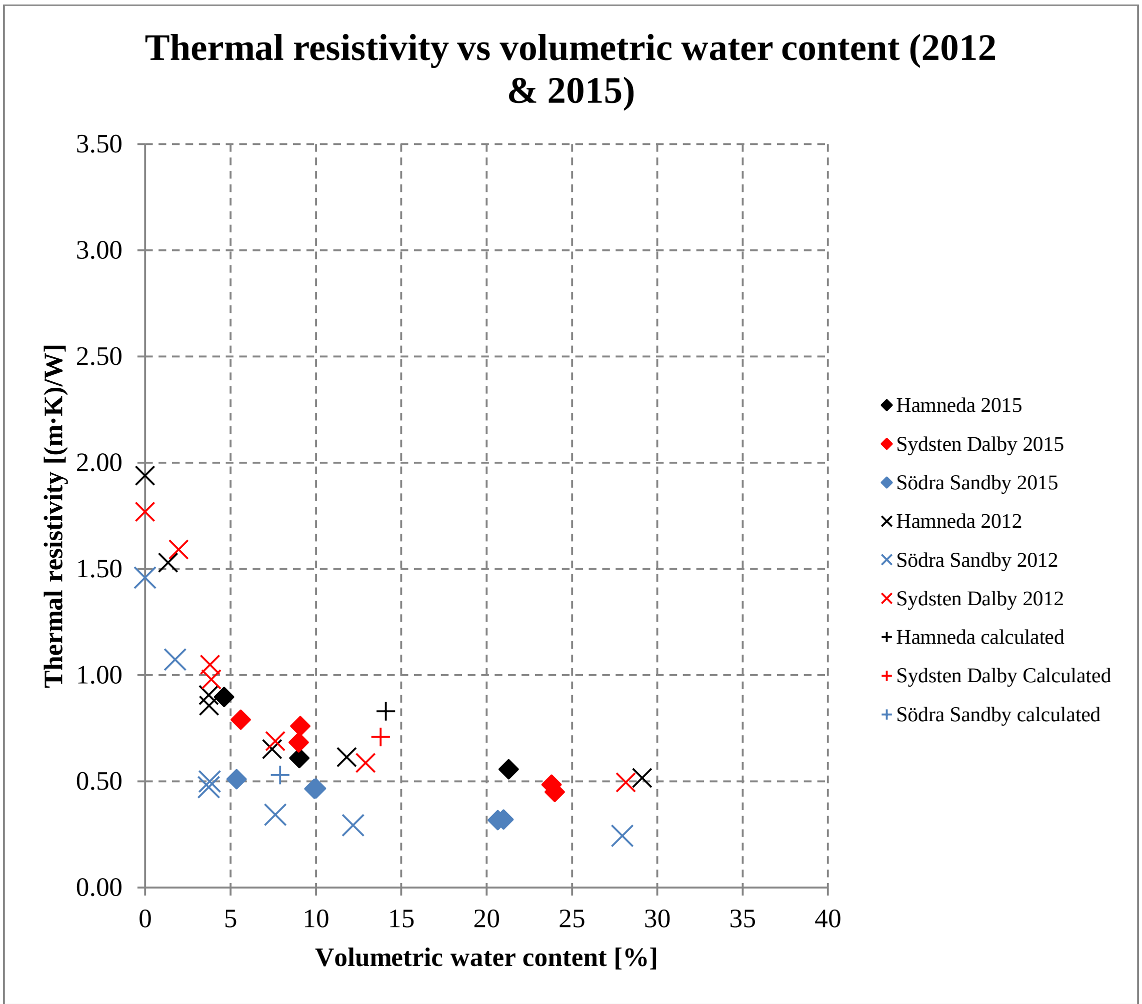

Figure 9 **Thermal resistivity measured on the three thermal sands with various water content. Values from 2012 performed by Vectura (Sundberg & Sundberg, 2012) and from 2015 by Chalmers.**

4.4.2 Thermal resistivity vs pressure head

Derived from volumetric water content by the help of extrapolation in the water retention curves, a graph of thermal resistivity plotted against pressure head is shown in Figure 10. Negative pressure [m] corresponds to a groundwater level x meters below the cables.

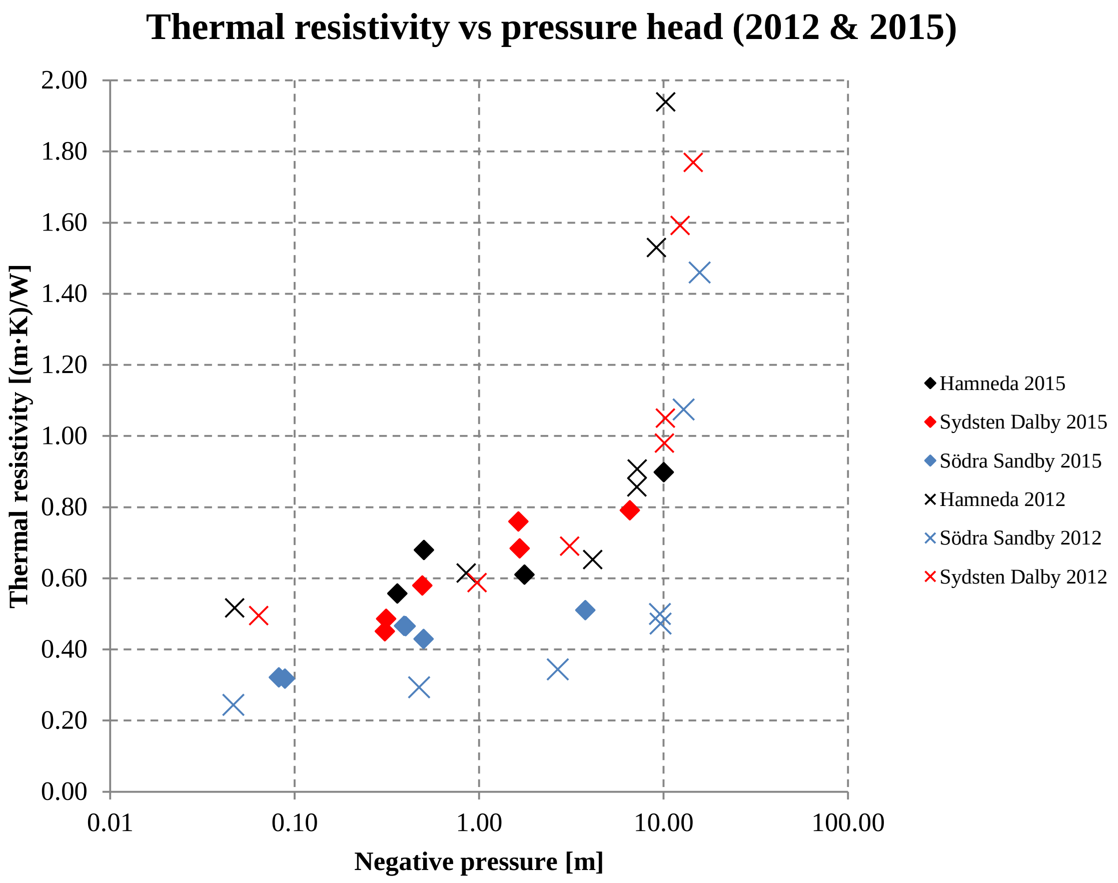

Figure 10. **Thermal resistivity measured on the three thermal sands plotted against negative pressure. Values from 2012 performed by Vectura and from 2015 by Chalmers. Observe that the negative pressure in this figure is converted from volumetric water content. Data from figure 8 and 9 are combined and extrapolated. For example the two red points (Sydsten Dalby 2012) with a negative pressure more than 10 m can also be found in figure 9, there with a volumetric water content between 0 and 2 %. The water retention capacity has on the other hand not been measured on these samples, therefore have their negative pressure been calculated through extrapolation of the water retention curve in figure 8. Negative pressure [m] corresponds to a groundwater level x meters below the cables.**

5 Results and analysis - Experiment 1

Experiment 1 is the main experiment which have been performed during long time, approximately four months. The setup is described in chapter 3.1.

5.1 Temperature development in heaters

The experiment started in June 29th and ended 27th of October, approximately 3000 hours. During the experiment the electrical effect was increased several times in order to reach the desired temperature around 70 degrees. The effect needed to be increased more than expected since the temperature did not reach 70 degrees, therefore more than 50 W/m was needed. During the experiment the groundwater level was changed with the vacuum pump. The start level was -0.5m which after approximately 1550h was lowered to -1.0m. After 1800h the level was lowered to -2.0m and after 2650h lowered to -4m.

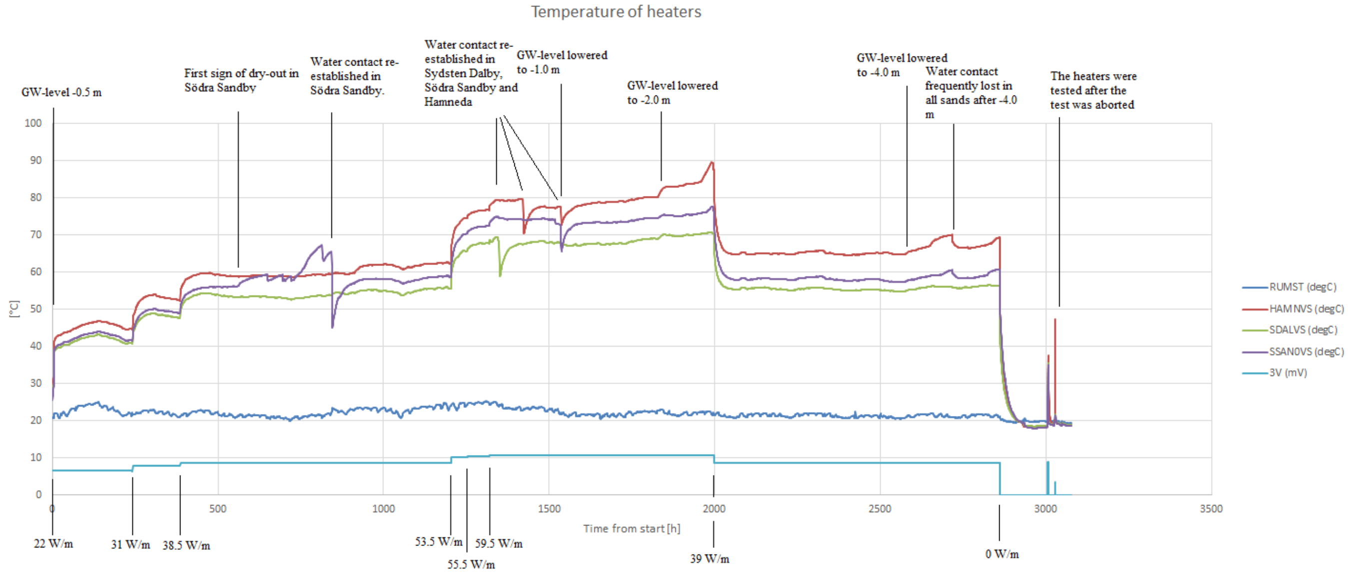

Figure 11. **Temperature development of experiment 1 with its sequence of events. Red curve is the temperature of Hamneda heater, purple curve is Södra Sandby and green symbolises Sydsten Dalby. Same figure but in a larger size is presented in Appendix 3.**

In Figure 11 the red temperature curve illustrates the heater for Hamneda (H), purple curve is Södra Sandby (SS) and green symbolizes Sydsten Dalby (SD). The thermal resistivity for the three sands was measured before, during and after the experiment. The thermal resistivity changes due to the water content and apparent temperature.

SD showed to have the highest thermal resistivity, SS the lowest and H in between. That is contradictory to the results and temperature curves in Figure 11. The green curve for SD should logically have the highest temperature and not the lowest. This was unfortunately caused by the longer tensiometer in the saucepan for SD, which acted as a thermal bridge where convection could take place, see Figure 3 and Figure 4. The shorter tensiometers in H and SS did not seem to have that convective effect, but it still acted as a moderate thermal bridge. This is the reasons for the need of higher electrical effects to reach certain temperatures than expected.

Some observations:

- According to the tensiometers there is a higher negative pressure in the saucepan than what is created by the vacuum pump, see Appendix 2.
- A smaller amount of water disappears out from the saucepans, most likely in form of vapour.
- The heater for Hamneda was observed to be slightly damaged after experiment was completed. No obvious errors in the result could though be observed.
- The Södra Sandby sand was more compacted than the others. Probably because less force was needed to compact the actual material.
- It was not possible to keep the negative pressure at -4.0m, the water contact was constantly broken. The effect at that time was 39 W/m, approximately 55-70°C. A groundwater level at -2.0m with the same effect was on the other hand stable, see from 2000h to 2600h in Figure 11.
- The water contact was broken at all negative pressures from -0.5m and more, if the effect was as high as 56 W/m with the temperatures of 70-85°C.

- Increased suction increases temperature in the experiments. This is due to water being replaced by air in the porous system, thus reducing the overall thermal resistivity of the material. However according to the experiments this effect is marginal, possibly due to vapour diffusion.

5.2 Calibration of numerical modelling

As previously mentioned, a Comsol model was set up in parallel to the experiment, to evaluate the soils behaviour during variations in water content, temperature etc. In order to produce a reliable model, it first needs to be calibrated. This is primarily made by setting up a base model with basic geometry and boundary conditions as well as theoretical values of parameters such as thermal resistivity and specific heat capacity.

When calibrating the model to suit experimental results, the following points where mainly used:

- The heater
- Thermocouple located 2 cm from heater
- Measured temperature on the steel side of the saucepan, inside the insulation

The following parameters where calibrated:

- Thermal resistivity in the insulation (due to imperfections and including of the tensiometers contribution
- Thermal resistivity in the sand, variable and constant

5.2.1 Sensitivity analysis

In order to grasp the magnitude of impact from changes in resistivity in the sand and in the insulation, a sensitivity analysis was performed. This was done by running a Comsol model where only one parameter was changed at a time. Three different values of resistivity was chosen (one reasonable value, one double that value and one half).

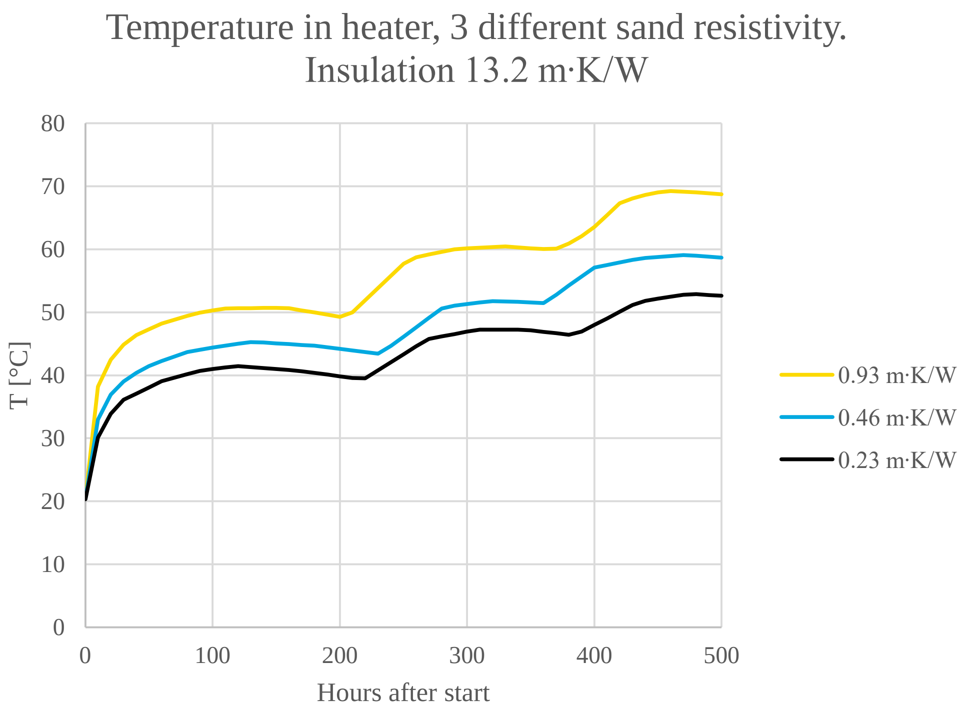

Figure 12 **Difference in heater temperature with three different values of resistivity in the sand.**

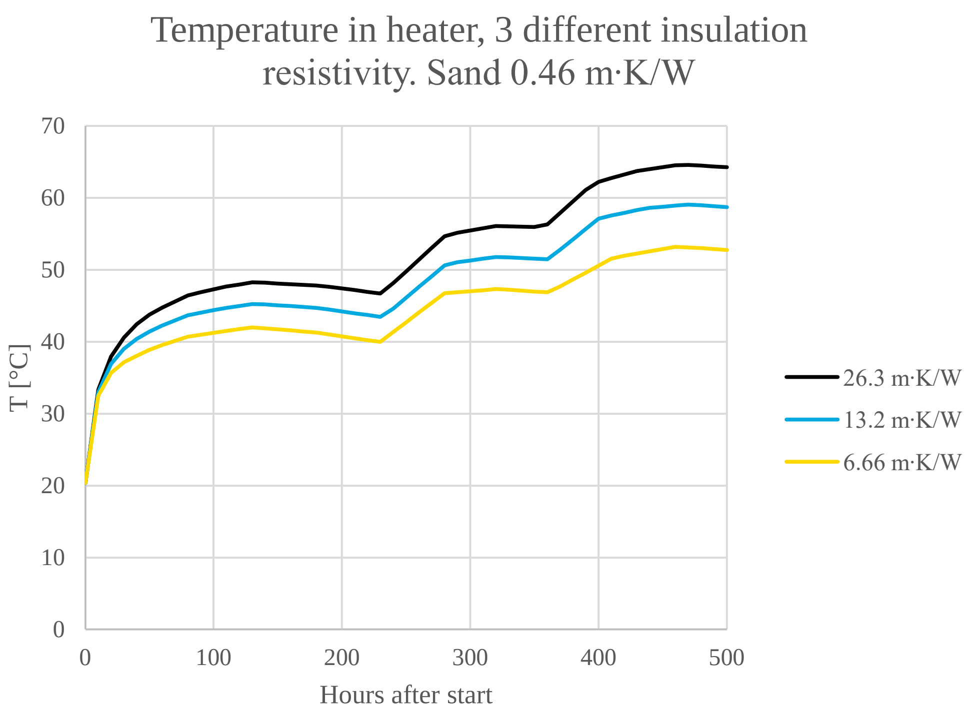

Figure 13. **Difference in heater temperature with three different values of resistivity in the insulation.**

5.2.2 The temperatures effect on thermal resistivity

When simulating the thermal sand behaviour in different temperatures and water content, the method conducted by Tarnawski was considered. It is based on measurements of thermal resistivity of fine, medium and coarse sands with temperatures ranging up to 90°C (Tarnawski, Leong, & Bristow, 2000). Adjusted to measurements from the three sands SS, H and SD, in saturated and dried condition, new curves for thermal resistivity depending on temperature and water content can be constructed. The Kersten function for this is as follows:

$$Ke = \frac{a + bT + cS_r + dS_r^2}{1 + eT + fS_r + gS_r^2}$$

Where the fitting constants are derived from soils named coarse in Tarnawski et al. (2000), which are similar to the three cable sands in this lab experiment:

Coefficient	Value
a	0.128
b	- 0.0012
c	0.556
d	1.167
e	-0.0074
f	-0.841
g	2.099
r2	0.932

To obtain the correct lambda for our three sands, the Ke-values are adjusted accordingly:

$$\lambda = \lambda_d + (\lambda_{sat} - \lambda_d)Ke$$

Calculated impact from temperature and volumetric water content on thermal resistivity in the three materials H, SD and SS, can be seen in Figure 14, Figure 15 and Figure 16 respectively.

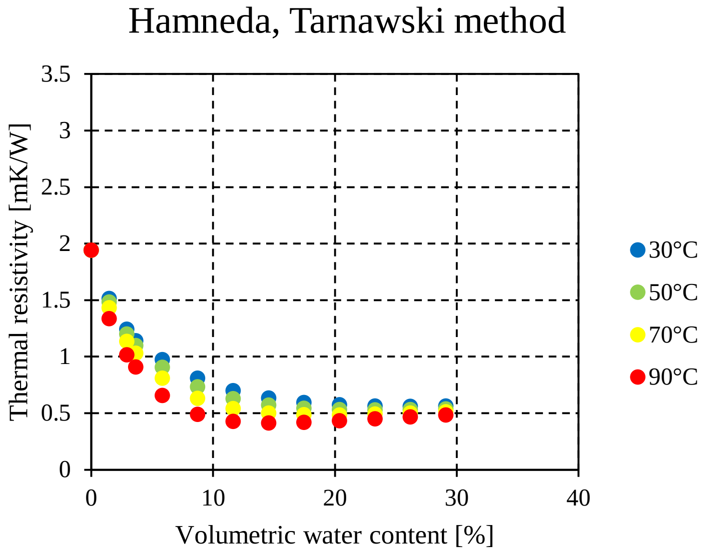

Figure 14. Calculated thermal resistivity versus volumetric water content in temperatures 30-90°C for Hamneda thermal sand.

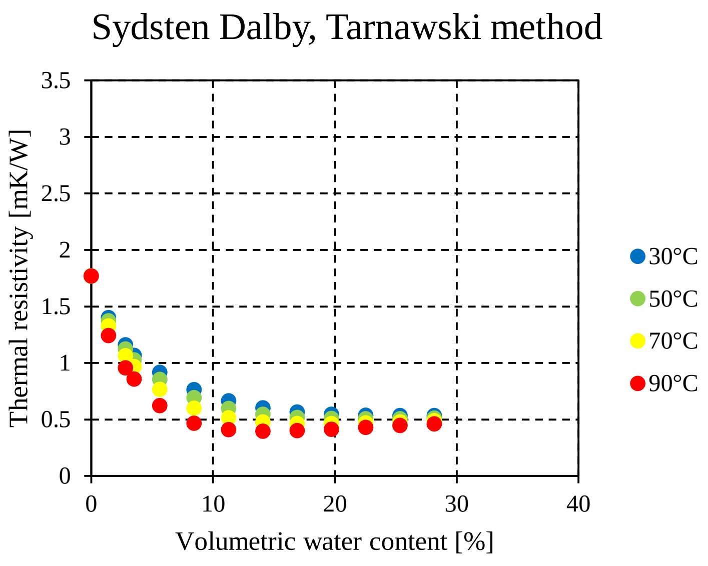

Figure 15. **Calculated thermal resistivity versus volumetric water content in temperatures 30-90°C for Sydsten Dalby thermal sand.**

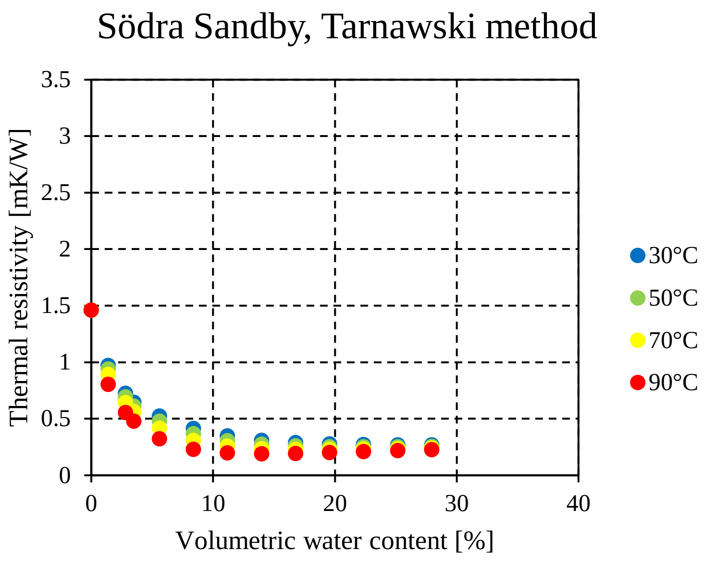

Figure 16. **Calculated thermal resistivity versus volumetric water content in temperatures 30-90°C for Södra Sandby thermal sand.**

5.2.3 Adaption of temperature curves from thermocouples

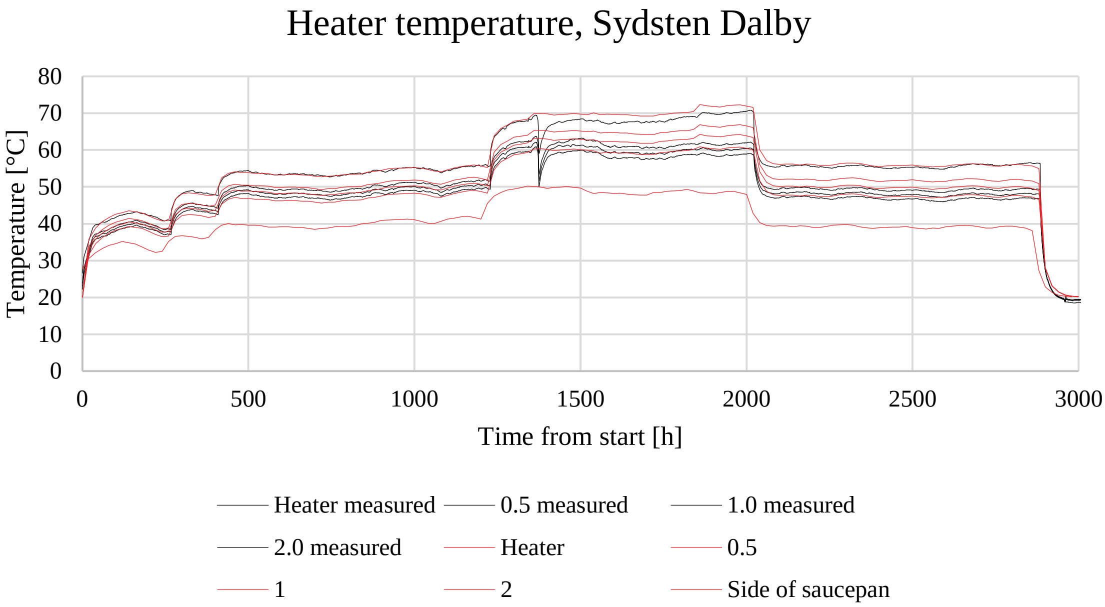

Figure 17. Comparison between measured temperatures in Sydsten Dalby and simulated. The simulation is based on a variable thermal resistivity dependent on temperature and water content.

Figure 17 shows the "best fit" simulation, which includes a variable thermal resistivity in the sand. The temperature in the heater and in the thermocouple located 2 cm from the heater fits very well, while the 1 cm thermocouple suits the 0.5 cm measured values very well. The 0.5 simulated temperature are slightly higher than measured. This is possibly due to a few millimetres of dislocation during the installation of the thermocouples.

5.3 Results and analysis, Numerical modelling vs experiment

5.3.1 Hamneda

Figure 18 shows the temperature in the heater in Hamneda together with three simulations in Comsol. The green line represents a variable thermal resistivity ranging from 0.41-0.89 (m·K)/W as a function of temperature and water content. The red and blue lines are constant measured resistivity of 0.61 (m·K)/W and 0.90 (m·K)/W measured at 5.0 % and 3.0 % gravimetric water content respectively (before and after the experiment). The insulation has a thermal resistivity of 13.16 (m·K)/W (a value that includes the 30 cm long tensiometer).

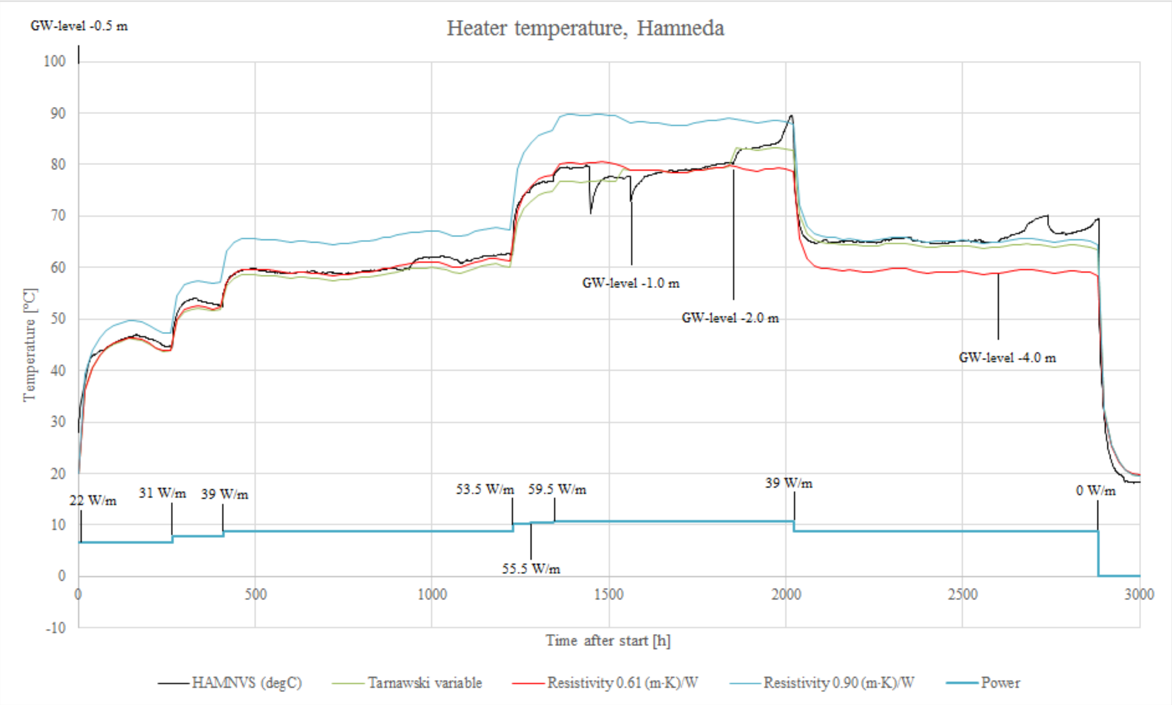

Figure 18 **Temperature in heater for Hamneda in experiment 1. The measured temperature compared to simulated, both variable and constant. The constant values used are the measured at 5% water content (0.61 (m·K)/W) as well as the measured after the experiment (0.90 (m·K)/W).**

Compared to the other two samples, the measurements of thermal resistivity in saturated and 5% gravimetrical water content differ significantly

5.3.2 Södra Sandby

Figure 19 shows the temperature in the heater in Södra Sandby together with three simulations in Comsol. The green line represents a variable thermal resistivity ranging from 0.26-0.52 (m·K)/W as a function of temperature and water content. The red and blue lines are constant measured resistivity of 0.47 (m·K)/W and 0.51 (m·K)/W measured at 5.0 % and 2.6 % gravimetric water content respectively (before and after the experiment). The insulation has a thermal resistivity of 13.16 (m·K)/W (a value that includes a 30 cm long tensiometer).

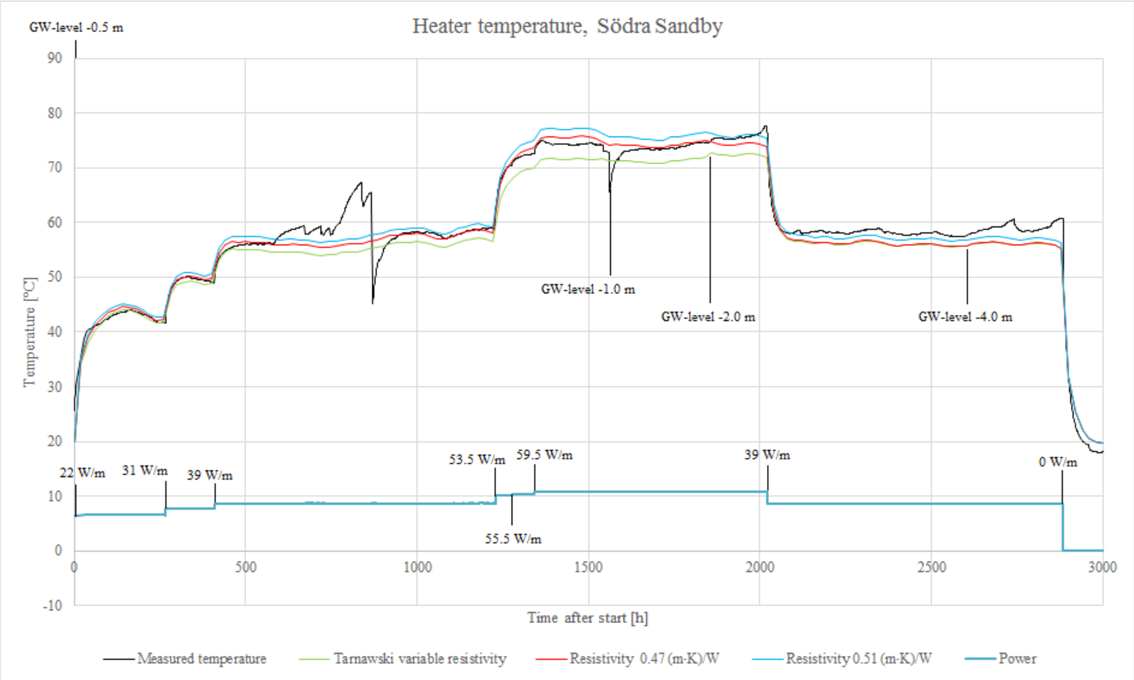

Figure 19 Temperature in heater for Södra Sandby in experiment 1. The measured temperature compared to simulated, both variable and constant. The constant values used are the measured at 5% water content (0.47 (m·K)/W) as well as the measured after the experiment (0.51 (m·K)/W).

The temperature in the experiment seems to increase in relation to the simulated temperatures after the water connection was lost after roughly 600 hours, and the temperature was allowed to rush.

The constant values of thermal resistivity are relatively high compared to the variable. This is because the thermal resistivity measurements performed on Södra Sandby in 2015 was slightly higher than in 2012. The variable values used is from 2012 since they contain both saturated and dry measurements, which produces a more reliable variable resistivity curve. After 500 hours the water contact is broken and the temperature rapidly increases, this is then re-established and after approximately 900 hours the temperature is stable but with a couple of degrees higher temperature. Because this dry out occurred it can be noticed that the thermal resistivity has been raised due to hysteresis effect.

5.3.3 Sydsten Dalby

Figure 20 shows the temperature in the heater in Sydsten Dalby together with three simulations in Comsol. The green line represents a variable thermal resistivity ranging from 0.42-0.80 (m·K)/W as a function of temperature and water content. The red and blue lines are constant measured resistivity of 0.76 (m·K)/W and 0.79 (m·K)/W measured at 5.0 % and 3.0 % gravimetric water content respectively (before and after the experiment). The insulation has a thermal resistivity of 7.69 (m·K)/W (a value that includes a 60 cm long tensiometer).

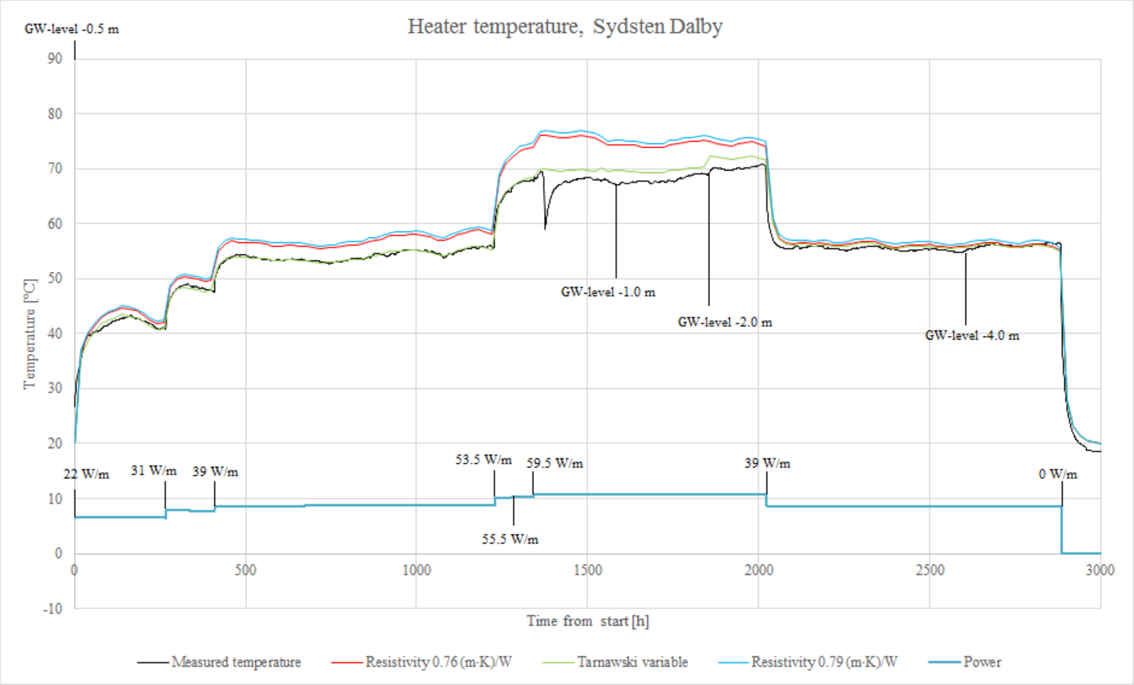

Figure 20 **Temperature in heater for Sydsten Dalby in experiment 1. The measured temperature compared to simulated, both variable and constant. The constant values used are the measured at 5% water content (0.76 (m·K)/W) as well as the measured after the experiment (0.79 (m·K)/W).**

The constant values of thermal resistivity are relatively high compared to the variable. This is because the thermal resistivity measurements performed on Sydsten Dalby in 2015 was slightly higher than in 2012. The variable values used is from 2012 since they contain both saturated and dry measurements, which produces a more reliable variable resistivity curve.

5.4 Conclusions experiment 1

- The experiment shows that the effective thermal resistivity in the sands becomes lower with increased temperature. The reason is judged to be influence of vapour diffusion. It is clearly illustrated in Figure 18 - Figure 19 were the gap between the black curve (measured) and the red and blue curves (constant resistivity) increases with temperature. The temperatures for the black curve decreases compared to the other two, which means lower resistivity with increased temperature.

- It requires a high effect in order to reach critical temperatures, approximately 45 W/m (also high heat flow and a large gradient). This can be compared with 22 W/m for the South west link.

- The temperature development for SS and SD are reversed compared to what was expected. Most likely caused by large heat dissipation through the longer tensiometer for SD.

- The water transport within the system goes from the ceramic plate up to the sand and heater. This indicates a vapour loss and that the tension within the saucepan is higher than the tension created by the vacuum pump, this was verified by the tensiometers.

- The water contact between the ceramic plate and the sand is broken at high temperatures, high effect and more less regardless of the negative pressure, low to high. After a while this leads to a dry out in close vicinity to the heater and the temperature increases even more.

- The reason for the broken water contact is not clear. It might occur due to dehydration of the ceramic plate, as a consequence of too high temperatures. The distance between the heater and the plate could be insufficient since the sand around the heater is likely of lower than average water content, possibly resulting in loss of water contact and allowing air to enter the ceramic plate. The broken water contact may also depend on air leakage in tubes and valve connections between the saucepan and the water filled glass container.

- Distance from heater to thermocouples were set to 0.5, 1.0 and 2.0 cm respectively, which means that small displacements resulted in relatively large differences in temperature when comparing to the simulated model where these are perfectly located. A setup with greater distances, as well as a thermocouple on the side of the steel saucepan, would make it more robust.

- The exact location of the thermocouple inside the heater is not known. Most probably it is located on a stainless steel plate in the centre with contact to the outer casing. It is however assumed to be of marginal impact on the registered temperature.

6 Results and analysis - Experiment 2

In Experiment 2 some things were changed compared to previous experiment. The purpose of the second experiment was to verify and falsify results and observations from the first experiment. Two sands were used instead of three. The two sands were Södra Sandby, SS and Sydsten Dalby, SD. It could not be confirmed that the damaged heater from experiment one was causing any problems, but since the experiment was electrically parallel connected, that heater was left outside of the second experiment for safety, and therefore only two sands could be tested.

The experiment was similar to the previous but with less uncertainties. The biggest change was that no tensiometers were placed in the saucepan, since they were believed to act as a thermal bridge in the previous experiment, this uncertainty was removed. The thermocouples were placed further from the heater, 20 mm and 80 mm. compared to 5 mm, 10 mm and 20 mm which the case was in experiment 1. Thermocouples were also placed on top of and on the edge of the saucepan, inside the insulation. The experimental setup can be seen in Figure 21.

Figure 21. Setup of experiment 2. Sydsten Dalby and Södra Sandby.

6.1 Temperature development at heaters

Experiment 2 covered roughly 400 hours, starting on the 14th of November and ending on the 1st of December. The main difference from experiment one was that the tensiometers where removed in order to create more stable temperature gradient, thus excluding an uncertainty. In addition to this, the setup was further developed by removing and improving some of the tube connections in order to reduce leakage of air into the system. The plan was to disconnect SD after the third power step (same power steps as the three first in experiment one) and preparing that sand for a third experiment. During these preparations, SS was allowed to continue without adjustments.

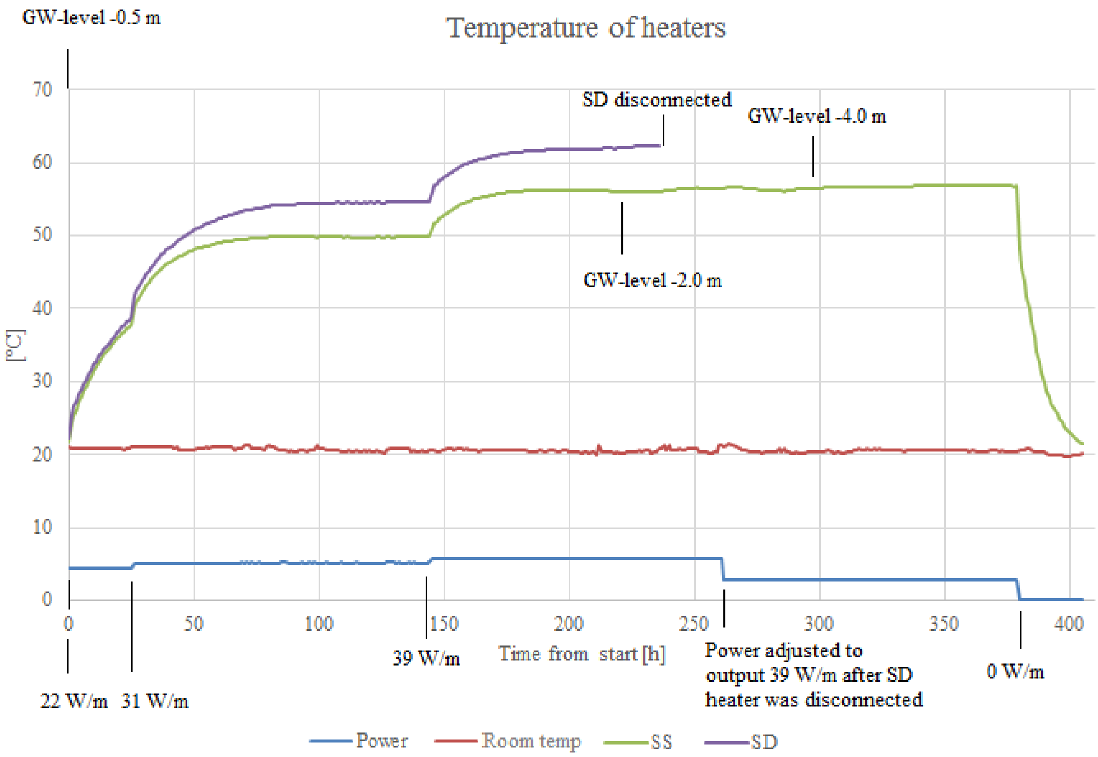

Figure 22 **Temperature development of experiment 2 with its sequence of events. Red curve is the room temperature, blue is a downscaled curve representing the power input, purple curve is Sydsten Dalby, and green symbolizes Södra Sandby.**

In Figure 22 a sequence of events covering experiment 2 can be seen, represented by temperature curves and power input. Purple curve shows the temperature of SD while green represents SS. The red curve is room temperature and the blue is a down scaled representation of the power in the heater. As can be seen, SD achieves a higher temperature than SS, reversed to what could be seen in experiment 1. This is also what was expected, a higher temperature in the sand with the highest thermal resistivity. Since SD had a very long tensiometer in experiment 1 (60 cm, of which around 40 cm were above the insulation) compared to the other two sands (30 cm, of which only 5-10 cm were above the insulation), the removal of these are the cause.

Observations:

- The room temperature is more stable compared to experiment 1 which leads to more stable temperature curves overall. This is due to the fact that this experiment was carried out during November, where the room temperature is heated to around 21°C while experiment 1, which was carried out mainly during the summer, fluctuated more since the temperature is not contained by the climate system below 21°C
- SD and SS shows temperatures that are in line with what was expected, with SD having a higher thermal resistivity and being warmer than SS. This was not the case in experiment 1.
- Removing the tensiometers adds to the stability and sluggishness of the temperature in the saucepan towards the room temperature.

6.2 Results and analysis, Numerical modelling vs experiment

6.2.1 Sydsten Dalby

Figure 23 displays Comsol modelling of SD in experiment 2, compared to the logged temperatures, in the heater and on the side of the saucepan.

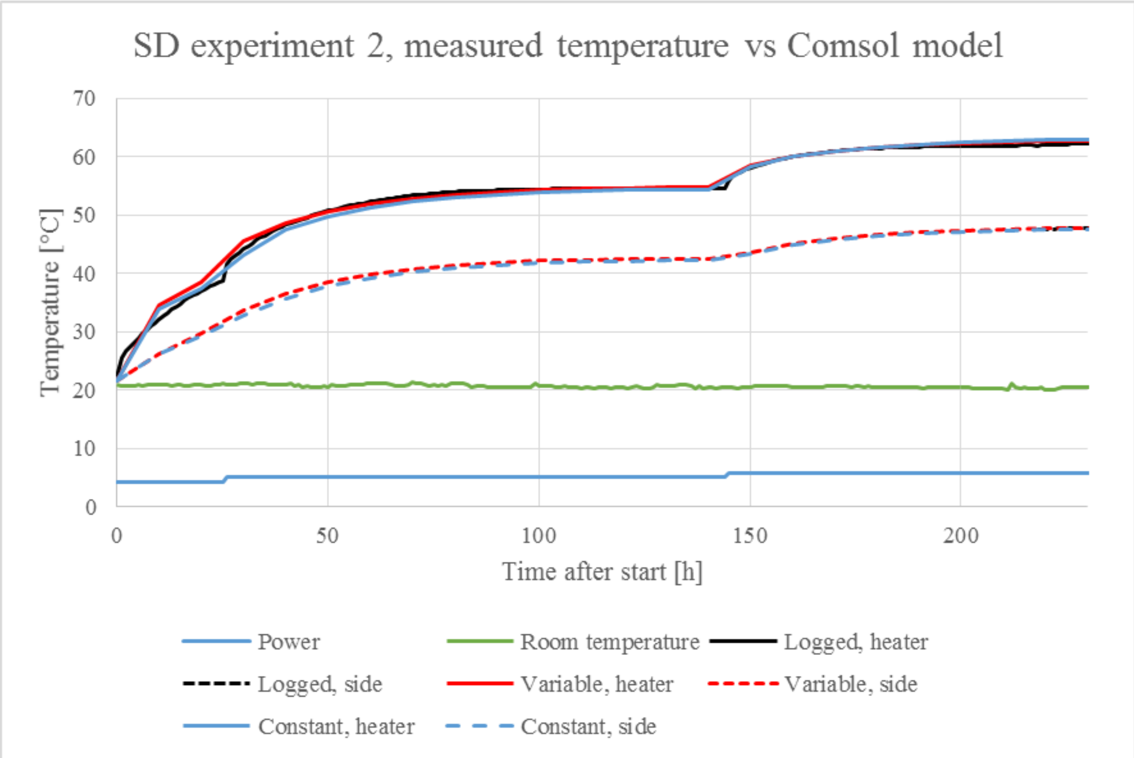

Figure 23 **Graph over temperatures in SD, both logged and from Comsol model. Black lines are logged, red are with a variable thermal resistivity ranging from 0.66-0.78 mK/W while green are a simulation with constant thermal resistivity of 0.68 mK/W. The dashed lines are for the side of the saucepan while the solid represent heater temperature.**

Calibration of the model showed that the resistivity of the insulation is 16.9 mK/W. Together with a thermal resistivity of the soil that varies with temperature, the model suits the measured values good on all points. The results from the Comsol simulations, as they fit with the experiment 2 logged temperatures with an insulation resistivity of 16.9 mK/W, further supports the claim that the difference between the sands in experiment 1 was due to fluid convection in the tensiometers.

6.2.2 Södra Sandby

Figure 24 displays Comsol simulations of SS in experiment 2, compared to the measured temperatures, in the heaters and on the side of the saucepan.

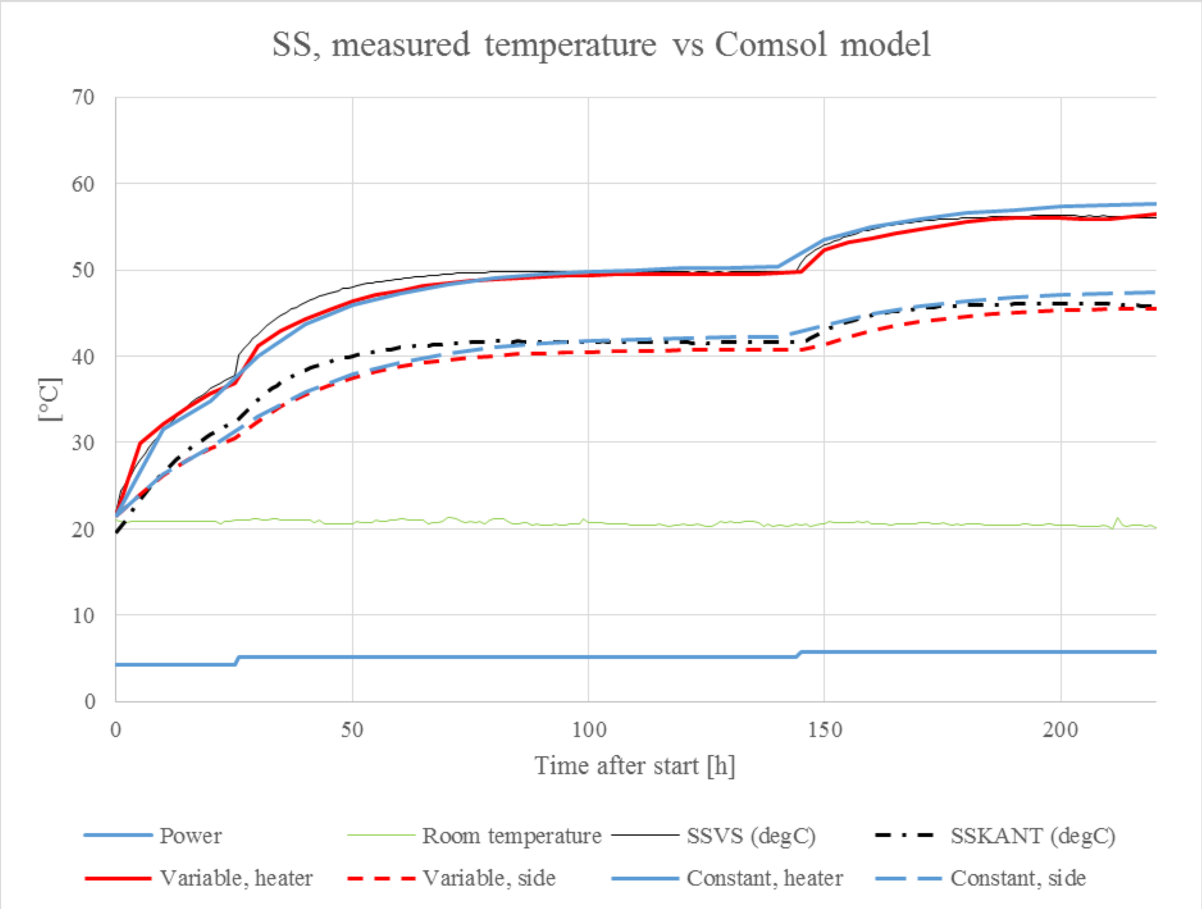

Figure 24 **Graph over temperatures in SS, both measured and from Comsol model. Black lines are measured, red are with a variable thermal resistivity ranging from 0.37-0.47 mK/W while green are a simulation with constant thermal resistivity. The dashed lines are for the side of the saucepan while the solid represent heater temperature.**

6.3 Conclusions Experiment 2

- The experiment shows, as suspected, that the misleading results with strange temperatures from experiment 1 were caused by the tensiometers. Especially the longer one that was used in the saucepan for Sydsten Dalby. It was clear that thermal convection had taken place in the longer tensiometer (SD) but only conduction in the shorter ones that were used for SS and H. The temperature difference with and without tensiometer were for SD approximately 10 degrees and less than 1 degree for SS, the effect at that time was 39 W/m.

- In this second experiment, results were reasonable regarding expected temperatures that was observed while comparing SS and SD. The higher measured thermal resistivity for SD also rendered in a higher temperature curve than SS.

- The experiment could verify relevant conclusion from experiment 1

7 Results and analysis - Experiment 3

Experiment 3 covered just above 300 hours, starting on the 1st of December and ending on the 15th of December. Experiment 3 was conducted in order to evaluate differences between the hand compacted sand from experiment 2 with a non-compacted sand given the same circumstances. The only compaction SD in experiment 3 experience is from natural settling when the water is drained after saturation. The purpose of the third experiment was to test whether the degree of compaction in the sand material would affect the ability for vapour diffusion to take place.

7.1 Temperature development at heater for SD

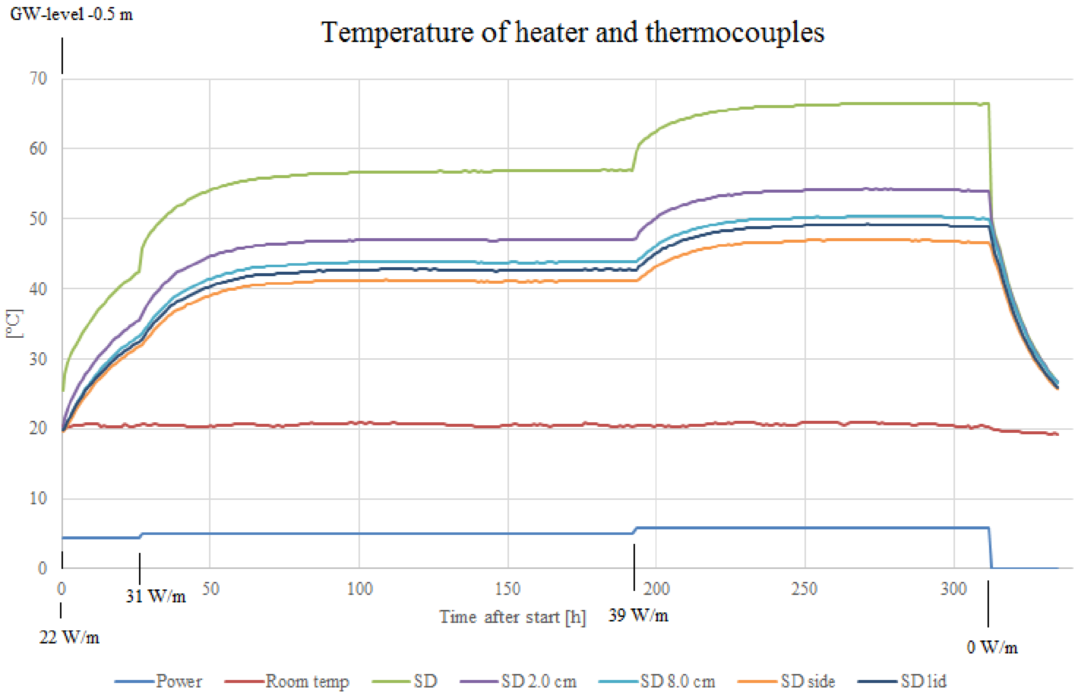

Figure 25 **Temperature development of experiment 3 with its sequence of events. Red curve is the room temperature, blue is a downscaled curve representing the power input, while the remaining curves are, in order from top to bottom; heater, thermocouples for 2.0 cm from heater, 8.0 dito, on the lid and on the side of the saucepan.**

The temperature development in experiment 3 can be seen in Figure 25. The blue curve shows a down scaled power input, the red represents the room temperature and the other 5 curves are thermocouples, in this order from the top; heater, 2.0 cm from the heater, 8.0 cm from the heater, on the lid of the saucepan and on the side inside the insulation. As in experiment 2, the power was increased in 3 steps.

Observations:

- The same stable temperatures as in experiment 2 was achieved by repeating the same circumstances; no tensiometers and more stable room temperatures.

7.2 Results and analysis, Numerical modelling vs experiment

7.2.1 Sydsten Dalby

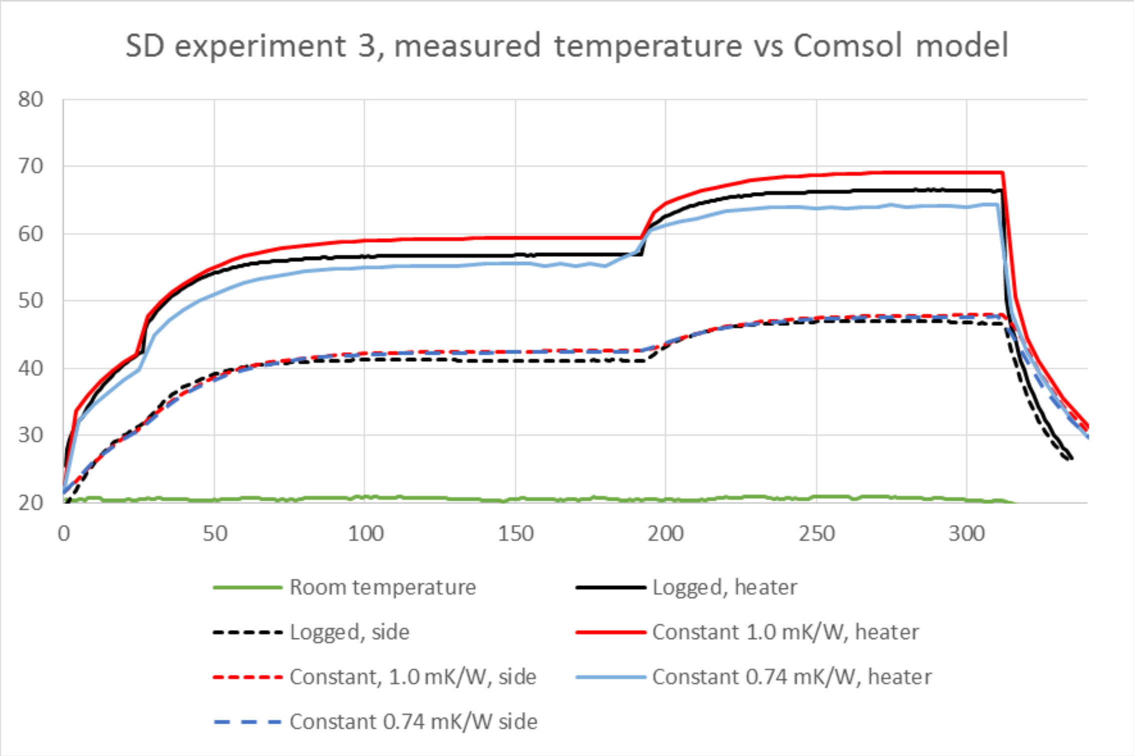

Figure 26 **Graph over temperatures in SD in experiment 3, both measured and from Comsol model. Black lines are logged, red are constant resistivity of 1.0 mK/W while blue are 0.74 mK/W. The dashed lines are for the side of the saucepan while the solid represent heater temperature.**

Figure 26 displays Comsol modelling of SD in experiment 3, compared to the logged temperatures, in the heater and on the side of the saucepan. Thermal resistivity of 1.0 mK/W and 0.74 mK/W is used in the modelling. This sand is, as previously mentioned, not hand compacted but instead only allowed to compact naturally when water was drained from it. This leads to the thermal resistivity in this experiment to behave differently from the hand compacted sands. Most importantly the resistivity is higher with lower compaction, since the temperatures are higher compared to SD in experiment 2. This can be seen when comparing the two experiments, as is done in Figure 27.

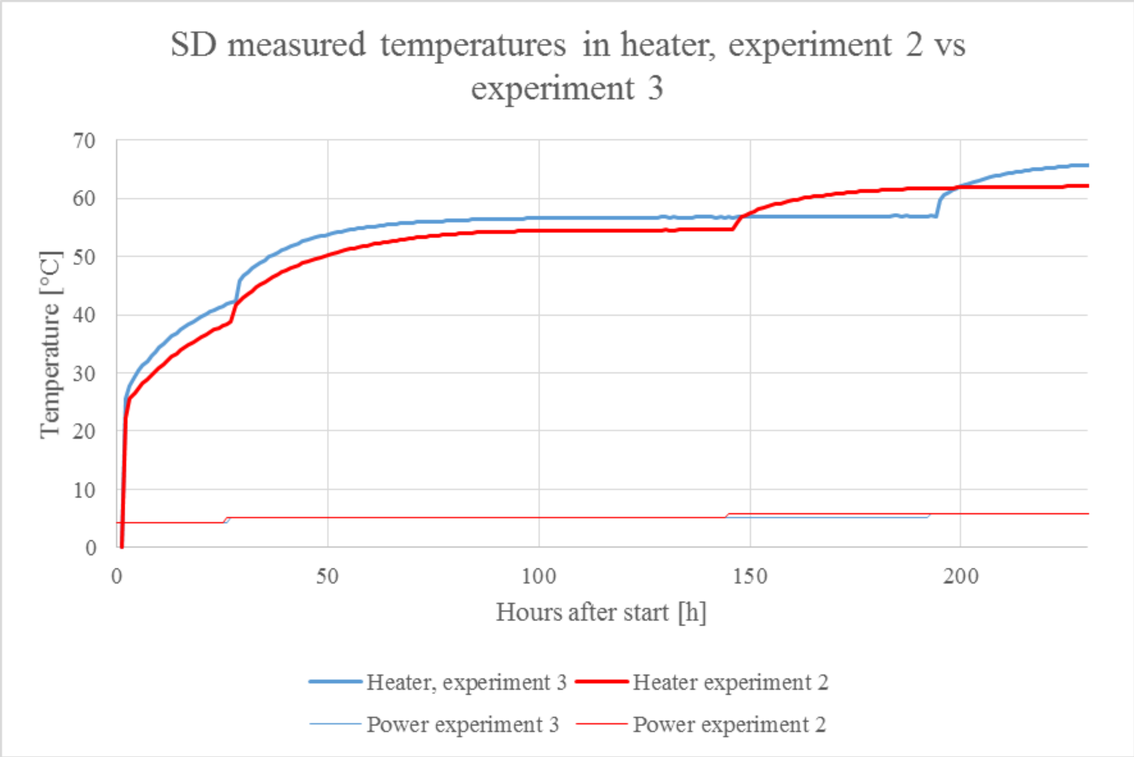

Figure 27 **Heater temperature in experiment 2 compared to experiment 3. Timing of increase in power input can be seen in the thinner curves at the bottom. Red color is experiment 2 while blue is experiment 3.**

7.3 Conclusions Experiment 3

- Experiment 3 clearly shows higher temperatures over the board compared to experiment 2. Since the only alteration is the level of compaction, it may be concluded that lower compaction leads to increased thermal resistivity in the sand and increased temperatures.
- It can also be concluded that vapour diffusion cannot compensate for the increased thermal resistivity due to lower compaction
- The experiment could verify relevant conclusion in Experiment 1

8 Discussion

8.1 Dry out phenomena

During this series of experiments it has been clear that the dry out phenomena do not start as long as there is a capillary connection to the underlying groundwater level. The water contact may be broken due to leakage of air into the shut-off valve connections, especially when high negative pressures are created with the vacuum pump. However, the reason for the broken water contact is not clear. It might also occur due to dehydration of the ceramic plate, as a consequence of too high temperatures. The distance between the heater and the plate could be insufficient since the sand around the heater is likely of lower than average water content, possibly resulting in loss of water contact and allowing air to enter the ceramic plate. It is most likely only an upscale of the experiment that can demonstrate whether the broken capillary water transport is caused by the experimental set-up or by high temperatures.

A couple of days after the water contact has been broken dehydration starts to take place in the vicinity of the heater. This phenomena, that constantly is repeated, with broken water contact followed by a temperature raise after a couple of days, clearly demonstrates that a water transport takes place from lower levels up to the heater, see Figure 28. This up-transport of water can also be verified by the tensiometers that shows higher tension (negative pressures) values closer to the heat source than what is created by the vacuum pump, something that confirms that a water transport towards the heaters takes place due to the unbalance in the system. Another confirmation of this is that the water level in the glass containers at lower levels constantly is decreased while the heaters are on (water is transported up to the saucepan and the heaters). The highest negative pressure that has been reached over a longer time (2 weeks) was -2m, and with perfectly sealed valve and tube connections it is likely that higher negative pressure could have been tested.

Dry out may occur close to the heater, but only if the water contact is broken. It takes a couple of days after broken water contact before dry out occur. The drying out process is verified by both temperature increase and higher tension values on the tensiometer (e.g. from 0.5 m to several meters in experiment 1).

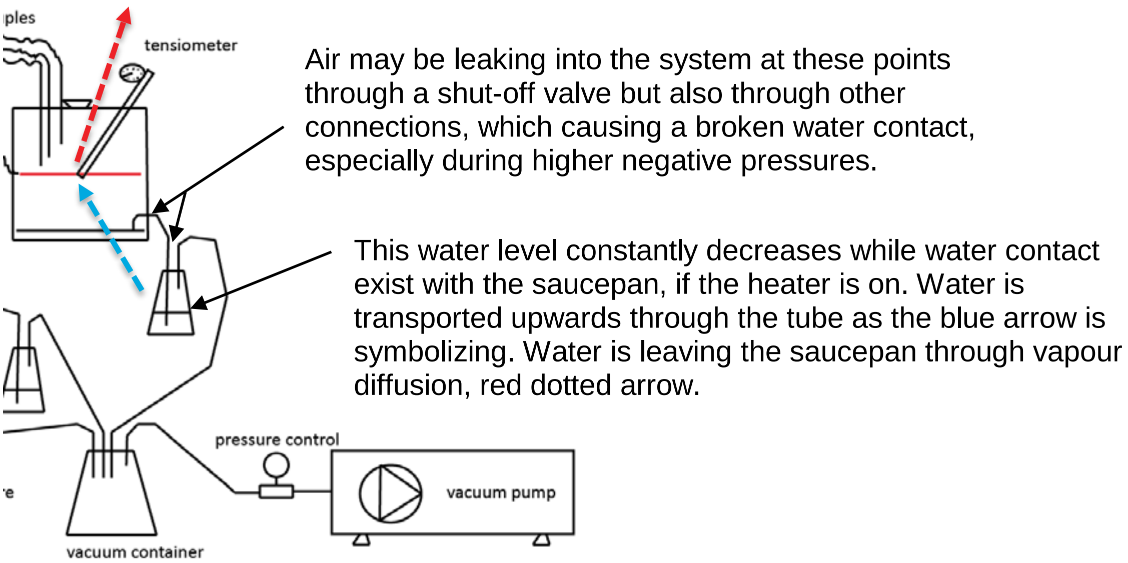

Figure 28 Illustration of water movement (blue) and vapour loss (red) within the experimental setup while the heater is on.

In this experiment it has been clear that the scale of the experiment is affecting the desire to establish a system that illustrates conditions in the nature. The hypothesis was that the vapour would condensate within the sand further away from the heat source and then flow back towards the heater due to unbalance in pressure. This did not happen due to the small scale and because vapour diffused out through the saucepan, see Figure 28.

The choice of including insulation around the saucepan has brought with it both positive and negative effects. On the plus side there are more ability to mimic natural soil conditions and less natural convection due to a smaller gradient between the saucepan's steel surface and the air. Since the saucepan needed to be insulated all around to reach the desired temperatures, an "oven" was created with a low thermal gradient and the condensation did not take place, the vapour diffused out through the saucepan. Large parts of the saucepan is also warm, possibly drying out the sand close to the porous ceramic plate and ruining the water contact. The desired water loop did therefore not take place within the sand in the saucepan but instead through transport from the glass containers with the lower groundwater level. So the hypothesis of balanced vapour diffusion and suction of water was confirmed, but not in the way that was expected.

It can be mentioned that if the saucepan would have been sealed as a pressure chamber (to avoid vapour loss) there would have been unnatural processes as a result. The vapour would have remained in the saucepan and higher pressures would have been created. The temperature would raise and the thermal resistivity would have been lower, this progression would not happen around buried cables in a cable trench.

8.2 Difference in heat transfer per unit area

In order to provide full opportunity to have a successful vapour-water loop and avoid vapour loss from the experiment (see Figure 28) it is necessary to have condensation within the soil material. To do this there is a need of an upscale of the experiment, including both more thermal sand and surrounding high resistivity soil.

It should be noted that this experiment represents a large downscale from the actual conditions in the South West Link, therefore the sand in close vicinity to the cable and heater (for the experiment) cannot be reliably compared. The total heat flow is much larger in the experiment compared to the real cable in SWL, up to 36 times higher, see Figure 29. This means that the experiment is conservative in contrast to SWL.

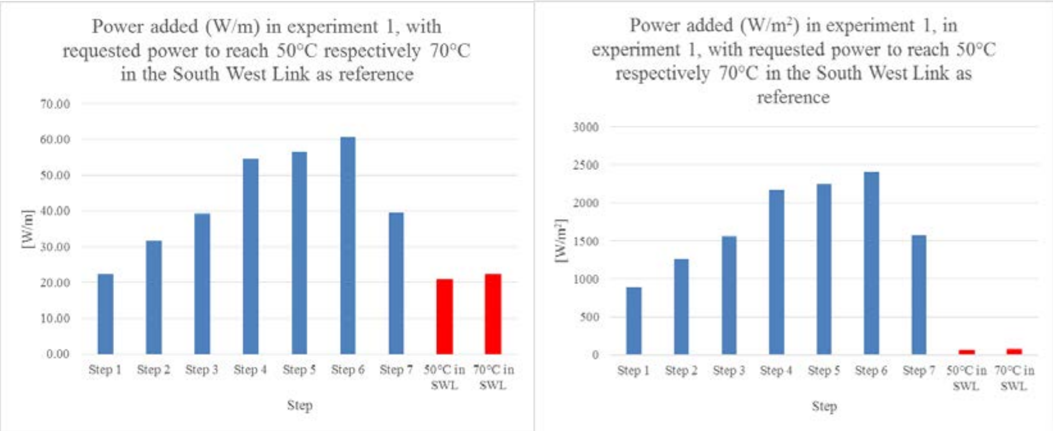

Figure 29 **The two figures illustrates the large difference in heat transfer in the experiment compared to the real project South West Link. In the left figure the power is expressed as W/m and in the right figure W/m^2**

8.3 Different parameters and their effect on dehydration of sand

Through these experiments it cannot be quantified how much impact the different parameters in bullets below have on dehydration of soil but a qualitative analysis can still be done.

- Water retention properties
- Pore pressure (groundwater level)
- Magnitude of heat flow (applied electrical effect)
- Temperature (from applied electrical effect and material properties)
- Thermal properties of the material under regular circumstances (low temperatures)

These orientating experiments show that the two first bullets, the water content which are linked to water retention capacity and the groundwater level are of more importance than the other bullets. The experiments show that even if a high magnitude of heat flow and high temperatures are present it will not result in a dry out if there is a constant water flow towards the heater. Whether it is a constant water flow or not depends on hydrological aspects and if the cable installation is located in a recharge area or discharge area. As a simplification, recharge areas can be said to be on hills and discharge areas in valleys. A recharge area is more sensitive to dehydration since the groundwater level is fluctuating, due to seasonal variations in rain, vegetation, temperature, infiltration etc. Whilst in a discharge area, water is flowing towards it and fluctuations in groundwater levels are small.

It is very hard to say when the magnitude of heat flow and temperature becomes more dominating than the ability of the water to flow back due to the difference in under pressure. In the experiments this cannot really be illustrated since the dry outs that occurs most likely happens after broken capillary connection due to leakage of air into the system.

9 Conclusion and recommendations

The performed orienting 3-D laboratory experiments are judged to have much better ability to emulate real field conditions, compared to earlier performed 1-D experiments. It can be concluded that dry out of the samples only occur if the water bridge is broken between the sand surrounding the heater and the simulated groundwater level. When the capillary contact is broken it takes about one week before the temperature rushes. The sand samples are a net recipient of water, in terms of water vapour diffusing through imperfections in the saucepan leading to water being transported via the vacuum system to uphold a constant pore pressure in the pans. This indicates that as long as there is access to water, rushed temperatures will not occur. In other words, no dehydration seems to occur. This is contradictory to earlier 1-dimensional laboratory steady state heat transfer experiments by e.g. Gouda et al. (1997), see discussion in Sundberg (2015).

The experiment clearly shows that the effective thermal resistivity in the sands becomes lower with increased temperature. There is therefore a possibility to account for increased heat transfer from vapour diffusion by the effective thermal resistivity. This coincides with the confined experiment results by Nikolaev et al. (2013), see discussion in Sundberg (2015). However, the decrease in effective thermal resistivity seems to be smaller.

No dehydration seems to occur if the pore water is in contact to the ceramic plate, despite the fact that the heat flow is up to 36 times higher than in the SW-link.

Increased temperatures from increased water tension has been observed, which is the result of less water content. The temperature increase is on the other hand relatively low and may depend on positive thermal effects from vapour diffusion.

The experiment indicates that temporary lowering of the groundwater table causes permanent decreases in water content and increased thermal resistivity in the soil, due to hysteresis.

Heat transfer through vapour diffusion cannot compensate for a higher thermal resistivity due to a lower degree of compaction in a sand material.

There are uncertainties in the results, mainly caused by the limited scale of the experiment. Examples are: the occurrence of vapour-water loop, the up transport of groundwater in the case of natural drying out conditions. The results must be verified in order to finally establish the achieved conclusions.

The following summary of main conclusion can be made:

- No dry out close to heater seems to occur. This may result in a less conservative thermal dimensioning, compared to if dry out tends to occur
- It seems to be possibly to account for a small-medium effect on decreased effective thermal resistivity due to vapour diffusion.
- Temporary lowering of the groundwater table causes permanent decreases in water content and increased thermal resistivity (hysteresis in the water tension curve)
- There is need to confirm the conclusions in larger scale due to uncertainties in the context of modelling reality in small scale.

The experiment clearly demonstrates some of the phenomena that can take place in the surrounding sand at buried cables in trenches in natural soil. A key-question is the unbroken capillary water transport. The broken water contact that occurred in the experiment have been judge to be caused by the experimental set-up rather than the temperature influence. However this could be a misjudgement. An upscaling of the experiment is though recommended in order give reliable prediction models and to really demonstrate and confirm some of the processes that happens, which only can be tested in a larger scale.

10 References

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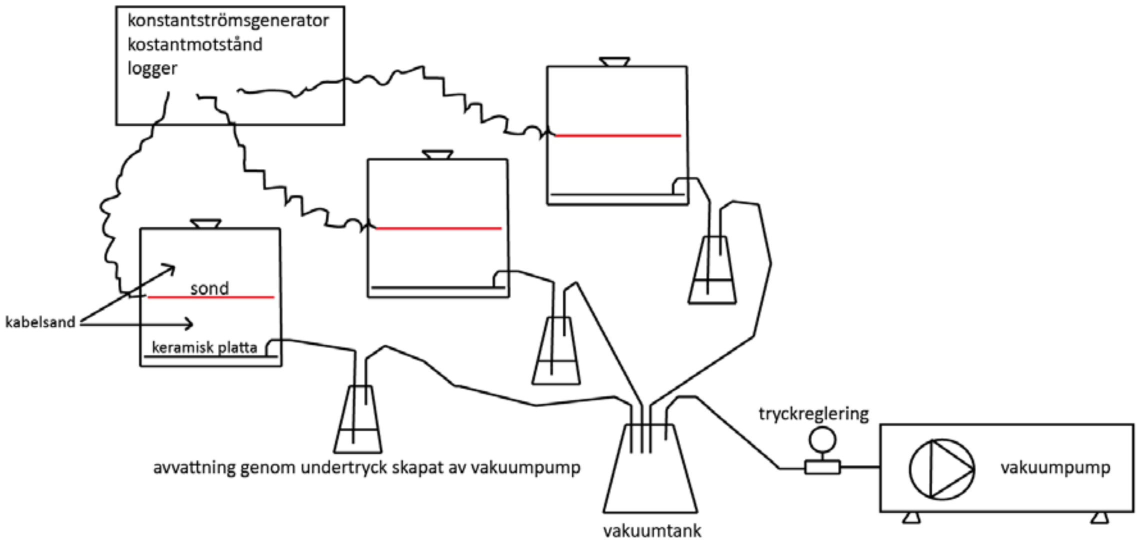
Appendix 1 - First draft of experiment program

Försöksprogram

I ett inledande skede undersöks om planerad utrustning är lämplig för ändamålet. Om så är fallet föreslås försöket fortgå enligt proceduren nedan. En detaljerad modellering av försöket genomförs i ett tidigt skede för att kunna fastställa försökets geometri samt skapa ett underlag som kan användas för jämförelse och utvärdering, modell vs laboratorieförsök. För modellering används programvaran Comsol Multiphysics.

Orienterande laboratorieförsök



Proceduren skulle kunna bestå av följande steg:

1. Beställning av keramiska plattor.

2. Införskaffande av sand typ A1, A2 och B från ovan nämnda bergtäkter.

3. De tre sandtypernas pF-kurvor analyseras på Ulltuna lab, mer tidseffektivt än egen analys.

4. Termisk resistivitet mäts vid vissa steg. Resultaten kontrolleras mot tidigare utförda försök.

5. Kornstorlekskurvor tas fram genom siktning (inkl våtsiktning) av de tre materialen. Resultaten kontrolleras mot tidigare utförda försök.

6. Försöksutrustningen monteras ihop. De tre kastrullerna med de olika proverna parallellkopplas till vakuumpumpen. Efterföljande steg gäller för de tre proverna.

7. Vägning av kastrull inklusive vattenmättad keramisk platta och sond med sladd.

8. Beräkna kastrullens volym med keramisk platta och sond.

9. Packning av sandmaterialet i kastrull med känd fukthalt, med sond på rätt nivå. Väg provet.

10. Vattenmätta provet och väg på nytt.

11. Provet dräneras genom undertryck till förbestämd nivå, förslagsvis 0,05 Bar (0,5-meters grundvattennivå *under "kabeln"*). Vänta tills steady state är uppnått. Väg provet och mät dränerad vattenvolym. Mät värmeledningsförmågan med sonden.

12. En detaljerad modellering av försöket görs parallellt med steg 1-11. Modellens temperaturkurva används som referens under nedanstående steg.

13. En känd effekt tillförs sonden, invänta stabil temperatur. Den initiala effekten uppgår till ca 85 % av förväntad nödvändig effekt för att uppnå 70°C baserat på modellering. Invänta stationära förhållanden. Låt stå ca två veckor. Effekten ökas så mycket att knappt 70 °C förväntas att nås (värdering av uppnådd effekt vid försöket i kombination med utförd modellering).

14. När 70 C° har uppnåtts och denna temperatur är förhållandevis stabil lämnas försöket 1 månad eller mer med aktuell tillförd effekt.

15. Kastrull inklusive prov vägs och vattenhalten beräknas och stäms av mot förväntad vattenhalt. Därefter ökas undertrycket till ca 0,6 Bar (6-meters grundvattensänkning) under ca två veckor med bibehållen effekt.

16. Därefter ges provet tillfälle att återfå den uttagna vattenmängden genom att simulera en stigning av grundvattenytan till den tidigare 0,5 meters nivån. Pumpen stängs av och den uttagna vattenvolymen återinförs provet. Värmeeffekten bibehålls. Provet lämnas till dess att vattnet getts tillfälle att genom kapillarkrafter fördelas i provvolymen och temperaturen uppnått stationäritet.

17. Strömmen slås av och temperaturmätning fortgår till dess att provet nått rumstemperatur, 20 C°. Värmeledningsförmågan mäts med sond.

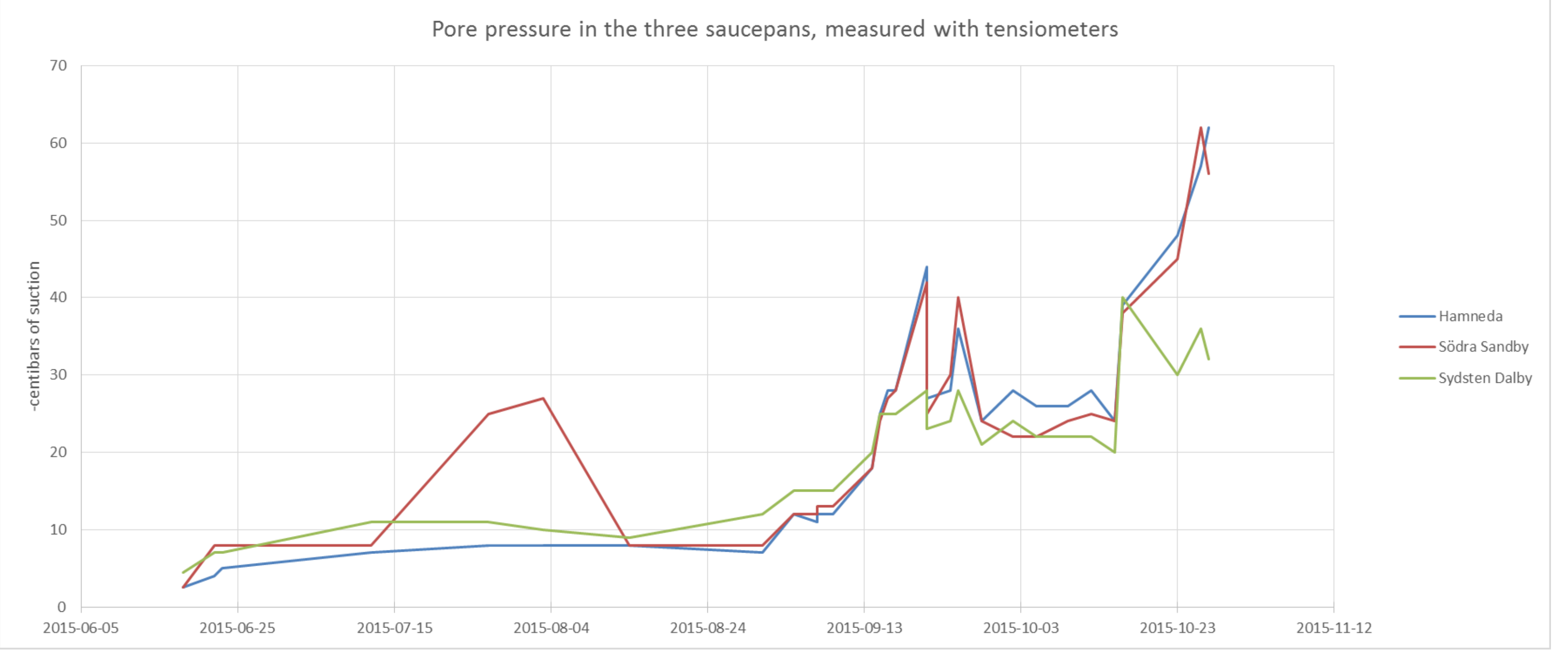
Genom att utföra parallella försök med olika material kan jämförelse ske och försöken blir tidseffektiva

Analys och utvärdering

Efter försöket planeras en analys och utvärdering av materialets vattenhållande och termiska egenskaper. Resultaten från de olika stegen ovan analyseras genom jämförelse med den skapade modellen. En kvalitativ analys sker genom att studera eventuella avvikelser från modellens temperaturkurva kontra försökets temperaturkurva.

Genom ovan beskrivna provförfarande kommer sondens begränsade längd och provets storlek att påverka temperaturutvecklingen som således kommer att bli något annorlunda än om en betydligt längre värmekälla använts. Detta orsakas av 3D effekter. För att hantera dessa kommer en detaljerad COMSOL modell att ställas upp baserad på ren konduktiv värmeledning. Baserat på denna kan förväntad värmeeffekt för att uppnå viss temperatur kalkyleras. En kvalitativ analys bör därför vara möjlig av temperaturförloppet och inverkan av ångdiffusion och uttorkning ske. Vissa kvantitativa beräkningar bör också kunna göras.

Appendix 2 – Tensiometer registrations
10 centibars of suction = a groundwater level of -1 meter



Appendix 3 - Temperature development for Experiment 1