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by

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Table of contents

List of figures

List of tables

List of acronyms

AR: aspect ratio
BHE: borehole heat exchanger
DAQ: data acquisition system
EP: energy pile
GHE: ground heat exchanger
LM: Langmarksvej
RN: Rosborg Gymnasium North extension
RS: Rosborg Gymnasium South extension
TRT: Thermal Response Test
TSA: temperature sensors array

1. Introduction

Centrum Pæle A/S, Aalborg University, VIA University College and INSERO Horsens are partners in the industrial PhD project: “Experimental and numerical characterisation of the thermo-mechanical behaviour of quadratic cross section energy piles”. This document aims to present the fieldwork undertaken in the project at two test sites in Denmark: one in Horsens and one in Vejle. The tasks have been carried out between January 2014 and February 2016.

The fieldwork consists mainly of several thermal response tests (TRT) of precast pile heat exchangers. Pile heat exchangers, also known as energy piles, are thermo-active ground structures that utilize reinforced concrete foundation piles as vertical closed-loop heat exchangers. The interpretation of the in-situ TRT yields the following properties of the soil and the ground heat exchanger (GHE): the effective thermal conductivity of the ground λ_s [W/m/K] and the borehole or pile thermal resistance R_b [K·m/W]. These estimated thermal parameters form the basis for dimensioning a planned ground source heat pump installation based on closed loop vertical ground heat exchangers. However, this report does not cover topics related to the interpretation of TRT data.

The report is organized as follows: firstly, the concept of TRT is explained. Secondly, the test sites are described. Thirdly, the field work is presented and a summary of the future work regarding the methodology to treat the data from the tests is provided. Finally, further documentation of the fieldwork, the pile heat exchangers and the TRT equipment is extended in diverse appendices.

2. Concept of thermal response testing

Thermal response testing (TRT) is a widely used field method for estimating soil thermal conductivity λ_s [W/m/K] and thermal resistance of traditional borehole heat exchangers (BHE) R_b [K·m/W] (Mogensen P., 1983, Gehlin, 2002). In the TRT, the heat carrier fluid (water) is circulated in the GHE at a specified rate while being continuously warmed by a heater. Heat dissipates to the GHE and subsequently the ground, and records of the fluid inlet- and outlet temperatures, the fluid flow rate and energy consumption are compiled every 10 minutes during the test (for at least 48 hours). Ambient temperatures inside and outside the TRT equipment are also recorded during the test. Figure 1 illustrates the TRT set-up.

The thermal conductivity of the ground λ_s and the GHE thermal resistance R_b are estimated in the interpretation of the measured heat carrier fluid inlet and outlet temperatures. The thermal conductivity of the ground λ_s is a measure of the ease with which the soil conducts heat. Heat is more easily extracted from highly conductive soils and such soils recuperate more rapidly from thermal depletion. The interpretation of the TRT yields an average soil thermal conductivity over the length of the GHE. It is not possible, in the interpretation, to distinguish individual soil layers. The presence of groundwater flow increases the effective thermal conductivity of the ground.

The GHE thermal resistance R_b is the integrated thermal resistance between the heat carrier fluid and the ground. As such, the piping, the flow rate and regime, heat exchanger configuration, grout and GHE diameter influence the GHE thermal resistance R_b. It should be as low as possible.

The analytical infinite line source approach is a standard method for analysing TRT of traditional vertical borehole heat exchangers (ASHRAE, 2011). However, there is a lack of scientifically supported guidelines for analysing TRT data from energy piles (Loveridge, 2012, GSHP Association, 2012). The quadratic cross section precast piles do not fulfil the basic geometrical assumptions for

vertical ground heat exchangers and, therefore, novel approaches that better characterize the heat transfer in and around such structures are required.

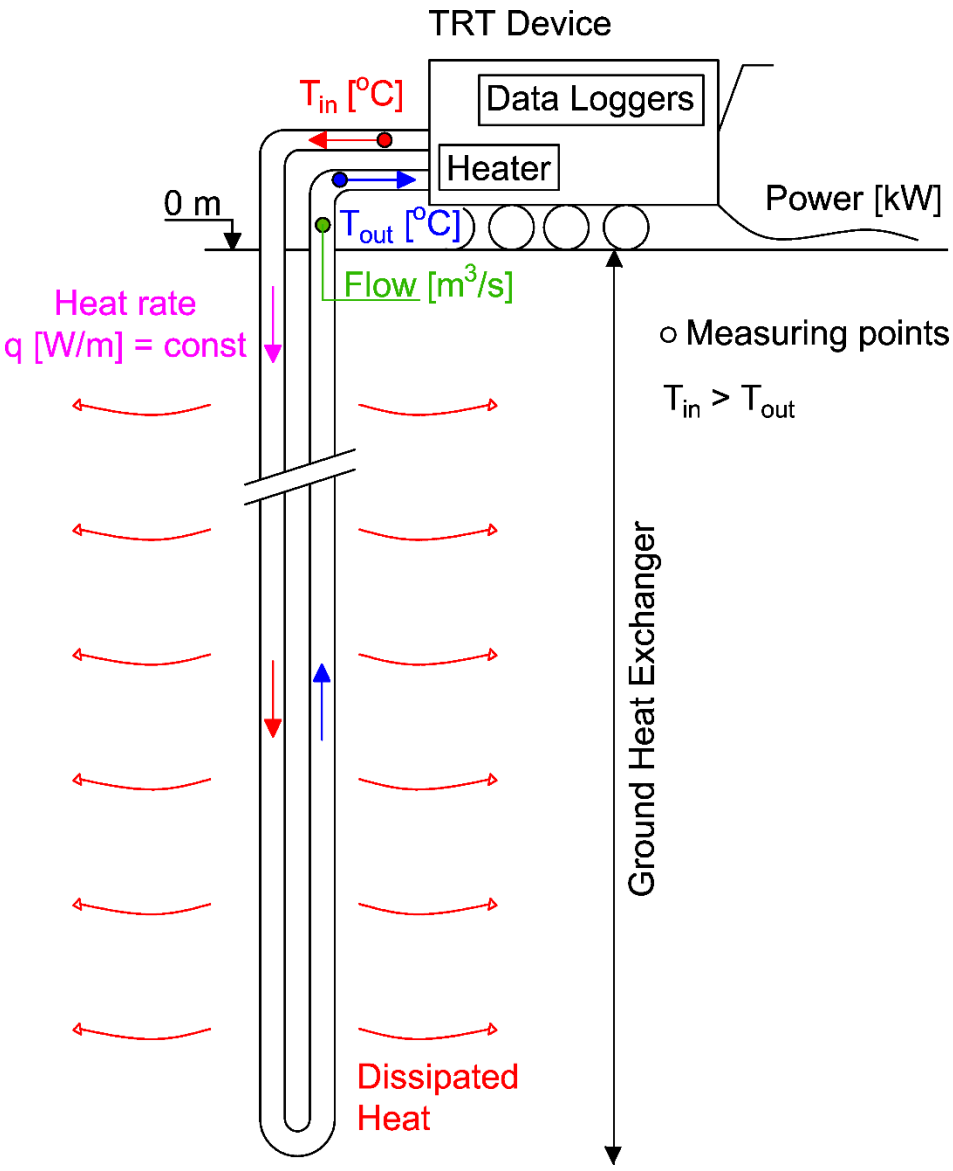

Figure 1: Thermal response test set-up.

3. Test sites

In the following, the two test sites will be described in terms of geology and types of GHEs.

3.1. Langmarksvej

The test site is situated at Langmarksvej 84 (street address), 8700 Horsens, Denmark, 800 m from the VIA University College campus (Figure 2). The test site was established in 2010 as part of a research collaboration between Centrum Pæle A/S, Horsens A.M.B.A. district heating company and VIA University College. After 4 years without operation, the test site is currently used in the present PhD project.

Figure 2: The Langmarksvej test site, Langmarksvej 84, 8700 Horsens, Denmark.

3.1.1. Geology

A monitoring drilling was executed on the 2/11/2015 by Franck Geoteknik A/S and a stratigraphic profile was compiled. Soil samples were collected each 0.5 m and for each sample the following properties were measured in the laboratory: bulk density ρ [g/cm^3], water content [%], thermal conductivity λ_s [W/m/K] and volumetric heat capacity S_{vc} [MJ/m^3/K]. The geological setting and thermal parameter measurements are listed in Figure 3 (see Appendix A for further details). The thermal properties have been estimated by means of a Hot Disk apparatus, Transient Plane Source (Hot Disk AB, 2014). Hot Disk AB (2014) defines the accuracy of the thermal conductivity measurements as ± 5%, while the accuracy for the thermal diffusivity defined between ± 5 and 10%. Five repeated measurements have been taken for each sample at a room temperature of 20°C.

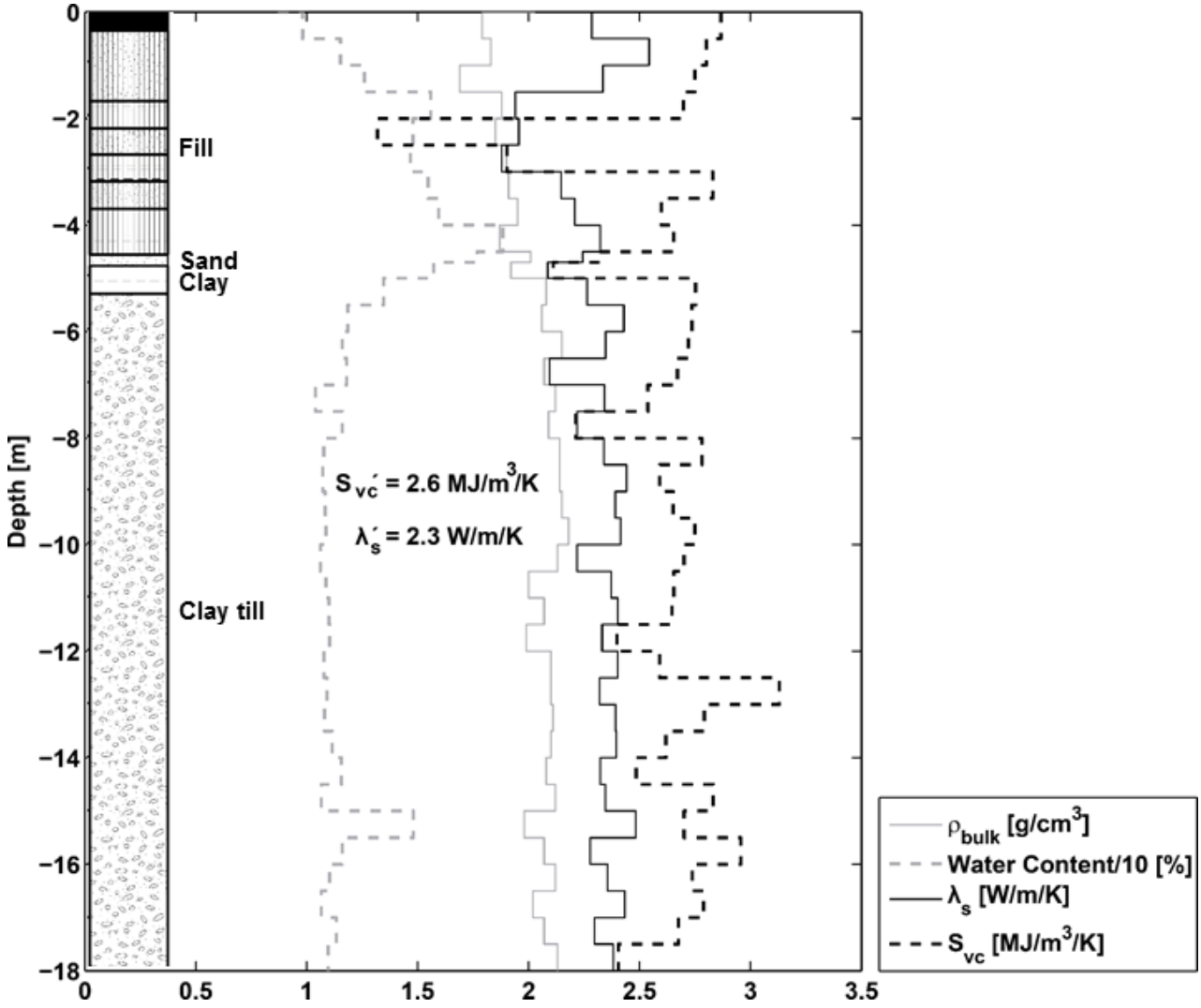

Figure 3: Stratigraphic profile at the Langmarksvej test site. Bulk density ρ, water content, thermal conductivity λ_s and volumetric heat capacity S_{vc} measured in the laboratory using the Hot Disk apparatus are also provided. S_{vc}' and λ_s' are weighted average estimates over the length of the drilling.

3.1.2. Ground heat exchangers

The test site comprises four energy piles, a BHE and a drilling instrumented with a temperature sensor array (TSA). The GHEs are located as shown in Figure 4. Additional pictures of the test site are provided in Appendix A.

Table 1 lists key information for the tested GHEs. Figure 5 depicts the cross section of the energy pile, which applies to all energy piles described in this document. These pile heat exchangers have a length between 12 to 18m, a quadratic cross section (0.30 x 0.30 m^2) and a W-shape pipe configuration heat exchanger fixed to the steel reinforcement. Appendix B provides technical drawings of the energy piles. A vertical profile for the TSA showing the location of the temperature sensors is provided in Figure 6. The temperature sensors are Pt100 type, described in Appendix C, and they are placed inside a pipe (2 cm diameter). The annulus between the pipe and the ground is filled with quartz sand. The sensors are connected to Labview software (National Instruments,

2015a), working on a nearby computer, which collects the ground temperature records every second during the TRT.

Table 1: Properties of tested GHE at the Langmarksvej (LM) test site (information provided by Centrum Pæle A/S and VIA University College).

Test Site	Langmarksvej 84, 8700 Horsens				
GHE name	LM-BHE	LM-EP8	LM-EP7	LM-EP4	LM-EP3
GHE pipe type	Double U [2U]	Single U [1U]	Single U [1U]	W-shape [W]	W-shape [W]
Borehole or energy pile length [m]	18	12	18	12	18
GHE active length [m]	16.5	10.8	16.8	10.8	16.8
Pipe length [m]	68.0	20.8	33.6	42.0	65.0
Pipe material	PEX-A	PEX-A	PEX-A	PEX-A	PEX-A
Pipe outer diameter [mm]	20	20	20	20	20
Pipe inner diameter [mm]	16.2	16.2	16.2	16.2	16.2
Pipe wall thermal conductivity [W/m/K]	0.42	0.42	0.42	0.42	0.42
Use of spacers	Yes	No	No	No	No
Shank spacing [m]	0.15	0.21	0.21	0.21	0.21
Grout material	Quartz sand 25 mm	Concrete	Concrete	Concrete	Concrete
Expected grout thermal conductivity [W/m/K]	2.4	1.8	1.8	1.8	1.8
GHE shape	Circular, 0.2 m diameter	Square, 0.3mx0.3m	Square, 0.3mx0.3m	Square, 0.3mx0.3m	Square, 0.3mx0.3m
Installation method	Auger drilling	Driven pile	Driven pile	Driven pile	Driven pile
Supplementary instrumentation	No	No	No	No	Pt100 temperature sensors in the ground at different levels (Figure 4)

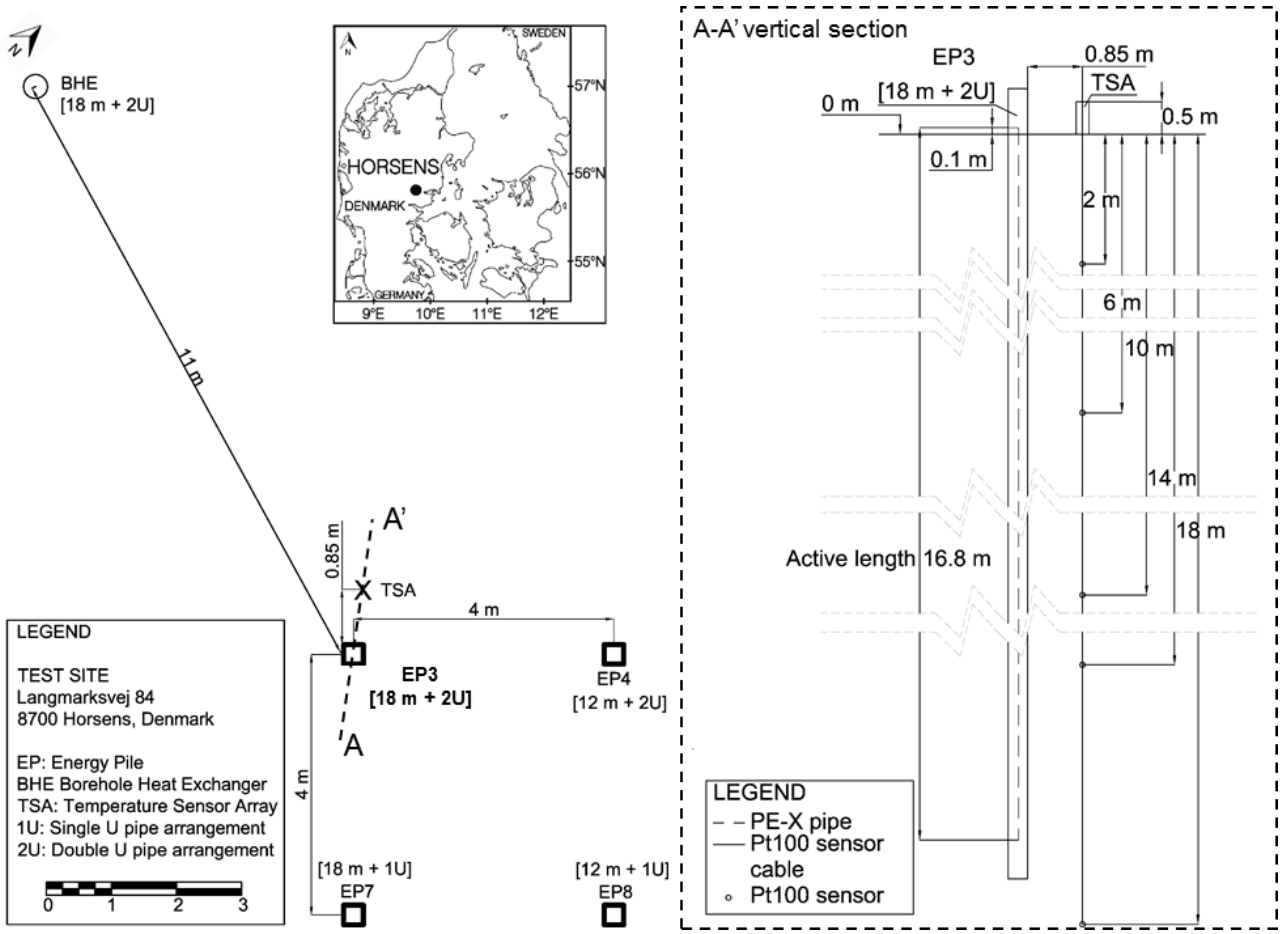

Figure 4: Ground heat exchanger location at Langmarksvej test site: top view and vertical section.

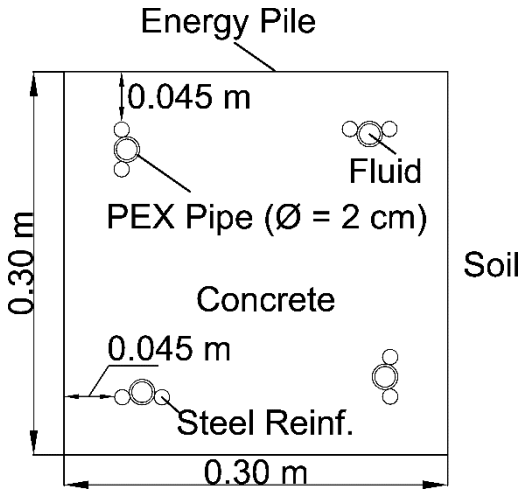

Figure 5: Precast energy pile cross section. Applicable to all the pile heat exchangers described in this document.

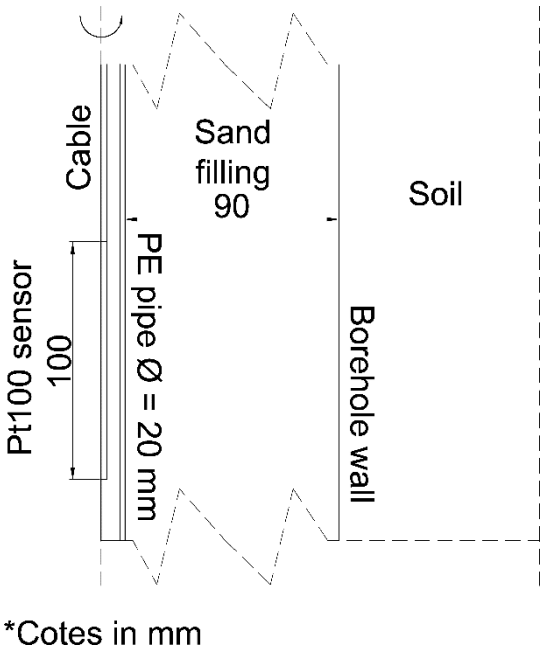

Figure 6: Vertical cross section of the location of a single Pt100 temperature sensor within the TSA drilling, located 0.85 m apart form EP3.

3.2. Rosborg Gymnasium

The test site is located at Vestre Engvej 61, 7100 Vejle, Denmark (Figure 7). The south extension of the Rosborg Gymnasium building is founded on 200 foundation pile heat exchangers. The thermo-active foundation has supplemented the heating and free cooling requirements of the building since 2011 (4,000 m^2 living area). More information about the performance of the installation can be found in Alberdi-Pagola et al. (2016). The north extension of the gymnasium complex is currently under construction. To date, the foundation, that consists of 220 energy piles, has been constructed.

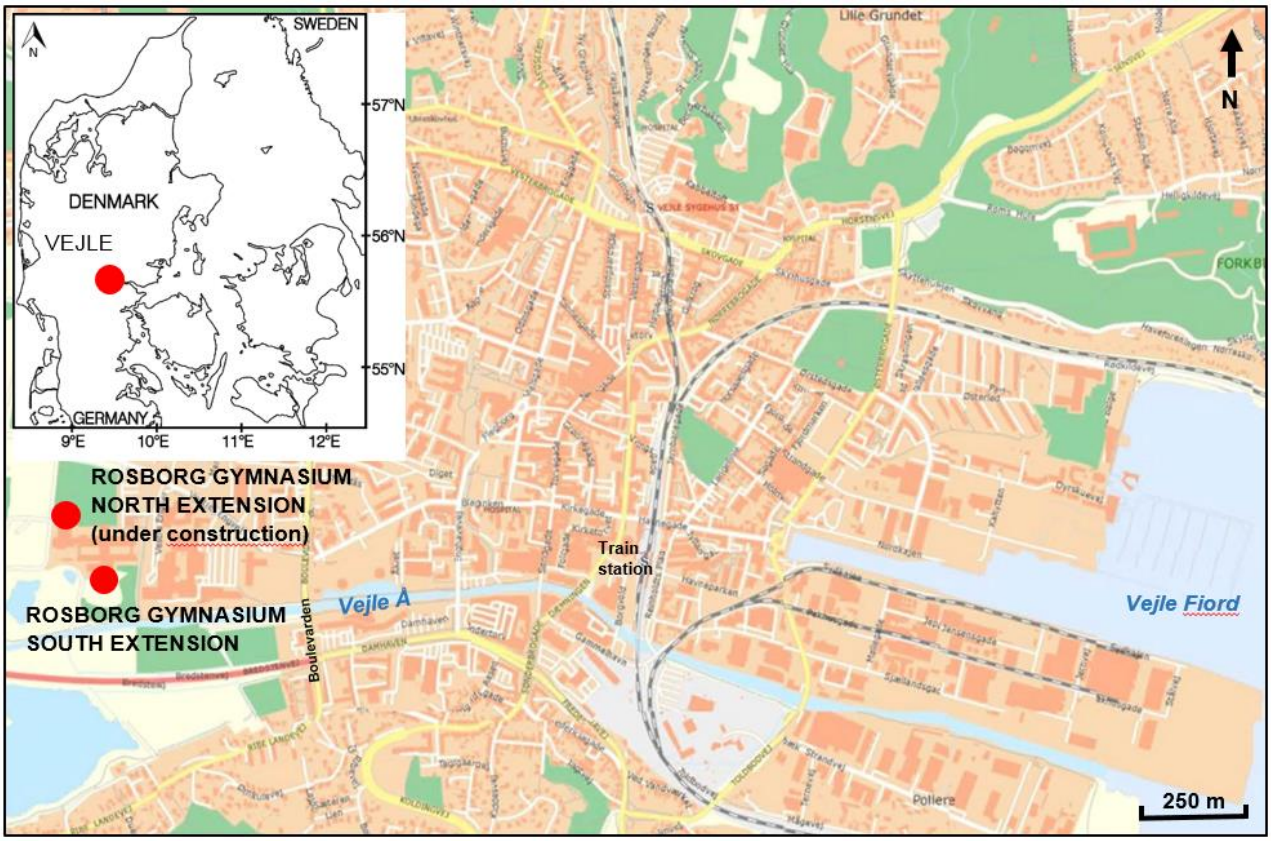

Figure 7: The Rosborg Gymnasium building at Vestre Engvej 61, 7100 Vejle, Denmark. The south and north extensions are founded on 200 and 220 energy piles, respectively.

3.2.1. Geology

The piles are founded in glacial sand 5-6 meters below terrain, which is overlain by postglacial, organic mud (Table 2). The groundwater table is situated around 0.70 m below terrain (Dansk Geoteknik A/S, 1973, Franck Geoteknik A/S, 2013). A more detailed stratigraphic column is provided in Appendix A. Both buildings are founded on similar geologies.

Table 2: Geological description of the field site at Rosborg Gymnasium.

Depth [m]	Description
0.0-0.3	SAND and slags, fillings.
0.3-0.6	PEAT, postglacial, fresh.
0.6-1.5	SAND, medium sized with organic mud spots, postglacial marine.
1.5-5.0	ORGANIC MUD, postglacial marine.
5.0-8.0	SAND, medium sized with organic mud parts and small stones, postglacial marine.

3.2.2. Pile heat exchangers

Figures 7 and 8 show the footprints of the north and south extensions at Rosborg Gymnasium, respectively. Two of the 200 energy piles at the south building extension are instrumented with Pt100 temperature sensors. Two additional piles, which are accessible from the canteen area in the building, are available for testing. One of these energy piles (marked in Figure 8) was tested and

analysed in Alberdi-Pagola and Poulsen (2015). Two of the 220 energy piles at the north extension are instrumented and a TRT has been executed in the energy pile indicated in Figure 9.

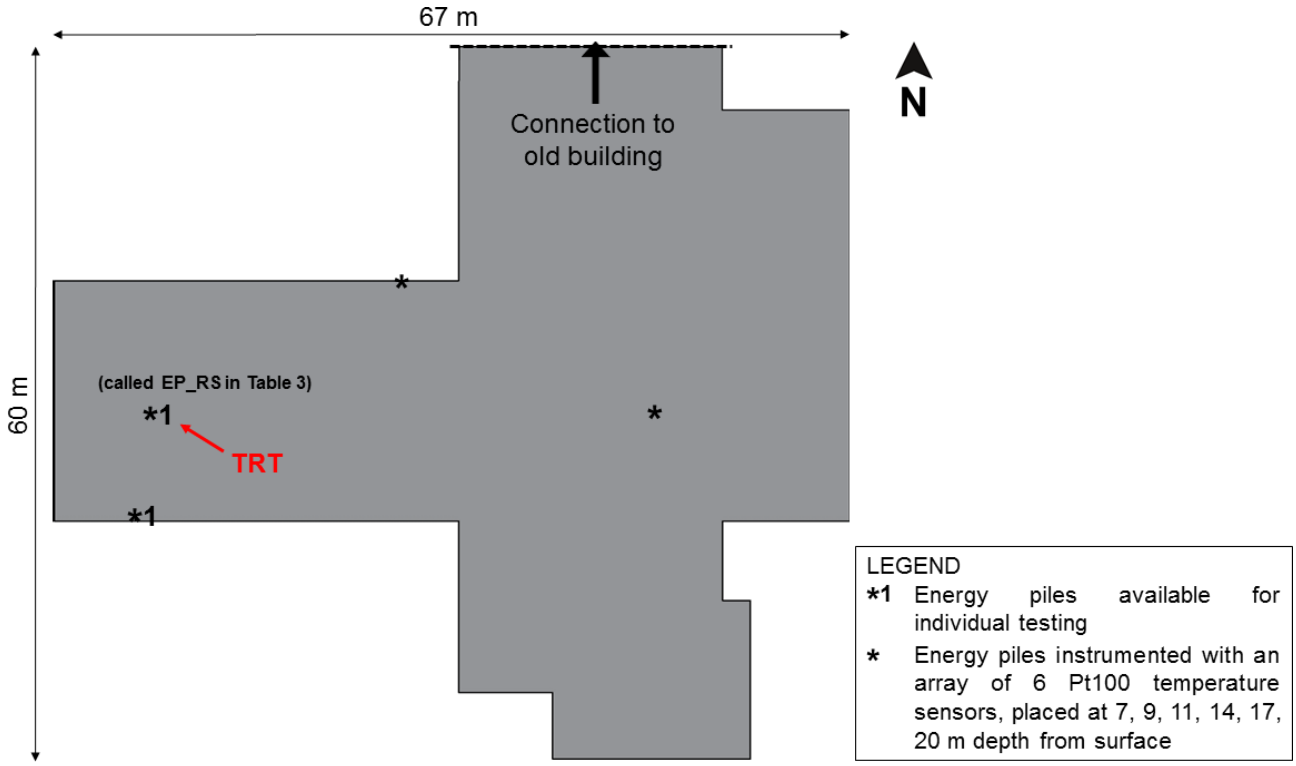

Figure 8: Footprint of the Rosborg Gymnasium's southern extension building. The location of instrumented piles and piles available for testing are also provided.

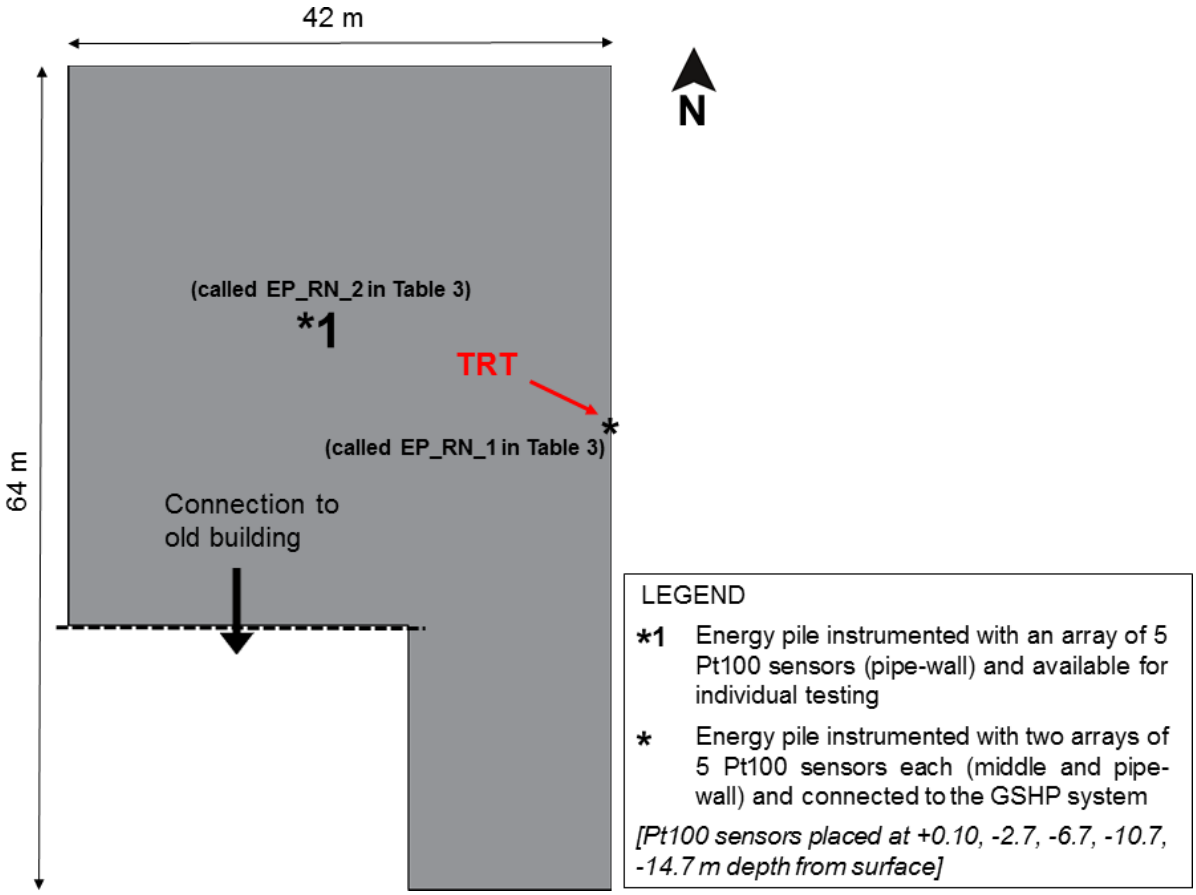

Figure 9: Footprint of the Rosborg Gymnasium's northern extension building. The location of instrumented piles and piles available for testing are also provided.

Table 3 lists key information about the tested energy piles at Rosborg Gymnasium and Figure 10 shows the depths of the Pt100 temperature sensors installed within the piles tested at the north extension. More details about the way the sensors were placed within the concrete is shown in Figure 19 (Appendix A).

Table 3: Properties of tested energy piles (EP) at Rosborg Gymnasium test site.

Test Site	Vestre Engvej 61, 7100 Vejle, Denmark		
	Rosborg Gymnasium South	Rosborg Gymnasium North	
GHE name	EP_RS	EP_RN_1	EP_RN_2
GHE pipe type	W-shape [W]	W-shape [W]	W-shape [W]
Energy pile length [m]	Unknown	16	16
GHE active length [m]	15	14.8	14.8
Pipe length [m]	54	58	58
Pipe material	PEX-A	PEX-A	PEX-A
Pipe outer diameter [mm]	20	20	20
Pipe inner diameter [mm]	16.2	16.2	16.2
Pipe wall thermal conductivity [W/m/K]	0.42	0.42	0.42
Use of spacers	No	No	No
Shank spacing [m]	0.21	0.15	0.15
Grout material	Concrete	Concrete	Concrete
Grout thermal conductivity [W/m/K]	1.8	1.8	1.8
GHE shape	Square, 0.3mx0.3m	Square, 0.3mx0.3m	Square, 0.3mx0.3m
Installation method	Driven pile	Driven pile	Driven pile
Supplementary instrumentation	No	2 Pt100 strings, 5 levels (Figure 10)	1 string Pt100, 5 levels, (Figure 10)

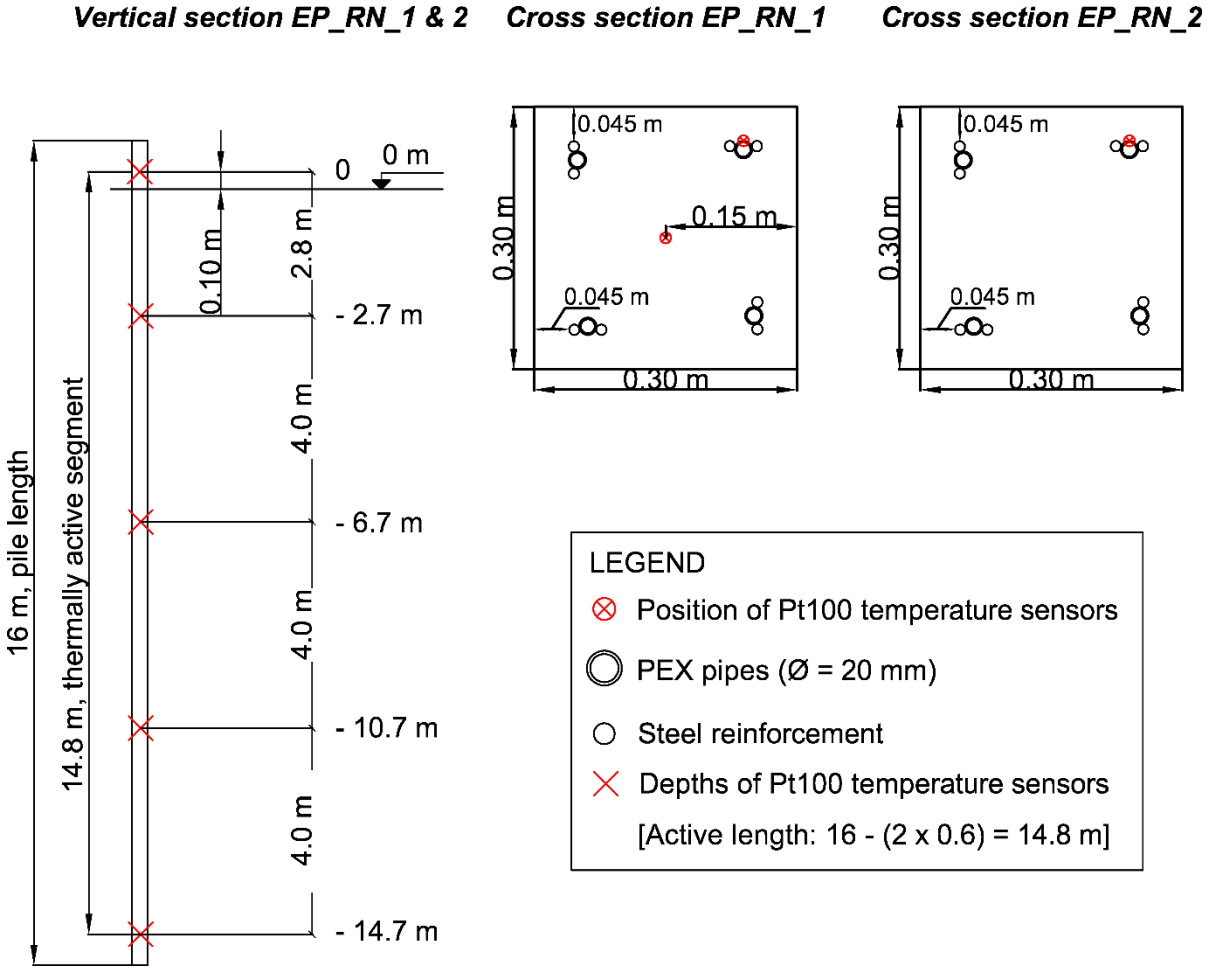

Figure 10: Schematic arrangement of Pt100 strings within the instrumented piles and their depths at Rosborg North, piles 1 and 2 (EP_RN_1 & 2): vertical section and cross sections.

4. TRT sets

In present TRTs, the heat carrier fluid (10°C water) is circulated without heating for approximately 30 minutes while maintaining a fluid pressure of 2 bar prior to switching on the heater (and thus starting the test). According to the international standards the minimum duration of a TRT of a borehole heat exchanger is 48 hours (ASHRAE, 2011). The duration of the TRT is determined by the amount of early data that has to be discarded in order to determine soil thermal conductivity λ_s (approximately the first ten hours) in accordance with the assumptions of the standard line source-based method of interpretation (Hellström, 1998). Energy consumption, inlet- and outlet temperatures, fluid flow and the power dissipated are recorded during the test. A total of 8 TRT data sets have been collected which are described in the following. Further documentation of the fieldwork, the tests and the equipment is provided in Appendixes A, D and E.

4.1. Langmarksvej

Five TRTs were performed:

a) Four TRTs of energy piles with different lengths and heat exchanger pipe arrangements (Figures 4 and Table 1). Key parameters for the TRTs are provided in Table 4.
b) One TRT of a single BHE (Figure 4, Tables 1 and 4).
c) Ground temperatures at different depths logged during a single TRT of EP3 at a temperature sensor array (Figure 4)

Table 4 summarises the main parameters of the TRT sets and it also compares the test conditions to the recommendations given by ASHRAE (ASHRAE, 2011). The discrepancies with the recommendations from ASHRAE regarding the late time difference between fluid inlet and outlet temperatures in TRTs of BHE and EP8, are due to: 1) The flow rate set is too high in the TRT of the BHE and 2) the length of EP8 is 12 m and it contains a single U heat exchanger pipe. These reasons hamper the efficient dissipation of heat into the ground. The TRT of EP7 was interrupted for 10 hours. The data is available in Appendix C.

Table 4: Key parameters for the TRTs performed at the Langmarksvej test site.

TRT Date	13-08-2015	17-11-2015	24-11-2015	01-12-2015	27-01-2016	ASHRAE recommendations
GHE name	BHE	EP8	EP7	EP4	EP3	
Equipment used	UBeG	UBeG	UBeG	UBeG	UBeG	-
Average Undisturbed Soil Temperature [ºC]	11.98	12.16	11.49	11.39	10.4	-
S_{vc} from Hot Disk measurements [MJ/m^3/K]	2.6	2.6	2.6	2.6	2.6	-
λ_s from Hot Disk measurements [W/m/K]	2.3	2.3	2.3	2.3	2.3	
Heat carrier fluid	Water	Water	Water	Water	Water	-
Measurement interval [min]	10	10	10	10	10	≤ 10
Volumetric flow rate [m^3/h]	0.89	0.50	0.48	0.56	0.51	-
Reynolds number	19349.00	10942.00	10468.00	12195.00	10998.00	-
Average heat injection rate [W/m]	60.32	101.36	115.89	159.35	167.61	> 50
Heat injection rate, standard deviation as % of average	1.83	4.33	-	4.70	3,74	Peaks < 10
TRT duration [h]	49.83	114.17	69.33	114.17	146.67	> 48
Average, late time $\Delta T = T_{in} - T_{out}$	1.02	1.95	3.50	2.65	4.89	> 3.0
Recovery test?	Yes	No	No	No	Yes	-
Recovery test duration [h]	50.67	-	-	-	115	-

4.2. Rosborg Gymnasium

Table 5 summarises key parameters for the TRT sets and lists test conditions compared to recommendations given by ASHRAE (ASHRAE, 2011).

Table 5: Summary of main parameters of the TRTs performed at Rosborg Gymnasium test site.

TRT Date	13-01-2014	20-04-2015	09-02-2016	ASHRAE recommendations
GHE name	EP_RS	EP_RS	EP_RN	-
Equipment used	VIA	UBeG	UBeG	-
Average Undisturbed Soil Temperature [°C]	10.2	10.12	9.84	-
Heat carrier fluid	Water	Water	Water	-
Measurement interval [min]	10	10	10	≤ 10
Volumetric flow [m^3/h]	0.385	0.537	0.536	-
Reynolds number	8519	11713	11981	-
Average heat injection rate [W/m]	152.5	183.29	157.83	> 50
Heat injection rate, standard deviation as % of average	4.29	5.39	3.0658	Peaks < 10
TRT duration [h]	96.33	69.17	49.33	> 48
Average, late time ΔT=Tin-Tout	5.10	4.52	3.78	> 3.0
Recovery test?	No	No	No	-

4.3. Test comparison

The TRT data are plotted in Figure 11 as normalised temperature Φ (Equation 1) vs. the Fourier number Fo (Equation 2) for a constant rate of heat transfer q [W/m]:

$$\Phi = \frac{2 \cdot \pi \cdot \lambda_s \cdot \Delta T}{q} \qquad (1)$$

$$Fo = \frac{\alpha_s \cdot t}{r_b^{\,2}} \qquad (2)$$

where ΔT is the change in temperature, λ_s is the soil thermal conductivity, α_s is the soil thermal diffusivity [m^2/s], defined as the ratio between the thermal conductivity λ_s and the volumetric heat capacity S_{vc}, of the soil and t is the elapsed test time. A λ_s of 2.30 W/m/K and a S_{vc} of 2.60 MJ/m^3/K are used to plot the TRT sets from Langmarksvej while a λ_s of 2.41 W/m/K and a S_{vc} of 2.40 MJ/m^3/K are chosen to plot the TRT data from Rosborg Gymnasium, as are the estimates from Alberdi-Pagola and Poulsen (2015). Figure 11 indicates a higher GHE thermal resistance for the single U heat exchangers relative to double U configurations, as expected. This can be deduced from the higher temperature increase measured in the single U heat exchanger tests. Besides, the test performed in the borehole heat exchanger yields the highest temperature increments, which implies that the double U heat exchanger pipe placed in the borehole is less efficient transferring heat to the soil relative to the tested energy piles.

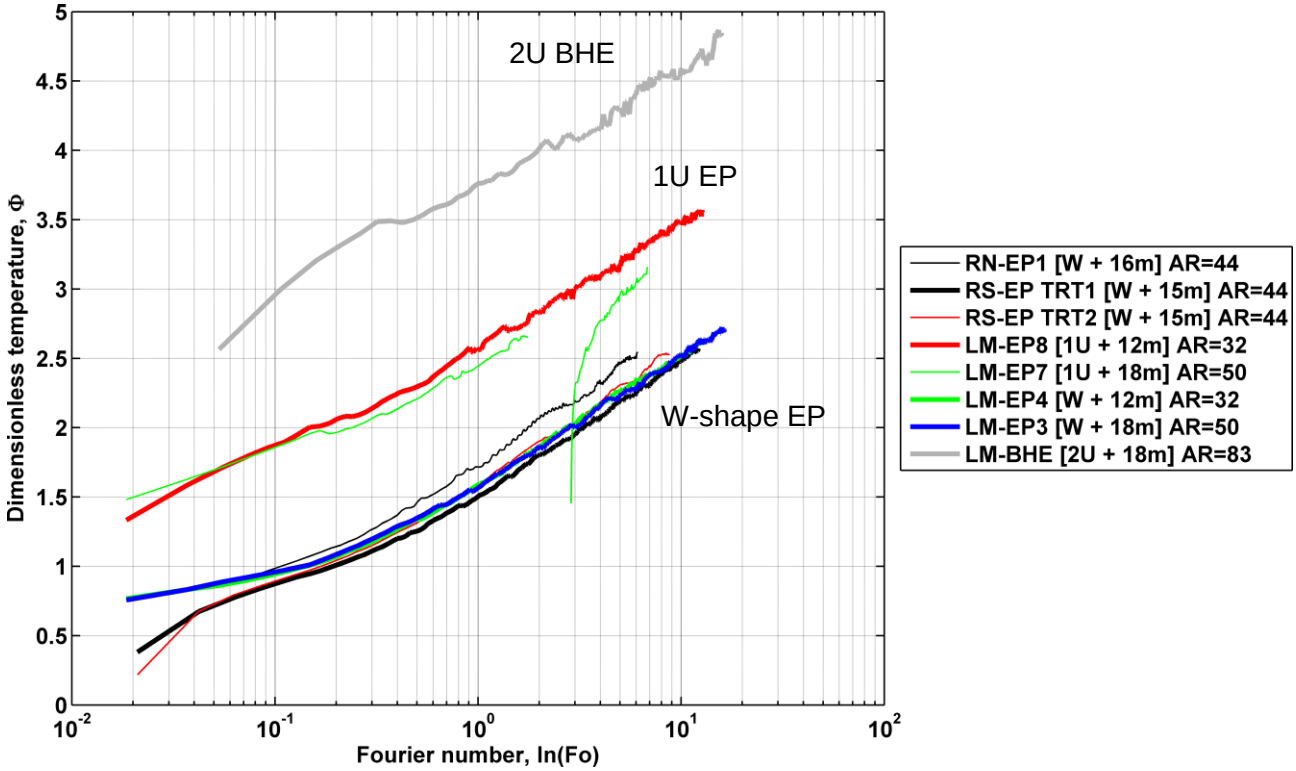

Figure 11: Short term GHE temperature responses in the TRTs. RS = Rosborg South, RN = Rosborg North, LM = Langmarksvej and AR = aspect ratio (GHE length/GHE width).

5. Future work

The future work will be focused on the analysis and interpretation of the recorded field data to validate models for quadratic cross section energy piles. The scientific objectives are:

Objective 1: Validating existing and novel, short run-time analytical and numerical models of the thermal behaviour of quadratic heat exchanger pile (2D - 3D implications).

Objective 2: Based on the validated models, investigate the feasibility of TRT methods for energy pile applications. Particular attention will be paid to the estimation of soil thermal conductivity λ_s [W/m/K] and pile thermal resistance R_b [K·m/W].

Objective 3: Make recommendations regarding interpretation methods, testing times and likely uncertainties for quadratic pile TRTs.

6. Acknowledgements

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UBEG UMWELT BAUGRUND GEOTHERMIE GEOTECHNIK, 2013. Thermal Response Test Equipment Data. Germany.

8. Appendices

A) Test site documentation

This section provides a detailed description of the geology at the field sites. Subsequently, pictures are provided (Figures 12 to 20).

i. Langmarksvej

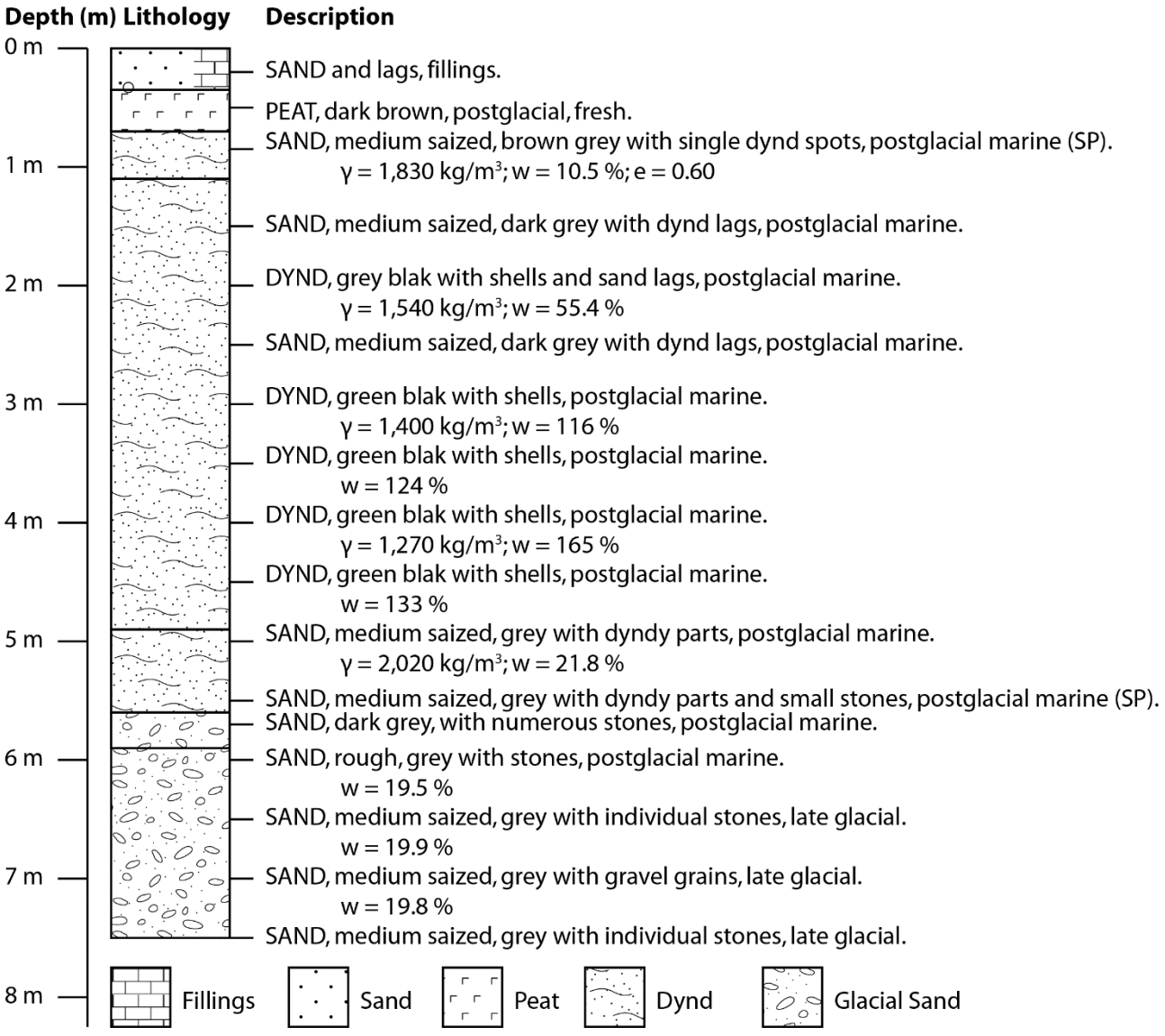


Figure 12: Soil description of the samples collected each 0.5 m in the drilling executed to host the temperature sensor array TSA.

Figure 13: Ongoing TRT at the 18 m deep BHE at Langmarksvej. Inlet- and outlet pipes are insulated to prevent disturbances from ambient temperature conditions.

Figure 14: A single EP at the Langmarksvej test site prior to connecting the TRT equipment.

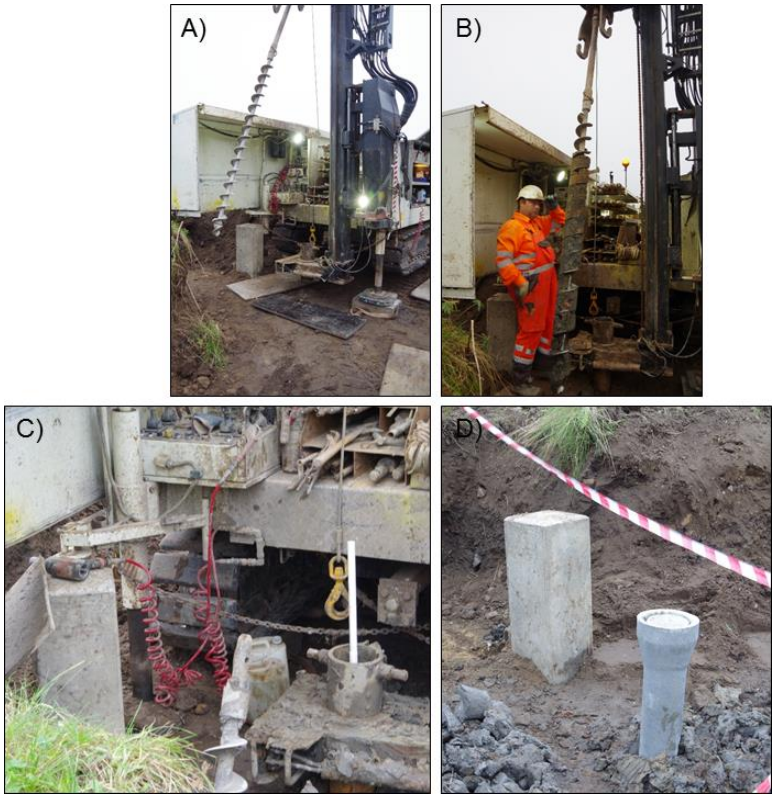


Figure 15: Monitoring drilling work. The drilling is located 0.85 m from EP3 (see Figure 12).

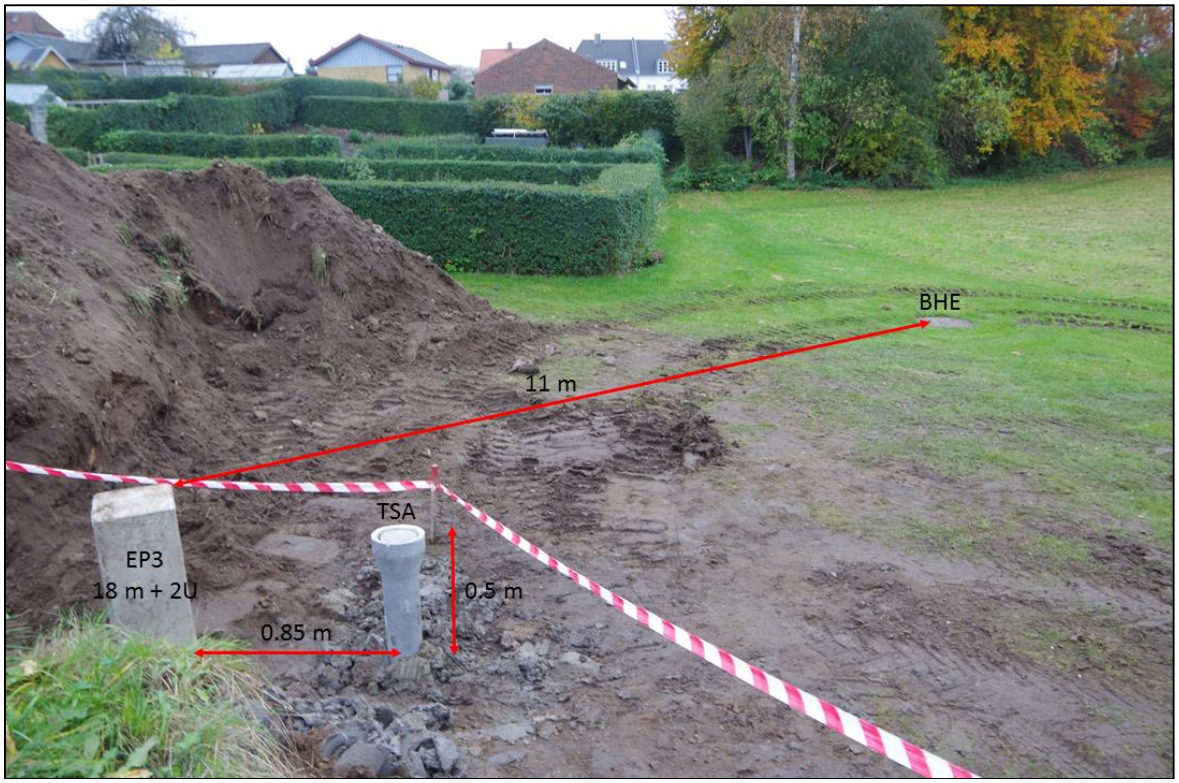


Figure 16: View of the EP3, the TSA and the BHE at the Langmarksvej test site.

Figure 17: Ongoing TRT of the 18 m long EP3 at Langmarksvej. Inlet- and outlet pipes are insulated to prevent disturbances from ambient temperature conditions. The adjacent box, covered by black plastic bags, contains the computer and the modules to log the temperature data from the underground Pt100 TSA.

ii. Rosborg Gymnasium

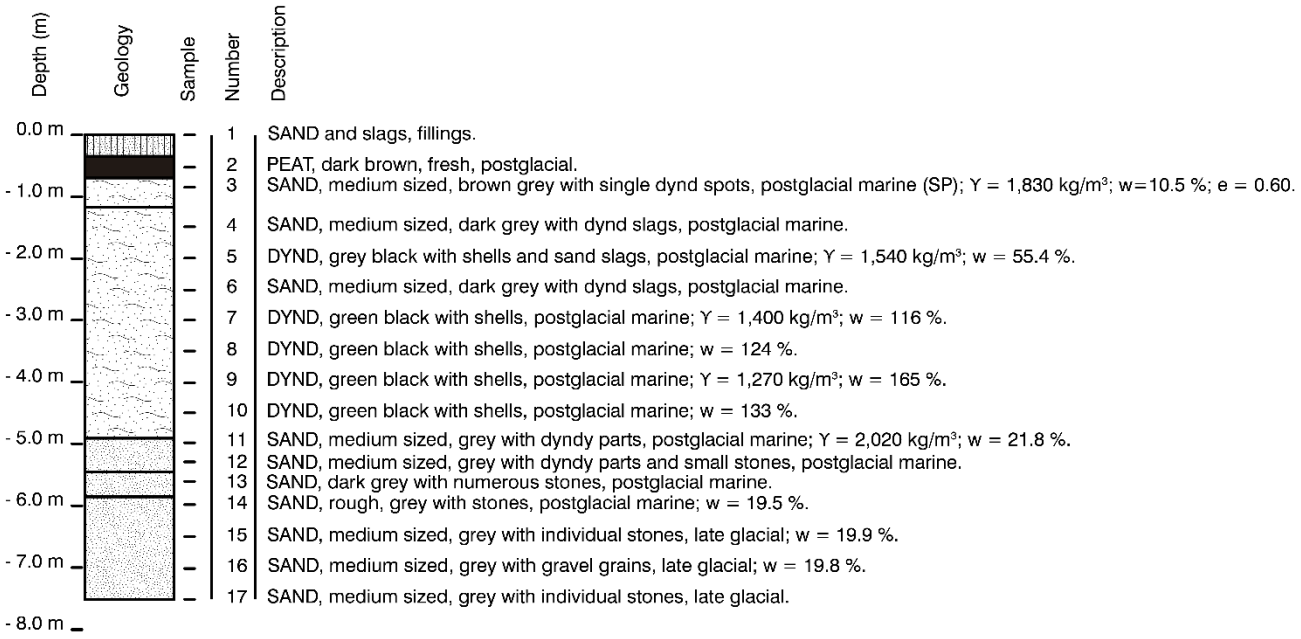


Figure 18: Soil description for the south extension at Rosborg Gymnasium (Dansk Geoteknik A/S, 1973).

Location of the Pt100 temperature sensors within the pile reinforcement, before the concrete was casted.

Figure 19: Pile instrumentation with Pt100 temperature sensors.

Figure 20: A) Ongoing TRT of the 16 m long EP at Rosborg North. Inlet- and outlet pipes are insulated to prevent disturbances from ambient conditions. B) The adjacent box, covered by black plastic bags contains the computer and the modules to log the temperature data from the Pt100 temperature sensors casted into the pile (see Figure 10).

B) Energy pile drawings

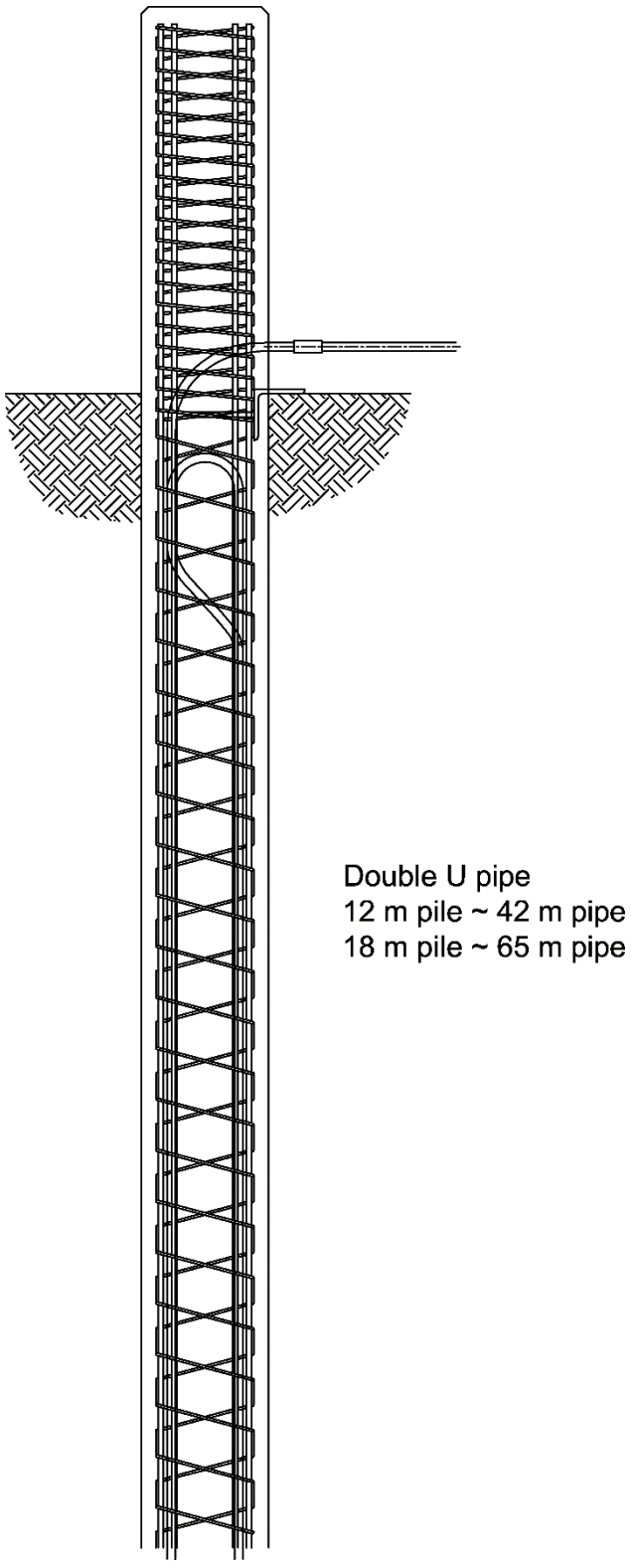


Figure 21: Vertical cross section of a W-shape driven energy pile.

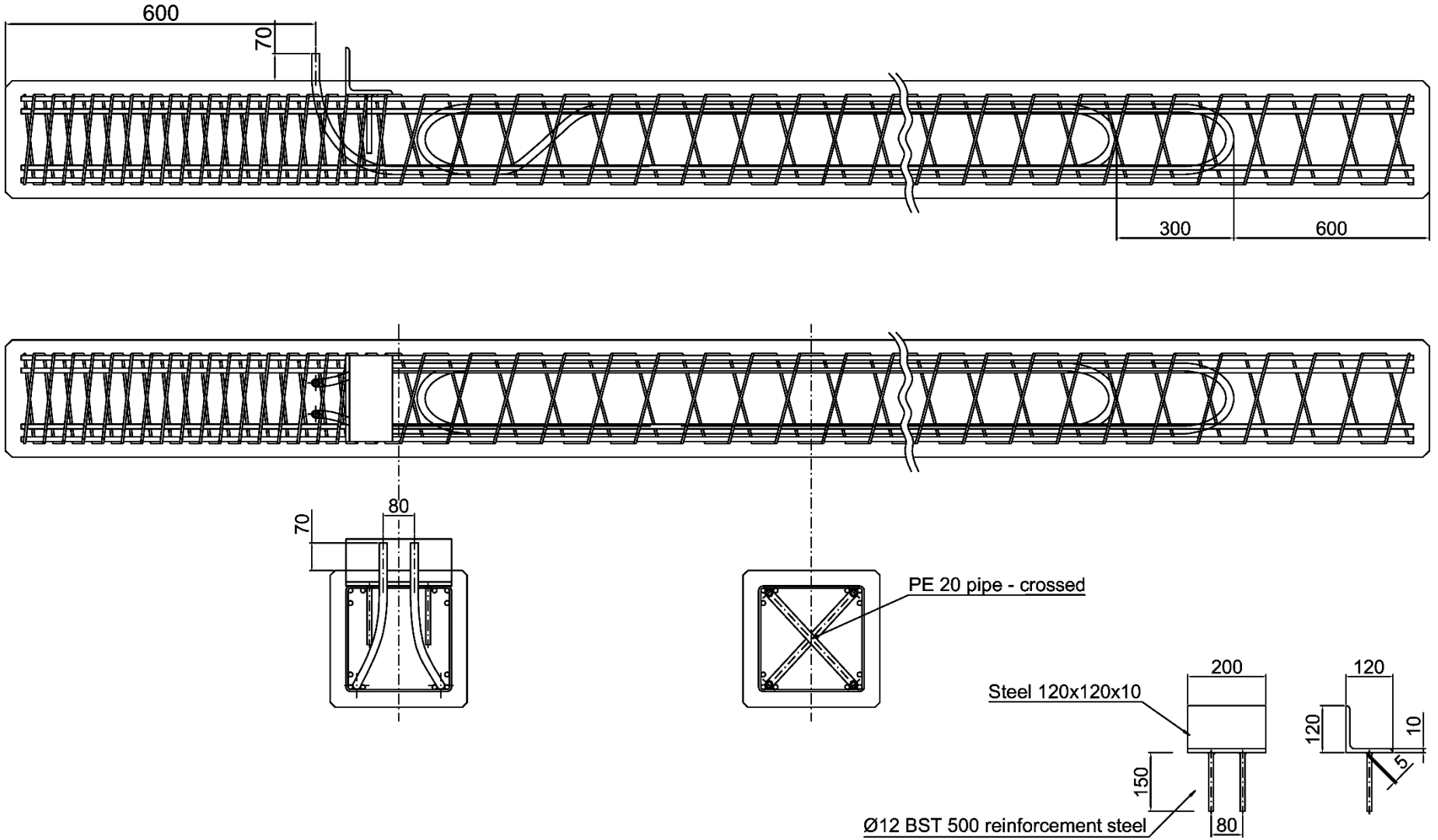


Figure 22: Geometry and dimensions in mm of a W-shape energy pile.

C) Temperature measurements

Resistance-temperature detectors (PT100) have been used to measure the ground temperatures during the TRT of EP3 at Langmarksvej and the pile temperatures during the TRT of RN_EP_1 at Rosborg North. Resistance-temperature detectors are temperature sensors based on the change in the electrical resistance resulted from a temperature change in a metal, in this case, Platinum (Pt) (A. J. Wheeler and A. R. Ganji, 2004). For the tests, a 2-wire Pt100 type was chosen.

The Pt100 temperature sensors have been calibrated for the range of expected experimental temperatures (from 0 to 50°C) at Aalborg University the 8/01/2016. The process consists of quantifying the deviation of the resistance readings (and thereby, temperature measurements) of the Pt100 from the temperature measurements taken with the reference thermometer (considered as the true value). This way, the resistance readings can be corrected and the right temperature displayed during the experiments. Five cable lengths where used connected to the sensors: 3, 7, 11, 15 and 19m. The setup schematic is provided in Figure 23 and the process breakdown is hereby described:

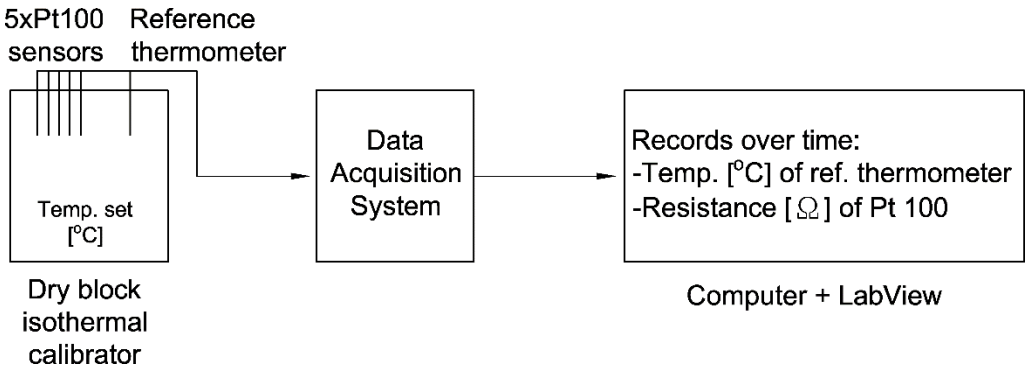


Figure 23: Schematic of the calibration setup.

1. The sensors (with the five cable lengths) and the reference thermometer are inserted into a dry block isothermal calibrator where the temperature can be selected.
2. A first temperature step at 50°C is set in the calibrator.
3. The sensors and the thermometer are connected to a data acquisition unit DAQ which addresses the readings to a nearby computer.
4. The computer has LabView software (National Instruments, 2015a) installed. Here the resistance measurements from the Pt100 and the temperature readings from the reference thermometer are logged every second.
5. Each temperature step lasts 30 minutes approximately. First, the sensors need 15 minutes to stabilise in the new temperature. Once they show constant readings, a 10-15 minutes period is recorded.
6. An average of the resistance readings corresponding to the 10-15 minutes period is plotted against the corresponding temperature reading from the reference thermometer (Point 1 in Figure 24).
7. The process is repeated for further temperature steps: 40, 30, 20, 10 and 0°C. Therefore, the total number of points in Figure 24 is 6.
8. At this moment, a line is fitted to the 6 points (by linear regression).
9. The coefficients of the trend line (slope and y-intercept) will be used in LabView to correct the readings of the Pt100 sensors during the experiments.
10. The process was repeated for each cable length. In this case, there are five calibration curves, one per length. Figure 24 provides the calibration curve for a 3m long cable.

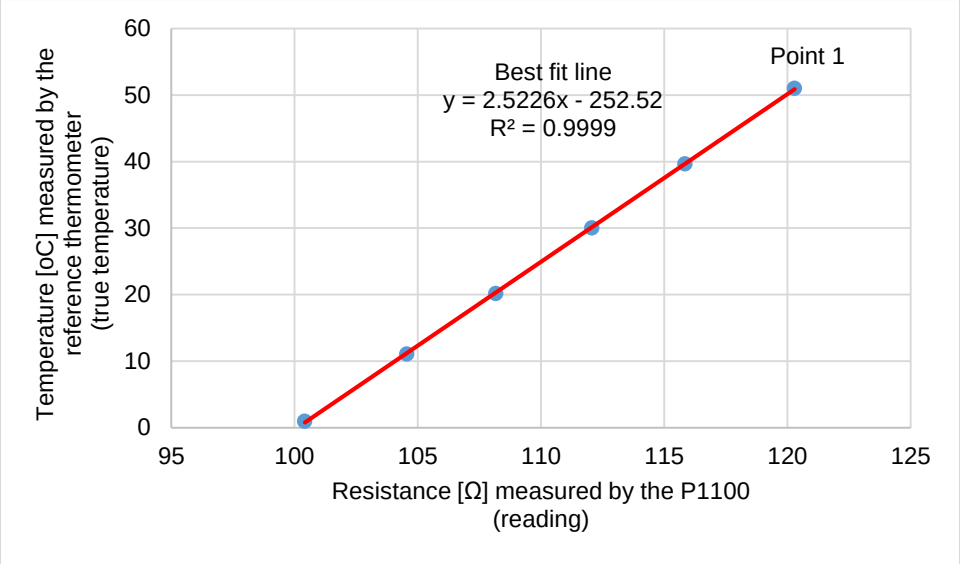


Figure 24: Calibration curve for the 3m length cable. True temperature VS resistance reading.

Finally, an estimation of accuracy was executed. The "typical" uncertainty for a Pt 100 module is ± 0.20°C (National Instruments, 2015b) and, therefore, the uncertainty resulted from the following analysis should be comparable. The accuracy of the temperature measurement is affected by many different factors. The sources of uncertainty are:

- Long term deviation of the reading. No information can be found about it and that, hence, a long term deviation equal to the long term deviation of the ASL F200 precision thermometer with Pt 100 sensor (the reference thermometer) is considered: ± 0.005°C/year.

- Uncertainty from the reference thermometer (A. Hamid, 2004).
  The calibrated Pt 100 precision thermometer has an uncertainty of ± 0.006°C**.**

- Uncertainty of the data acquisition system, NI 9216 module, to account for errors in the resistance readings.
  The module data sheet (National Instruments, 2015b) provides the following: an offset error of ± 0.012 Ω and a gain error of ± 0.007%.
  The change of resistance over 50°C of span is 19.73Ω (119.73Ω at 50°C – 100 Ω at 0°C)(A. J. Wheeler and A. R. Ganji, 2004).
  The conversion from resistance uncertainty to temperature uncertainty is:
  50°C / 19.73Ω = 2.534°C/Ω.
  Thus:
  Offset error: 0.012 · 2.534°C = ± 0.030408°C
  Gain error: 0.007% · 119.73Ω · 2.534°C/Ω = ± 0.02124°C

- Uncertainty of the ambient temperature disturbance (stability) on the data acquisition module.
  A deviation of 10°C in the ambient temperature is assumed (day-night variation during the TRT).
  The module data sheet (National Instruments, 2015b) provides the following: an offset drift of ± 0.0033Ω and a gain drift of ± 0.000007/°C.
  Offset drift: 0.0033 Ω/°C · 10°C · 2.534°C/Ω = ± 0.083622°C
  Gain drift: 0.000007/°C · 119.73 Ω · 2.534°C/Ω = ± 0.0021238°C

- Uncertainty of the isothermal calibrator Isocal Venus 2140 B (Isothermal Technology, 2000).
  According to the manufacturer, the maximum uncertainty on the temperature homogeneity of the isothermal metal block is ± 0.004°C.

- Uncertainty derived from the cable length, i.e., the effect of the cable length in the measured temperature.

An uncertainty in the measurement of the length of the cable of 0.02 m is assumed.
The measurements from the calibration process allow to obtain the relation between the length of the cables and the resistance. An average value between the coefficients (slopes derived from the resistance VS length relation for each temperature step) has been taken : 0.0962Ω/m.
The uncertainty in the temperature reading resulted from the cable length:
0.02m · 0.0962Ω/m · 2.534°C/Ω = ± 0.0049°C

- Uncertainty of the sensor itself. The following information has been taken from Dansk Standard (2008):
  Temperature coefficient resistance α: 0.00385Ω/Ω/°C, which is defined as:

$$\alpha = \frac{R_{100} - R_0}{100 \cdot R_0}$$

  Being R_0 the resistance of the sensor at 0°C and R_{100} the resistance of the sensor at 100°C. This relation can be used to calculate the uncertainty of the resistance temperature detector:

$$\Delta R = R_0 \cdot \alpha \cdot \Delta T$$

  To calculate the uncertainty within a range of 50°C, from 0°C to 50°C:

$$\Delta R_{50} = R_0 \cdot \alpha \cdot \Delta T$$

  The resistance of the sensor at 0°C is given by the standard for different type of sensors and a Class B sensor has been assumed, being: 100.00Ω ± 0.12Ω at 0°C. Therefore, the uncertainty at 0°C is ± 0.12 Ω.
  The uncertainty in the resistance for a detector ranging temperatures from 0°C to 50°C is:
  ΔR = 0.12Ω · 0.00385Ω/Ω/°C · 50°C = ± 0.0231Ω
  Translating it to temperature units, the uncertainty of the Pt100 sensor is:
  0.0231Ω · 2.534°C/Ω = ± 0.0585354°C

Subsequently, the global uncertainty (U) of the calibrated Pt 100, estimated by quadrature addition and under a perfect calibration assumption, would be:

$$U = \sqrt{0.005^2 + 0.006^2 + 0.03041^2 + 0.02124^2 + 0.0836^2 + 0.0021^2 + 0.004^2 + 0.0049^2 + 0.0585^2}$$
$$= \pm 0.107°C$$

This uncertainty is slightly lower than the typical expected error.

D) Thermal response test data

This appendix provides the figures (from Figure 25 to Figure 35) of the data sets collected during the 8 TRTs performed at the Langmarksvej and Rosborg Gymnasium test sites.

i. Undisturbed ground temperature profiles

Prior to the execution of a TRT, the undisturbed temperature of the ground must be measured. Figures 25 and 26 show the undisturbed temperature profiles at Langmarksvej and at Rosborg, respectively.

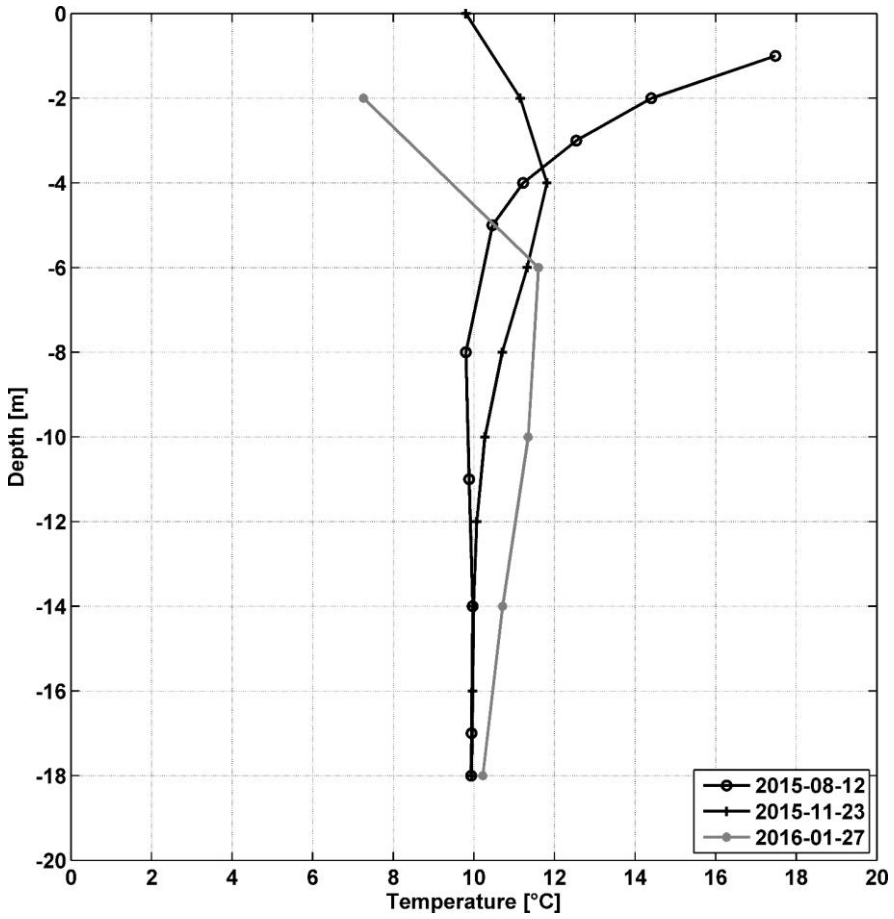


Figure 25: Undisturbed soil temperatures measured during the testing periods at the Langmarskvej test site.

Figure 26 shows the temperature profiles for the thermally active length of the heat exchanger. The average undisturbed soil temperature is 9.8 ^{o}C on the 9th of February 2016. It was not possible to measure a temperature profile prior to the TRT executed in January 2014 and April 2015 at the south extension.

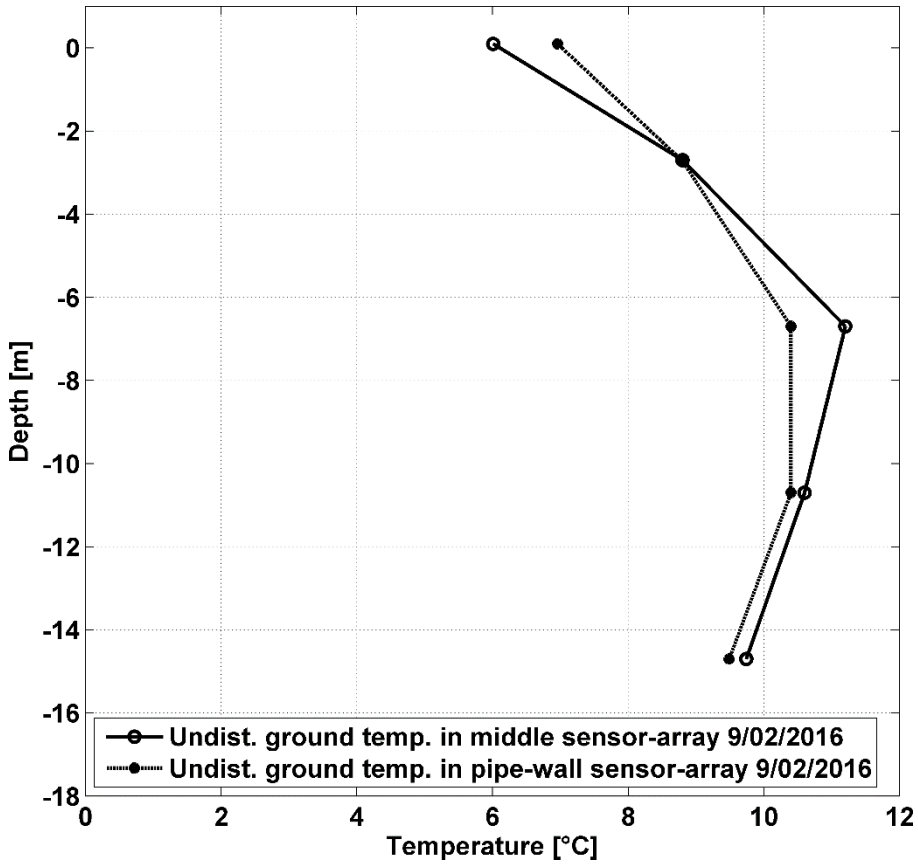


Figure 26: Undisturbed soil temperatures measured prior to the TRT of the energy pile at Rosborg North (EP_RN_1) the 9/02/2016.

ii. Langmarksvej BHE [W + 18 m]

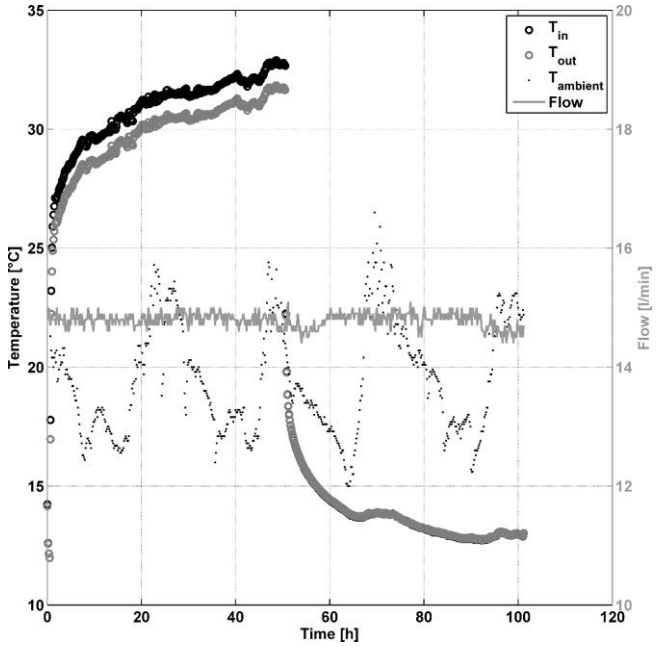


Figure 27: Measured temperature and fluid flow profiles during the TRT of the BHE at Langmarksvej test site. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively. Notice that recovery data (water circulation without heating) was also collected for 50 hours following the test.

iii. Langmarksvej EP8 [1U + 12 m]

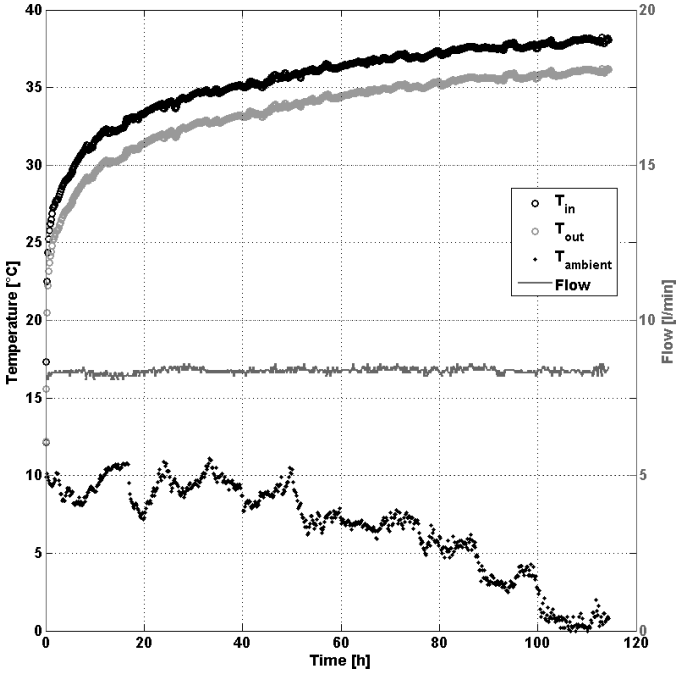


Figure 28: Measured temperature and fluid flow profiles during the TRT of EP8 at the Langmarksvej test site. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively.

iv. Langmarksvej EP7 [1U + 18 m]

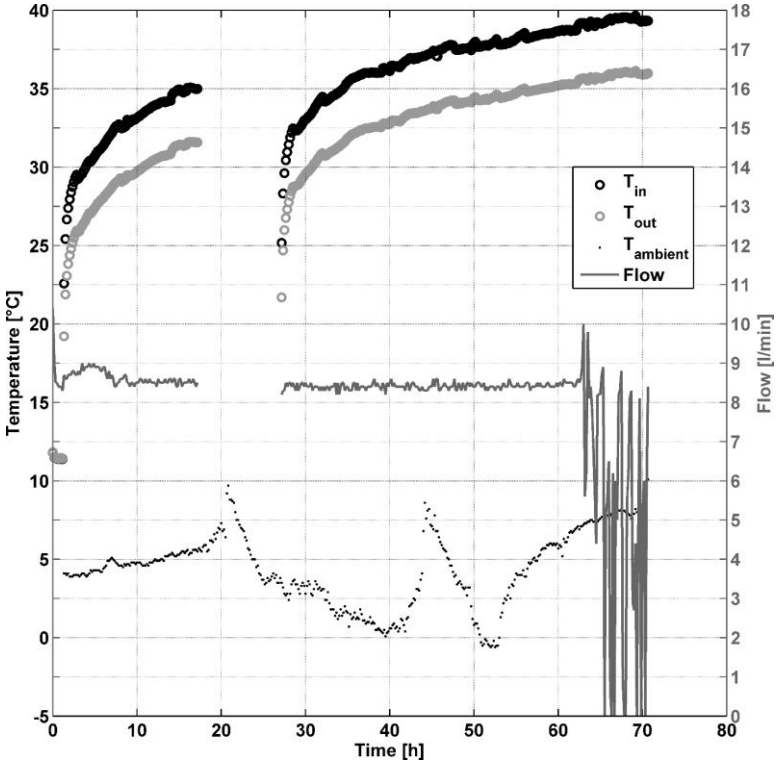


Figure 29: Measured temperature and fluid flow profiles during the TRT of EP7 at the Langmarksvej test site. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively. Notice that the power was interrupted for 10 hours during the test.

v. Langmarksvej EP4 [W + 12 m]

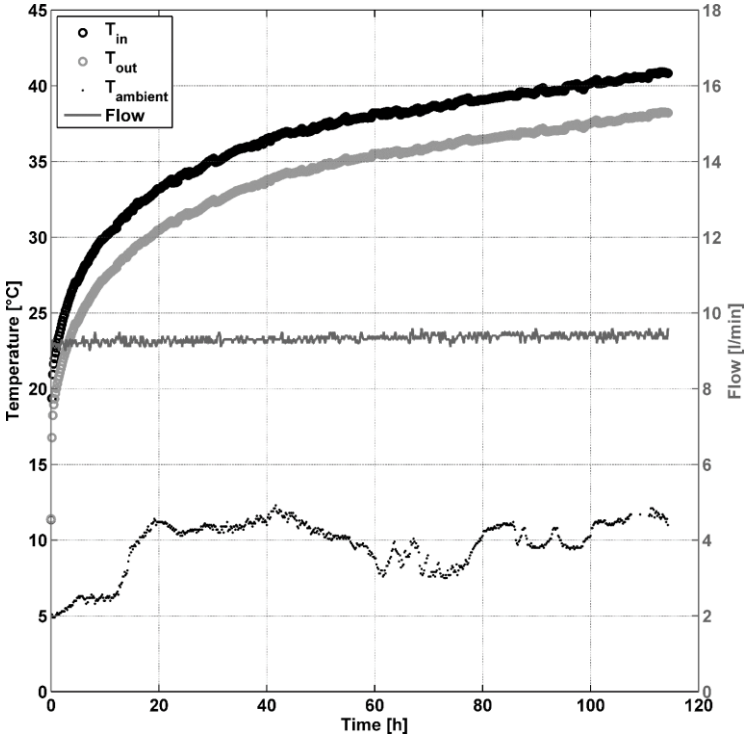


Figure 30: Measured temperature and fluid flow profiles during the TRT of EP4 at the Langmarksvej test site. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively.

vi. Langmarksvej EP3 [W + 18 m]

The soil temperatures shown in Figure 32 imply that heating is observed at a distance of 0.85 m from the energy pile after approximately 25 hours of testing.

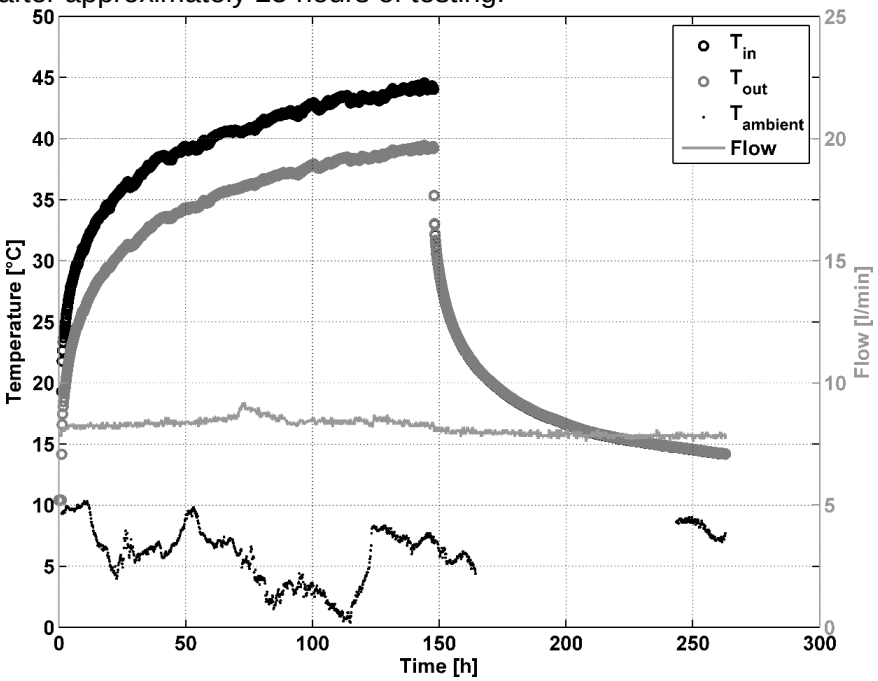


Figure 31: Measured temperature and fluid flow profiles during the TRT of EP3 at the Langmarksvej test site. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively. Notice that recovery data (water circulation without heating) was also collected over 115 hours.

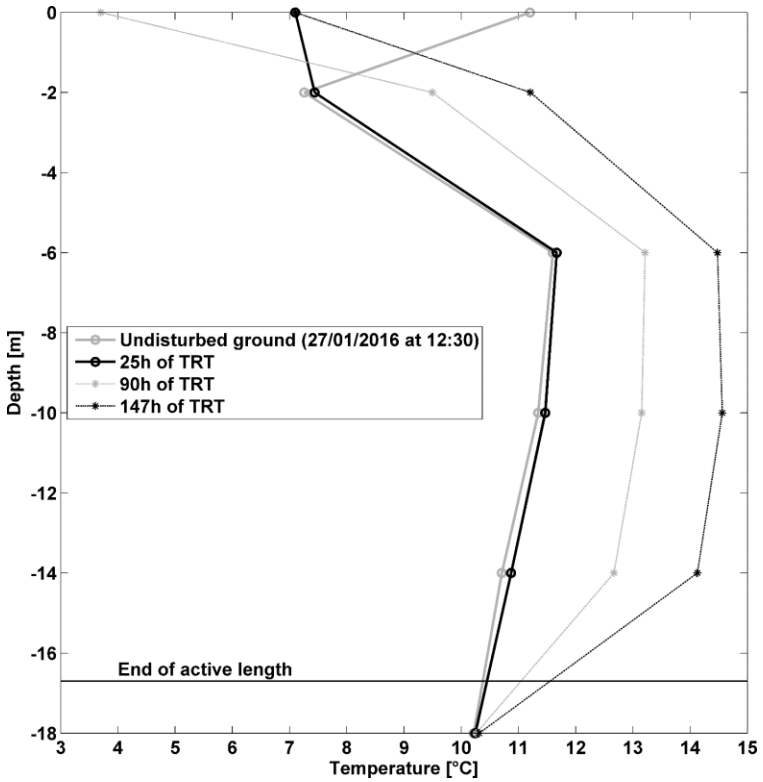


Figure 32: Measured ground temperature profiles from the TSA (0.85 m from EP3, Figure 4) at different levels (0, -2, -6, -10, -14, -18 m below terrain) and at different times (0, 25, 90, 147 hours) during the TRT of EP3 at the Langmarksvej test site.

vii. Rosborg Gymnasium South: EP_RS

This test is analysed in Alberdi-Pagola and Poulsen (2015).

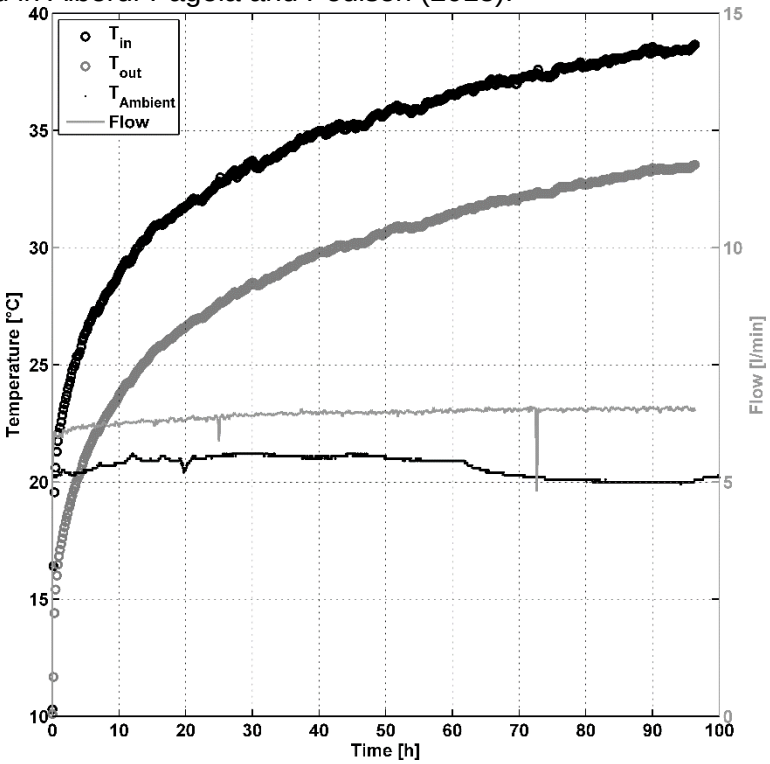


Figure 33: Measured temperature and fluid flow profiles during the TRT of EP_RS at the north extension of Rosborg Gymnasium. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively.

viii. Rosborg Gymnasium North: EP_RN

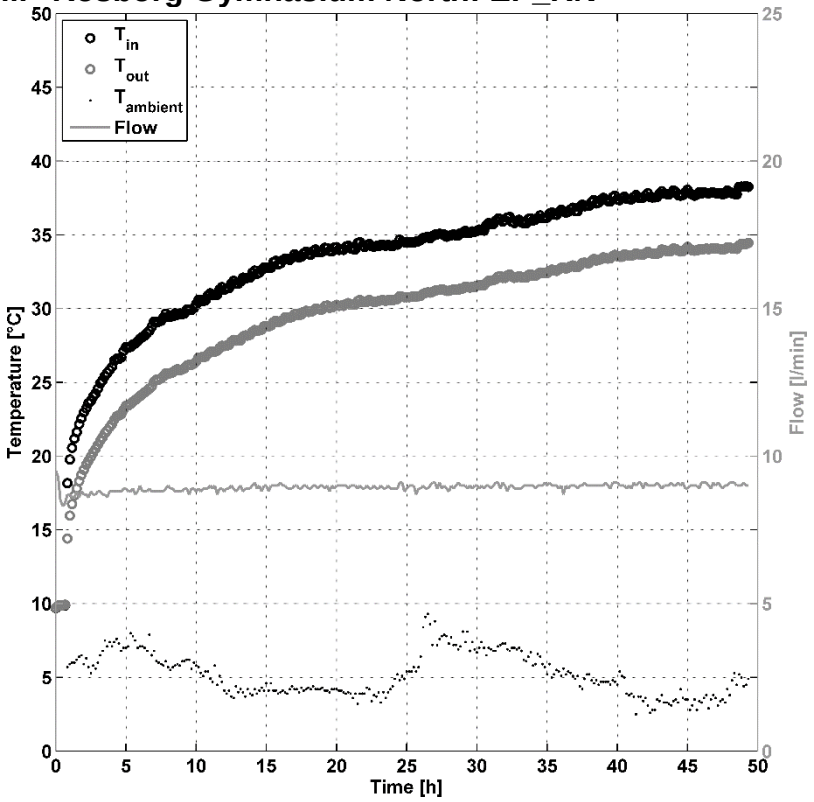


Figure 34: Measured temperature and fluid flow profiles during the TRT of EP_RN at the north extension of Rosborg Gymnasium. T_{in} and T_{out} are the inlet- and outlet fluid temperature, respectively.

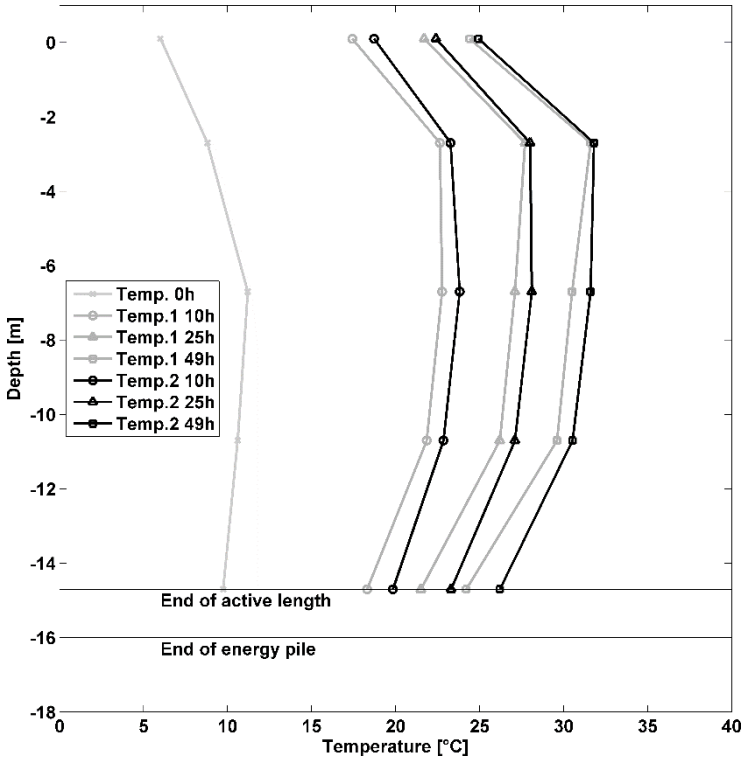


Figure 35: Pile temperatures measured with the Pt100 temperature sensors casted in the concrete at different levels (+0.1, -2.7, -6.7, -10.7, 14.7 m relative to the ground surface) and at different times (0, 10, 25, 49 hours) during the TRT of the energy pile EP_RN [W + 16 m] at the north extension of Rosborg Gymnasium. Temp.1 = middle sensor-string and Temp.2 = pipe-wall sensor-string (Figure 10).

E) TRT equipment data sheet

The TRT equipment is produced by UBeG Umwelt Baugrund Geothermie Geotechnik (2013).

Thermal Response Test Equipment Data

Country: Germany

Contact Person: Marc Sauer

Organisation/Company: UBeG Dr. E. Mands & Dipl.-Geol. M. Sauer GbR

Address:
Reinbergstraße 2
35580 Wetzlar

Phone: +49 (0) 6441-212910

Email: ubeg@ubeg.de

General TRT data

Type: *Heat injection*

No TRTs: *6; 10 exported*

Size, weight: *1100x800x550, ca. 70 kg (only box)*

Aim: *commercial*

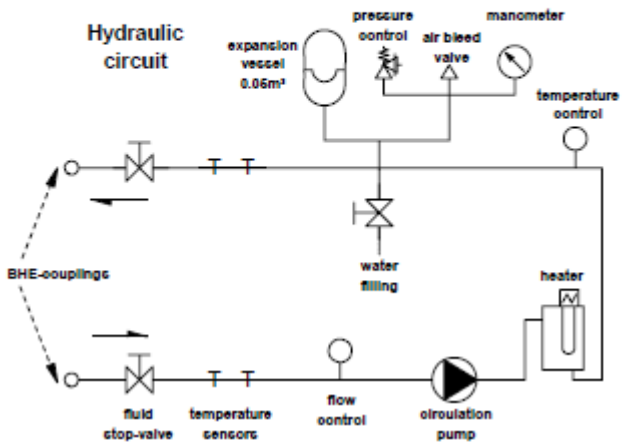
Pump: *~2m³/h*

Powered by: *Electricity*

Heater: *electrical, 9 kW step less*

Built on/in: *Caterpillar*

HP/Cooler: *without*



Temperature measurements:
inside box, at heat exchanger head, double PT 500 & PT 1000, direct installation and immersion sleeves ± 0,05°C

Flow rate measurements:
direct installation as IDM or mechanical

Voltage stabilization: *optional*

Electricity measurement: *Yes, ±0,1 kWh*

GPS: *No*

Remote Control: *optional*

Remote Data Collection: *optional*

Logger: *automatic*

TRT Experience

Years of operation: *10*

Number of performed measurements: *~ 400 commercial*

Typical borehole depths: *tested up to 300m*

Applications: *BHE*

Typical collector type: *2U, sometimes U1 and coaxial pipe, any types of filling*

Typical fluid type: *water*

Typical groundwater temperature: *∅ 12,5°C, min. 8,8 – max. 19,8°C*

Geographical area: *Europe*

Analysis Method: *Numerical / Line source + parameter estimation (own software) / continuous temperature depth profiling (optional)*