STSM Scientific report:

Validation of thermal response testing of energy piles for the estimation of the thermal properties of the ground and the pile thermal resistance

April 2016

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Research Title: Validation of Thermal Response Testing (TRT) of energy piles for the estimation of the thermal properties of the ground and the pile thermal resistance.
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Home Institution: Aalborg University
Host Institution: University of Southampton
Duration: 1 month
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Table of contents

List of figures

List of tables

1. Purpose of the STSM

An industrial PhD project is being carried out by the grant holder, Maria Alberdi-Pagola, at Aalborg University (Denmark) in the field of foundation pile heat exchangers. The project is supported by the Danish company Centrum Pæle A/S, which produces precast energy foundation piles.

The first phase of the PhD focuses on the thermal characterization of the pile heat exchanger. To this end, thermal response testing (TRT) serves as a basis for estimating the pile thermal resistance and the thermal conductivity of the soil, both important parameters for dimensioning energy pile foundations.

Eight TRTs of energy piles and one TRT of a borehole heat exchanger have been executed at two test sites in Denmark: the Langmarskvej test site in Horsens and the Rosborg Gymnasium's building in Vejle. A detailed geological study and laboratory tests supplement the TRTs, providing a complete data set for model validation.

The technical content of the short term scientific mission (STSM) will be focused on the analysis and interpretation of the recorded field data to validate models of quadratic section energy piles. The scientific objective of the STSM is to validate existing and novel, short run-time analytical and numerical models of the thermal behaviour of quadratic heat exchanger pile (2D - 3D implications). The variability of interpretation results from different methods will be quantified as well as the errors due to quadratic cross section.

This work will help to investigate the feasibility of TRT methods for energy pile applications and to make recommendations regarding interpretation methods, testing times and likely uncertainties for quadratic pile TRTs.

2. Description of the work during the STSM

Before the analysis of the data overtaken during the STSM is described, the test sites and the obtained records are shortly exposed.

2.1. Experimental data

The fieldwork consists mainly of several thermal response tests (TRT) of precast pile heat exchangers. The experimental phase has been undertaken at two test sites in Denmark: one in Horsens (Langmarksvej (LM) test site) and one in Vejle (Rosborg (R) Gymnasium's buildings). A more detailed description can be found in Alberdi-Pagola et al. (2016).

Regarding Langmarksvej test site, the compiled experimental data are:

a) Four TRTs of energy piles with different lengths and heat exchanger pipe arrangements.
b) One TRT of a single borehole heat exchanger.
c) Ground temperatures at different depths logged during a single TRT of LM-EP3 in Figure 1.
d) Results from laboratory experiments conducted on soil samples taken from the site and on the pile concrete, including measurements of: water content, density and thermal properties by means of the Transient Plane Source (Hot Disk).

At Rosborg Gymnasium's southern and northern extensions the compiled experimental data are:

a) Three TRTs of energy piles with two different lengths.
b) Pile temperatures logged at certain depths during a single TRT (RN-EP1 in Figure 1).

The diameter considered for the quadratic cross section energy piles is the diameter corresponding to a circle with an area equivalent to the area of the 0.30 m side square, i.e., 0.3385 m. The aspect ratio (AR) is the relation active length to diameter of the ground heat exchanger (GHE). In this study, the GHE lengths vary between 10.8 and 16.8 m. All the ground heat exchangers are described in Alberdi-Pagola et al. (2016).

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

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

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

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 volumetric heat capacity S_{vc}, of the soil and t is the elapsed test time. A λ_s of 2.3 W/m/K and a S_{vc} of 2.6 MJ/m³/K are used to plot the TRTs from Langmarksvej. Those estimates are obtained from laboratory measurements of soil samples collected at different depths at Langmarksvej. A λ_s of 2.40 W/m/K and a S_{vc} of 2.40 MJ/m³/K are chosen to plot the TRT data from Rosborg Gymnasium as are the estimates from Alberdi-Pagola and Poulsen (2015). From Figure 1 a higher GHE thermal resistance is expected for the single U (1U) heat exchangers relative to double U (2U) configurations. Besides, the BHE test yields the highest temperature increments, which implies that the 2U BHE is less efficient transferring heat to the soil relative to the tested energy piles. Notice that LM-EP7 shows an interrupted TRT.

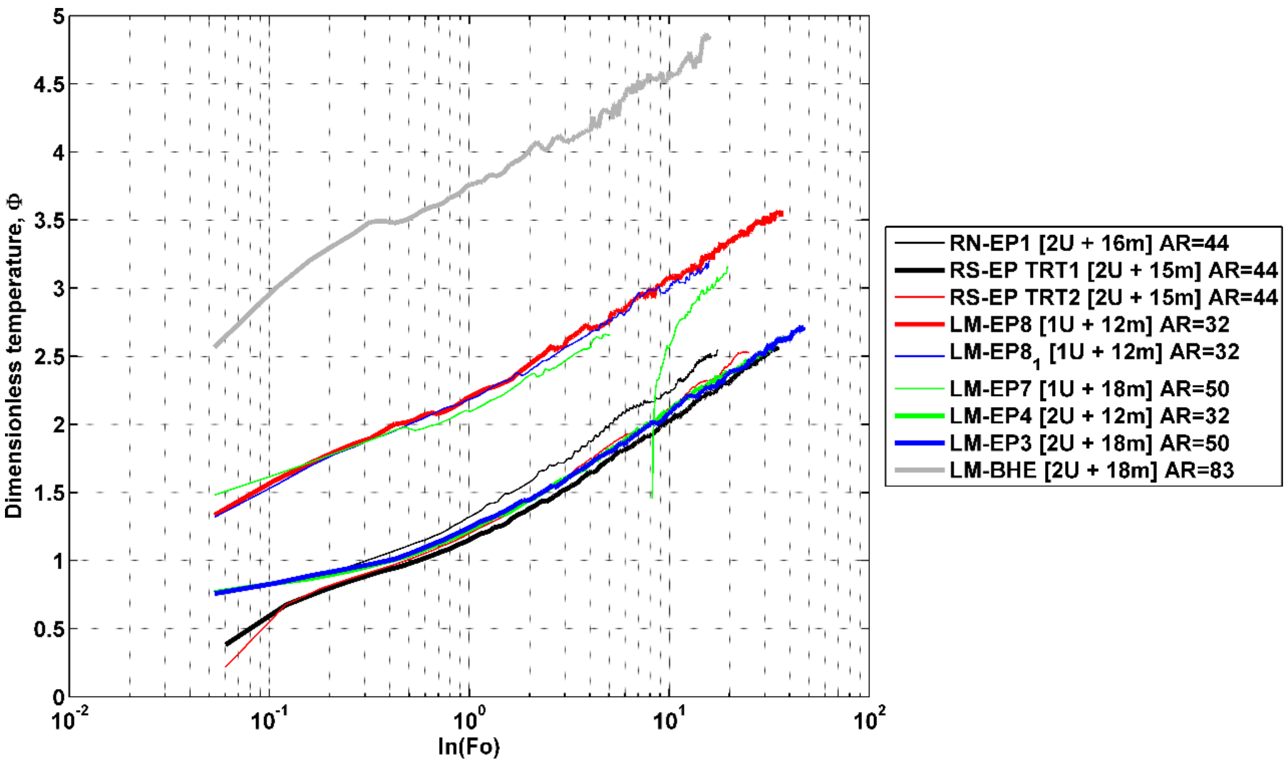

Figure 1: Normalised TRT data showing the short term GHE temperature responses. RS = Rosborg South, RN = Rosborg North, LM = Langmarksvej and AR = aspect ratio (GHE length/GHE diameter), 1U = single U, 2U = double U, BHE = borehole heat exchanger, EP = energy pile.

2.2. Data analysis

The aim of the analysis is to quantify the deviation from the “real” value set in the finite element models (FEM) for the λ_s obtained from the existing analytical and numerical options, considering as the more reliable approach the 3D FEM. To address this issue, the TRT data has been processed by different analytical and numerical methods to estimate the thermal conductivity of the soil λ_s and the GHE thermal resistance R_b. The data sets from 9 thermal response tests conducted at the two different locations have been used for the simulations. The estimates are compared in Table 1 and the studied models include:

a) 1D temperature response models or analytical models: infinite line source ILS (Carslaw and Jaeger, 1986), infinite line source superposition ILSS, infinite cylindrical source ICS or hollow cylinder (Ingersoll, 2008), infinite solid cylindrical source ISC (Man et al., 2010).
b) 2D finite element transient temperature models: they have been set in COMSOL Multiphysics 5.2.
c) 3D finite element transient temperature models: they have been set in COMSOL Multiphysics 5.2.

In the following, the different models are described and the data treatment explained:

2.2.1. Analytical models

The thermal resistances of the GHEs have been added to the analytical models following the process provided in Beier (2008), in much the same way as it is done for the ILS model. The modelled average loop temperature curve is obtained and compared to the observations from the field tests. To interpret the data from the interrupted test, the ILS superposition method has been used as described in Sauer (2013).

It is common to neglect the measured data during certain initial time. This is done to avoid the complexity of the transient heat transfer process in the GHE and to use a period when the ground thermal properties have relatively larger influence on the thermal response. Therefore, the amount of initial data disregarded for each of the analysis has been the corresponding to the same time criterion t_c accepted for the approximation of the exponential integral in the ILS model ($t_c \geq \lambda_s \cdot 5r^2/S_{vcs}$) (Gehlin, 2002).

2.2.2. Parameter estimation

The parameter estimation process has been utilised to estimate the values of two variables: the ground thermal conductivity λ_s and the GHE thermal resistance R_b. By systematically varying these two variables, the minimum difference between the experimental and modelled values is found, which indicates the best estimate of the two variables.

The optimization process is done by PEST (Model-Independent Parameter Estimation) (Doherty, 2010). PEST utilizes the Gauss-Marquardt-Levenberg algorithm for minimizing the discrepancy between computed and observed fluid temperatures in a least-squares sense. PEST calculates confidence intervals for each parameter estimated in the calibration.

2.2.3. 2D finite element models

To investigate the validation of the TRT of energy piles, 2D FEM of the pile heat exchangers have been developed first. The models have been created in COMSOL Multiphysics 5.2 software and comprise a horizontal cross section through a pile. The model includes the precast concrete quadratic cross section pile as Figure 2 depicts (half section for the 1U pipe heat exchangers and a quarter of a section for the 2U, to take advantage of symmetries).

An undisturbed ground temperature equal to the first measured observation (10.2ºC) is assumed constant everywhere in the model domain for each simulated TRT. The model boundary is situated at a radial distance of 5 m at which the boundary does not affect modelled fluid temperatures. The ground is assumed to be thermally homogeneous and isotropic. The possible presence of groundwater flow is ignored in the calculations. Heating is simulated by a time-varying heat source specified for the model elements comprising the fluid pipes.

The model is used to back calculate the thermal conductivity of the ground λ_s and the GHE thermal resistance R_b. In the optimization process, two parameters are allowed to vary: the thermal conductivity of the ground λ_s and the thermal conductivity of the concrete λ_c. The inverse modelling with COMSOL software is overtaken by the Optimization module. The calibration data is the measured heat injection rate q in the pipe and it is equally distributed within the heat exchanger pipes.

Besides, the models are used to compute the temperature at the heat transfer pipes and at the ground concrete interface with time. The temperature at the pipes is taken to be equivalent to the average fluid temperature. The actual thermal resistance of the pile R_b is subsequently computed as:

$$T_f - T_b = q \cdot R_b \tag{3}$$

where T_f [°C] are the observed mean fluid temperatures over the TRT, T_b [°C] are the computed temperatures at the soil-pile interface and q [W/m] is the heat injection rate over the TRT. Equation 3 assumes uniform temperatures at the pile boundaries.

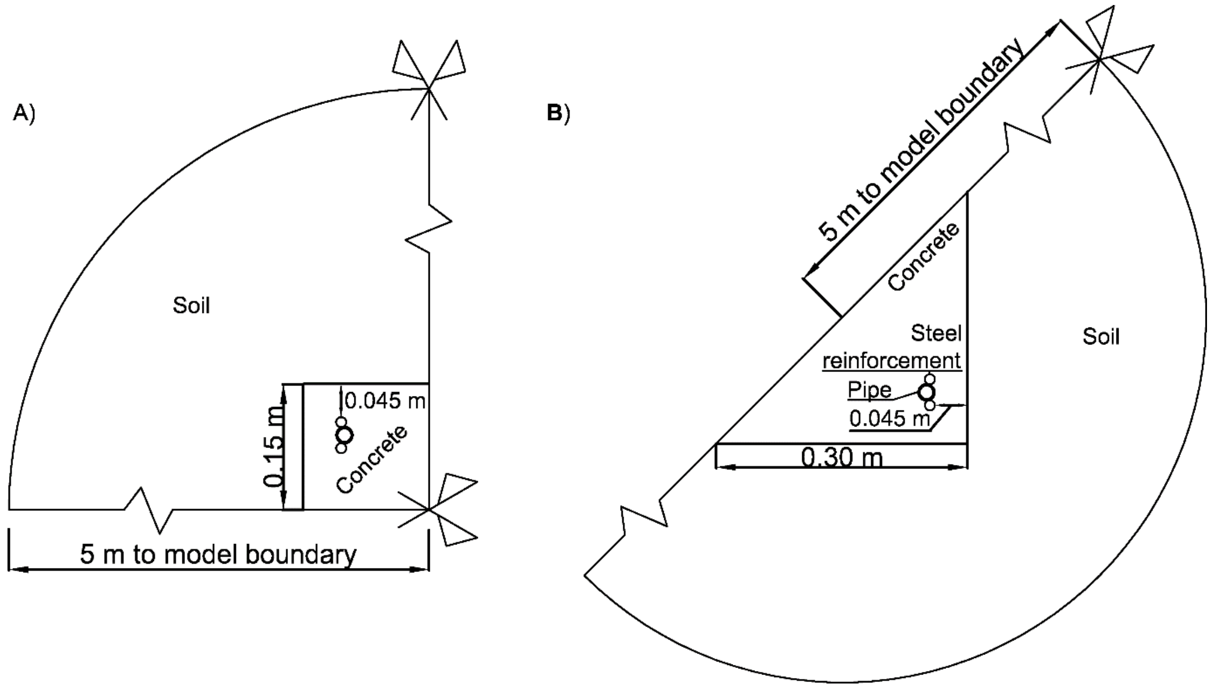

Figure 2: Schematic of the 2D finite element method heat transfer models: a) double U (2U) pipe heat exchanger and b) single U (1U) pipe heat exchanger.

A constant heat injection rate q has been applied to the 2D models to simulate a 200 hour TRT and the computed temperature response (Figure 3) has been used as synthetic data to treat it as a conventional TRT analysis, as developed in Signorelli et al. (2007). This will quantify the error when using 1D analytical expressions to analyse TRT data of quadratic cross section energy piles.

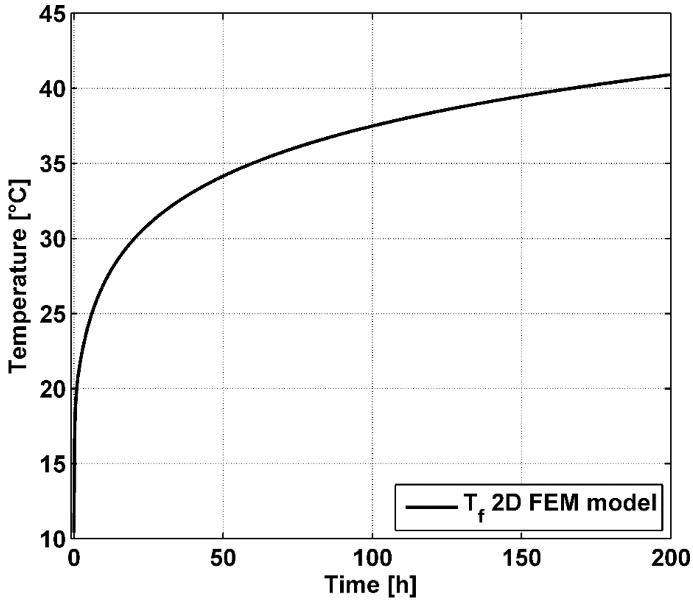

Figure 3: Simulated average fluid temperatures T_f resulted from the application of a constant heat injection rate in the 2D finite element model.

2.2.4. 3D finite element models

To date, transient 3D finite element models have been set up in COMSOL Multiphysics 5.2, which closely fit the measured data. However, the required computation time for these models is too high for routine application and parameter estimation. Consequently, these simulations will serve as a reference for comparison of existing and novel, simpler and faster analytical and numerical models. The idea is to use these 3D models to quantify the errors of the analytical solutions in the estimation of λ_s and R_b by inverse modelling and to determine the sensitivity of the 1D and 2D models to testing times, GHE length and ambient influences.

Two types of 3D models have been set: 1) to apply inverse modelling to obtain the best fit parameters and 2) to reproduce synthetic data and treat the computed temperatures as conventional TRT data. However, due to time limitation, it was not possible to perform the inverse modelling on the 3D FEM, neither to reproduce the synthetic data.

The thermal interaction of the pile heat exchanger with the surrounding soil is modelled by conduction (heat transfer within concrete and soil) and convection (heat transfer due to heated circulating fluid). The 3D model contains three domains (Figure 4): the soil, the concrete pile and the heat exchanger pipe which contains the fluid and is casted within the concrete. Two COMSOL modules are used to reproduce the heat transfer phenomena: the non-isothermal pipe flow module and the heat transfer in solids module in time dependent option.

An undisturbed ground temperature equal to the first measured observation (around 10.4°C) is assumed constant everywhere in the model domain for each simulated TRT. A constant temperature boundary of 10.4°C is applied to the ground level of the soil block. The model boundary is situated at a radial distance of 5 m at which the boundary does not affect modelled fluid temperatures. The ground is assumed to be thermally homogeneous and isotropic. The possible presence of groundwater flow is ignored in the calculations. To reproduce the actual TRT data, the temperature at the inlet to the pipe is imposed to be the same to the observed inlet fluid temperature. The outlet fluid temperature and the soil temperature observations are used as calibration data and, therefore, used to back calculate the thermal conductivity of the ground λ_s and the thermal resistance of the pile R_b.

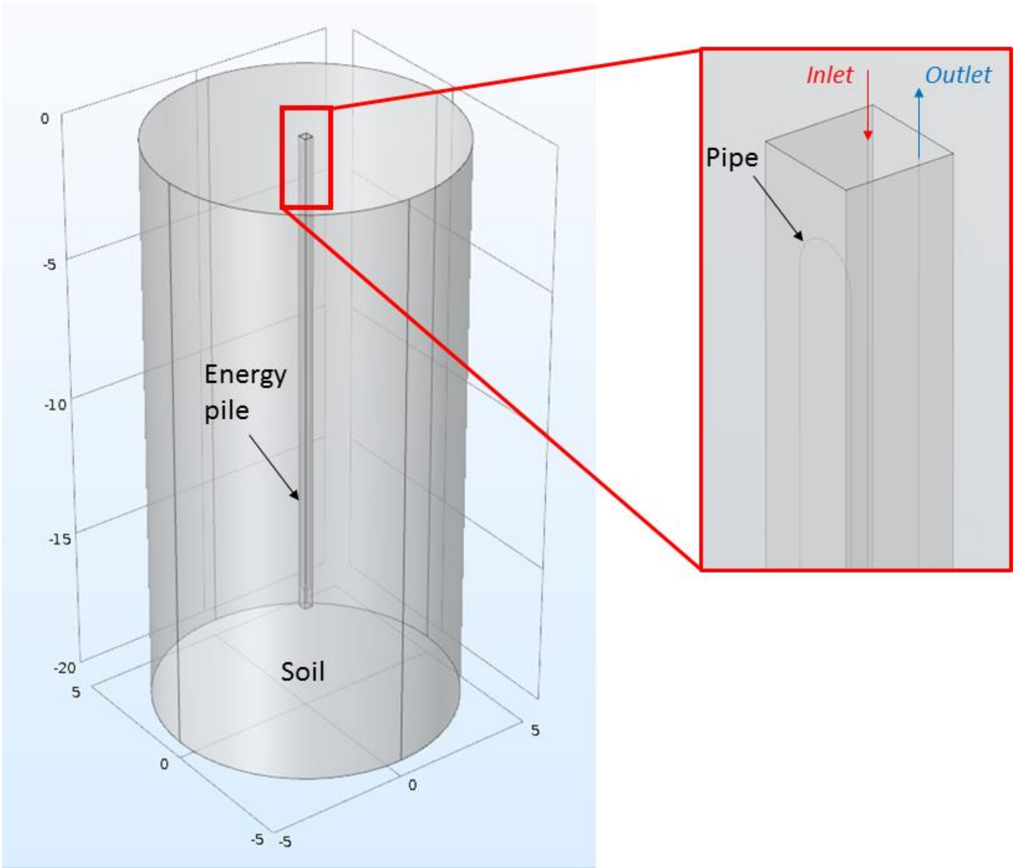

Figure 4: 3D COMSOL model geometry.

3. Description of main results obtained during the STSM

The variability of interpretation results from the different methods are compared in Table 1. In the following a deeper analysis for each model type is provided.

3.1. Analytical models

Hereby, two examples are provided (Figures 5 and 6) where the infinite line source sequential interpretations of the TRTs of the BHE and EP3 at Langmarskvej test site are compared to different estimates. The analytical solutions show a large variability in the estimations in both cases. The independent laboratory measurements indicate a λ_s of 2.30 W/m/K for the soil samples collected at Langmarksvej.

For the 16.5 m long BHE (Figure 5), the variation between the different interpretation methods is 25%, meaning that even for a BHE, the analytical models are not reliable when it comes to short BHEs.

Regarding EP3 (Figure 6), the estimations fall closer, the TRT duration was longer than the TRT of the BHE, and the sequential interpretation reaches a stable value, but the variation between estimates still remains around 20%. Considering the best estimate the one provided by the 2D back analysis, the ILS estimate is 11% higher.

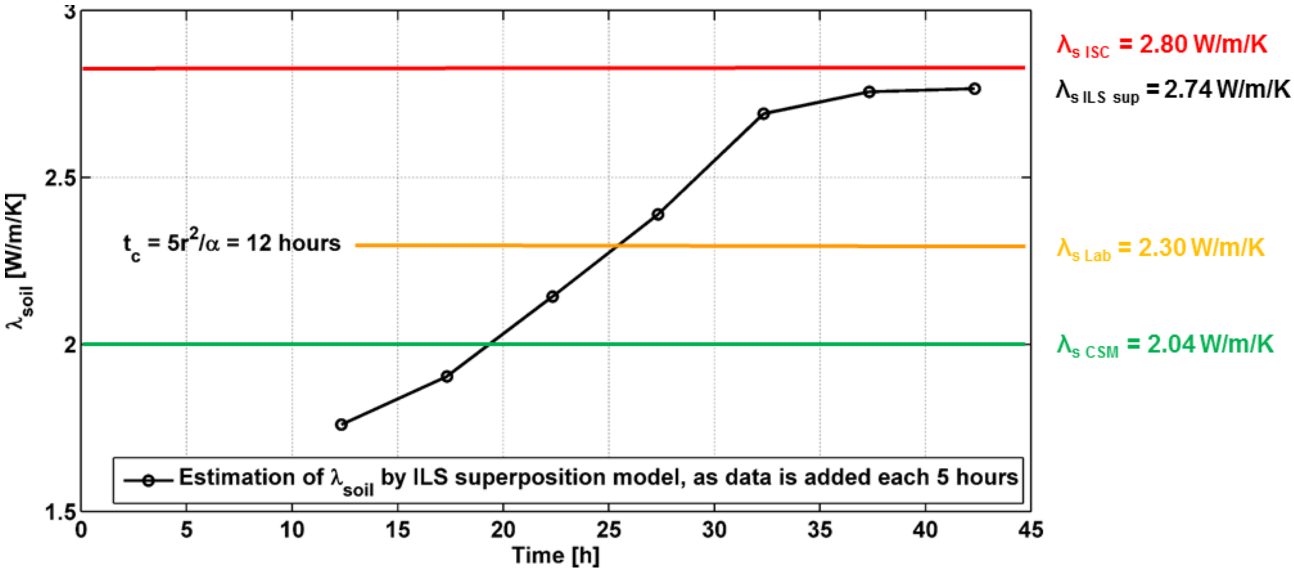

Figure 5: TRT of BHE [2U + 16.5m] at Langmarksvej. ISC = infinite solid cylinder, ILS = infinite line source, CSM = cylinder source model.

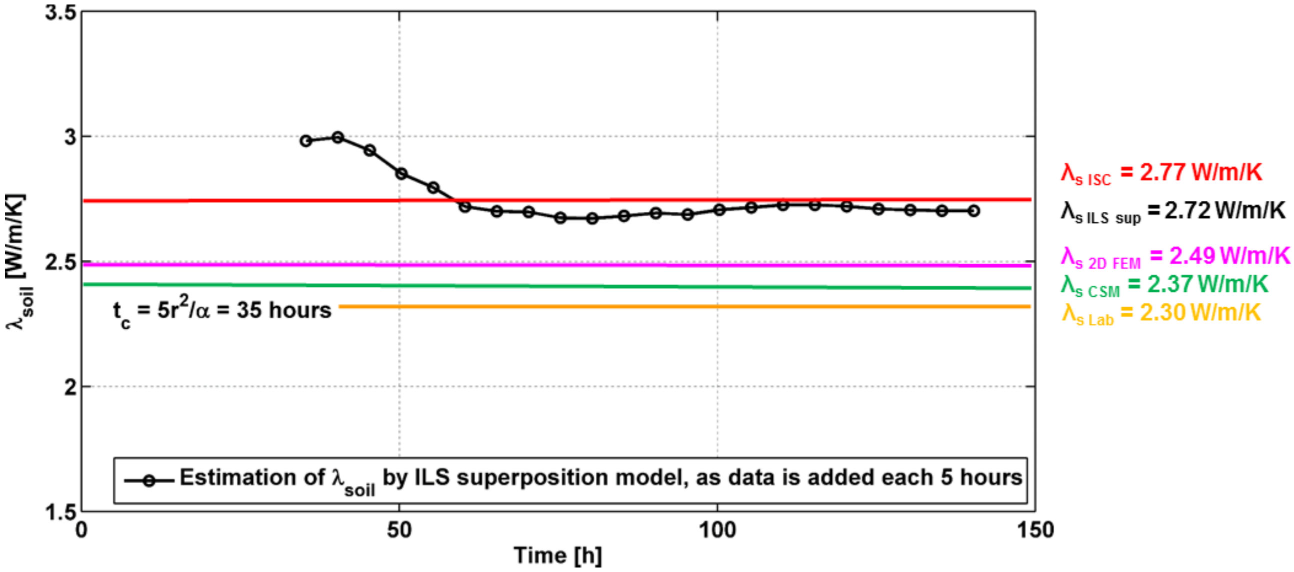

Figure 6: TRT of EP3 [2U + 16.8m] at Langmarksvej. ISC = infinite solid cylinder, ILS = infinite line source, CSM = cylinder source model.

3.2. 2D finite element models

The estimations from the 2D inverse modelling are relatively consistent (Figure 7). The steady state thermal resistance estimations for the 2U heat exchangers provide fall in the range from 0.062 K·m/W to 0.078 K·m/W whereas the 1U heat exchanger estimations fall from 0.128 K·m/W to 0.170 K·m/W. The estimates for the 2U are in close agreement with the values provided in Alberdi-Pagola and Poulsen (2015). The discrepancies between the results in EP8 might be due to the difference in testing time in the two TRTs executed in this pile. The duration might not be enough for the first trial (50 hours). Regarding the estimates for the thermal conductivity of the soil λ_s, they seem more stable, ranging from 2.33 W/m/K to 2.66 W/m/K in close agreement to the independent laboratory measurements. Again, the result for EP8_1 overestimates the λ_s to 3.2 W/m/K.

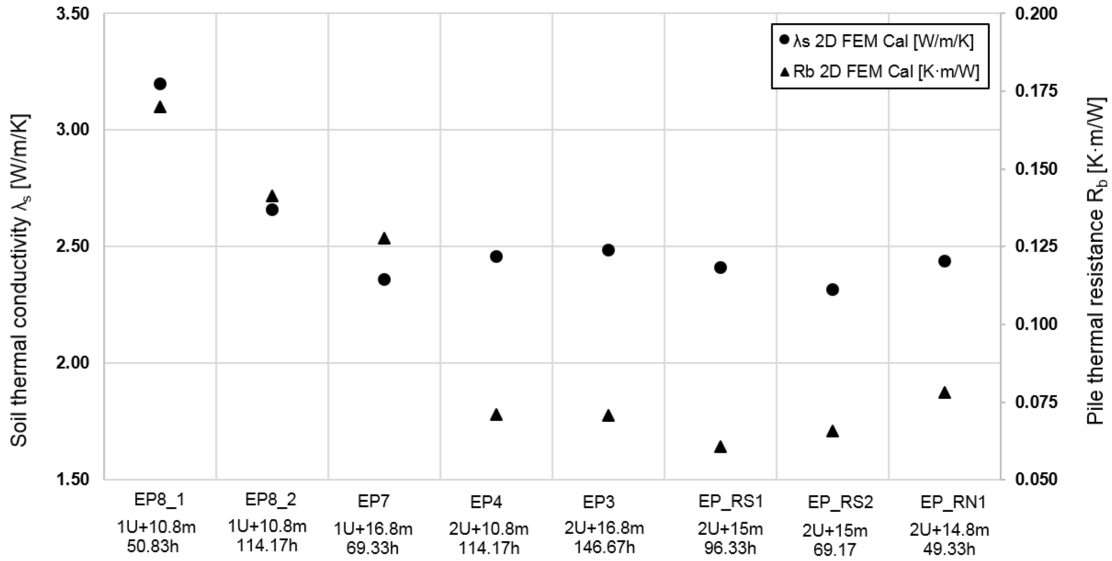

Figure 7: Soil thermal conductivity λ_s and pile thermal resistance R_b estimations from the inverse modelling executed in the 2D COMSOL models.

The inverse modelling indicates a lower thermal conductivity of the concrete λ_c than the expected from laboratory measurements (1.80 W/m/K approx.) for pile heat exchangers EP8_1, EP3, EP4 and EP_RN (see Table 1). It could be due to the fact that different aggregates where used in the concrete mixture. More laboratory measurements are expected.

To quantify the errors derived from using the described 1D analytical equations to interpret TRT data from quadratic cross section energy piles, synthetic data computed from the 2D model has been used. I.e. the analytical solutions have been applied to the synthetic data.

The error derived from using the 1D solutions in synthetic TRT data from quadratic energy piles (without considering the length) goes up to 10% for the infinite hollow cylinder, 5% for the line source solution and 3% for the solid cylinder, as shown in Figure 8.

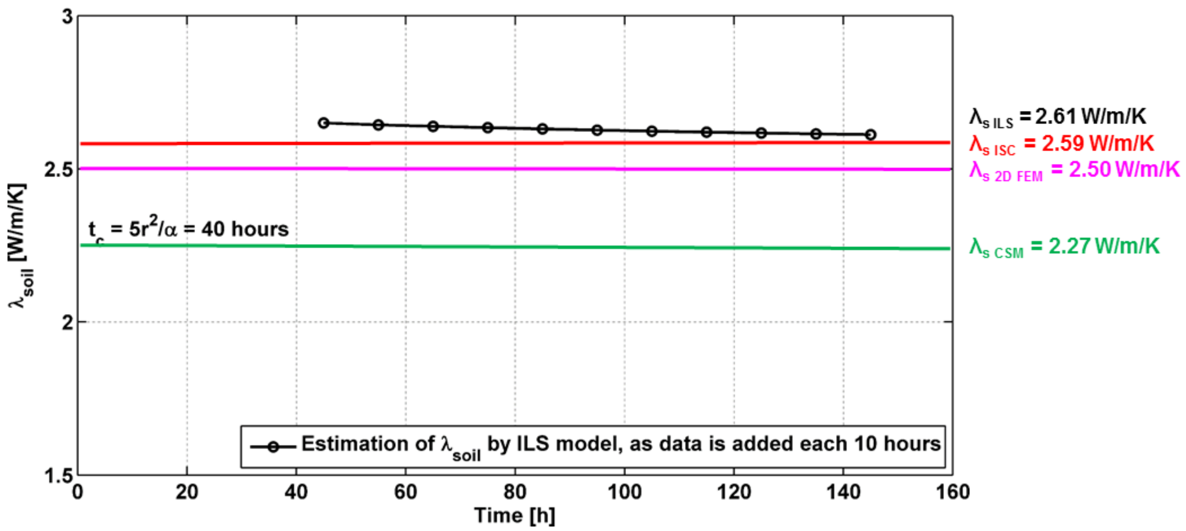

Figure 8: Interpretation of a synthetic 200-hour long TRT data for a 2U energy pile with a 2D FEM.

3.3. 3D finite element models

The 3D model setting has not been finished. The model now is able to closely reproduce the TRT data (Figure 9). However, it is aimed to reproduce synthetic 3D data and this is an on-going task. The inverse modelling process will be coupled to PEST to back calculate the thermal conductivity of the ground λ_s and the thermal resistance R_b.

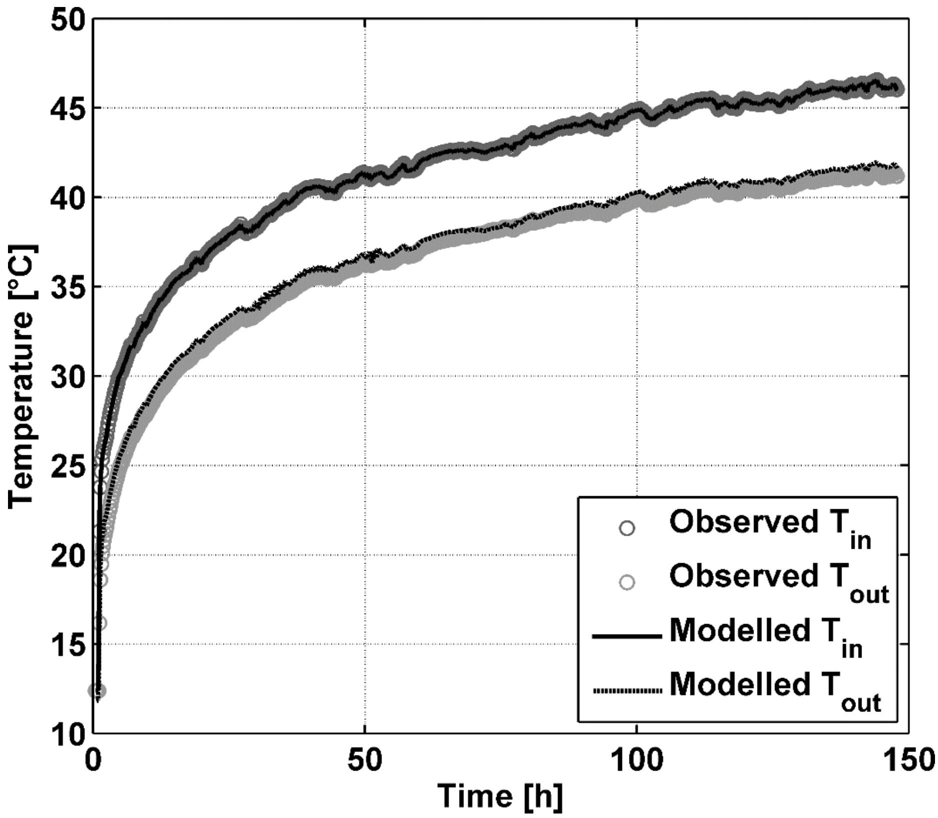

Figure 9: Observed data VS COMSOL simulation results for the TRT of EP3 [2U + 16.8m] at Langmarksvej.

Table 1: Best-fit parameter estimations for the nine TRT data sets and the six analysis models. The main characteristics of the TRTs are also provided and compared to the recommendations given by ASHRAE (2009).

	Langmarksvej						Rosborg Gymnasium			
TRT Date	13-08-2015	03-09-2015	17-11-2015	24-11-2015	01-12-2015	27-01-2016	13-01-2014	20-04-2015	09-02-2016	ASHRAE
GHE name	BHE	EP8_1	EP8_2	EP7	EP4	EP3	EP_RS1	EP_RS2	EP_RN1	-
Equipment used	UBeG	UBeG	UBeG	UBeG	UBeG	UBeG	VIA	UBeG	UBeG	-
Average Undisturbed Soil Temperature [^oC]	11.98	14.40	12.16	11.49	11.39	10.40	10.20	10.12	9.84	-
S_{vc} from Hot Disk measurements [$MJ/m^3/K$]	2.60	2.60	2.60	2.60	2.60	2.60	2.40	2.40	2.40	-
λ_s from Hot Disk measurements [W/m/K]	2.30	2.30	2.30	2.30	2.30	2.30	2.41	2.41	2.41	-
Heat carrier fluid	Water	Water	Water	Water	Water	Water	Water	Water	Water	-
Measurement interval [min]	10	10	10	10	10	10	10	10	10	≤ 10
Volumetric flow rate [m^3/h]	0.890	0.664	0.500	0.480	0.560	0.510	0.385	0.537	0.536	-
Reynolds number	19349	14465	10942	10468	12195	10998	8519	11713	11981	-
Average heat injection rate [W/m]	60.32	74.84	101.36	115.89	159.35	167.61	152.50	183.29	155.18	> 50
TRT duration [h]	49.83	50.83	114.17	69.33	114.17	146.67	96.33	69.17	49.33	> 48
Maximum difference ILS VS observations [^oC]	0.40	0.16	0.29	-	0.30	0.41	0.10	0.41	0.57	< 0.3
Average residual ILS VS observations [^oC]	0.19	0.07	0.13	-	0.12	0.18	0.00	0.21	0.21	-
Average, late time ΔT = Tin - Tout	1.02	1.05	1.95	3.50	2.65	4.89	5.10	4.52	3.78	> 3.0
Recovery test?	Yes	No	No	No	No	Yes	No	No	No	-
Recovery test duration [h]	50.67	-	-	-	-	115	-	-	-	-
λ_s ILS [W/m/K]	**2.81**	**1.86**	**3.06**	**Interrupted**	**2.96**	**2.71**	**2.75**	**2.37**	**4.10**	-
R_b ILS [K·m/W]	**0.225**	**0.130**	**0.143**	**Interrupted**	**0.084**	**0.079**	**0.071**	**0.073**	**0.097**	-
λ_s ILS + PEST [W/m/K] tc = 45h	**2.81**	**2.01**	**3.12**	**-**	**2.93**	**2.77**	**2.73**	**2.37**	**2.59**	-
R_b ILS + PEST [K·m/W]	**0.225**	**0.126**	**0.153**	**-**	**0.084**	**0.079**	**0.072**	**0.072**	**0.088**	-
λ_s ILS sup + PEST [W/m/K]	**2.74**	**2.13**	**3.17**	**2.62**	**2.90**	**2.72**	**2.62**	**2.76**	**2.61**	-
R_b ILS sup + PEST [K·m/W]	**0.222**	**0.132**	**0.153**	**0.139**	**0.083**	**0.079**	**0.070**	**0.080**	**0.087**	-
λ_s ISC + PEST [W/m/K]	**2.80**	**1.51**	**2.98**	**-**	**3.00**	**2.77**	**2.72**	**2.30**	**2.71**	-
R_b ISC + PEST [K·m/W]	**0.221**	**0.102**	**0.147**	**-**	**0.082**	**0.076**	**0.068**	**0.066**	**0.086**	-
λ_s CSM_IHC + PEST [W/m/K]	**2.04**	**1.43**	**2.69**	**-**	**2.51**	**2.37**	**2.25**	**1.84**	**2.92**	-
R_b CSM_IHC + PEST [K·m/W]	**0.194**	**0.085**	**0.139**	**-**	**0.068**	**0.063**	**0.052**	**0.044**	**0.086**	-
λ_s 2D FEM Cal [W/m/K]	**-**	**3.20**	**2.66**	**2.36**	**2.46**	**2.49**	**2.41***	**2.32**	**2.44**	**-**
R_b 2D FEM Cal [K·m/W]	**-**	**0.170**	**0.142**	**0.128**	**0.071**	**0.071**	**0.062***	**0.066**	**0.078**	**-**
λ_c 2D FEM Cal [W/m/K]	**-**	**1.00**	**1.61**	**1.87**	**1.50**	**1.51**	**1.89**	**1.65**	**1.27**	**-**
*From Alberdi-Pagola and Poulsen (2015)										

3.4. Concluding remarks

The existing 1D analytical equations do not reproduce properly the thermal performance of the quadratic cross section energy piles since they provide unreliable and varied estimations for the thermal conductivity of the soil λ_s and the pile thermal resistance R_b (difference of 20 % between diverse approaches).

Analyses done with 2D finite element models quantify the error derived from using the 1D solutions in TRT data from quadratic energy piles (without considering the length) up to 10% for the infinite hollow cylinder, 5% for the line source solution and 3% for the solid cylinder. To date, the 3D finite element models represent the best approach for accurate simulations.

After this STSM many issues remain open. These are some of the aspects that are expected to be developed in the following months:

Regarding the 3D numerical models, synthetic TRT data needs to be reproduced and the inverse modelling executed. The validated 3D models that provide the best fit to experimental data will be utilized for investigating the accuracy of pile thermal resistance and soil thermal conductivity estimates from actual TRT data. The synthetic data produced by the 3D models will be used to quantify the errors derived from the quadratic cross section and pile heat exchanger length.

Depending on the results from the 3D analysis, it might be interesting to try other analytical methods such as: the finite line source (Eskilson, 1987), the finite solid cylindrical source (Man et al., 2010), commercial tools such as GPM (Shonder and Beck, 2000) and the G-functions for single pile heat exchangers by Loveridge and Powrie (2013). 2D thermal resistance models can also be studied: Loveridge and Powrie (2014), Shonder and Beck (2000), Remund (1999), Sharqawy et al. (2009), Hellström (1991).

After these analyses, recommendations regarding interpretation methods, testing times and likely uncertainties for quadratic pile TRTs will be shown. The results will be published as part of a journal paper.

4. Future collaboration and foreseen publications resulting from the STSM

A joint publication on the work is expected. The abstract for the journal paper has already been submitted and the deadline for the finished article is June 2016:

"Validation of thermal response testing (TRT) for precast quadratic cross section energy piles". Proceedings of the Institution of Civil Engineers ICE. Geotechnical Engineering themed issue on geotechnics in energy provision. Authors: Maria Alberdi-Pagola, Department of Civil Engineering, Aalborg University; Fleur Loveridge, Faculty of Engineering and the Environment, University of Southampton; Søren Erbs Poulsen, VIA Building, Energy & Environment, VIA University College; Rasmus Lund Jensen, Department of Civil Engineering, Aalborg University; Søren Madsen, Department of Civil Engineering, Aalborg University.

The collaboration might continue beyond this STSM.

5. Confirmation by the host institution of the successful execution of the STSM

A letter of STSM confirmation and its approval is attached to this document and signed by Dr. Fleur Loveridge on behalf of the University of Southampton.

Grant holder signature:	Date:
Maria Alberdi-Pagola	2016/03/30

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