STSM – Short Term Scientific Missions within the Action TU1405 – "European Network for Shallow Geothermal Energy Applications in buildings and infrastructures "(GABI)

STSM report

Topic (correlation with the existing working groups within the Action): WG2: energy performance assessment

Research Title: Experimental validation of a thermal model of pile heat exchanger

Name of the Applicant: Charles MARAGNA

Home Institution: BRGM (French Geological Survey)
Host Institution: University of Southampton

Duration: 3 weeks
Schedule: 29th of February 2016 08:30:00 to 18th of March 2016 17:00:00

Table of Contents

COST Association
Avenue Louise 149 I 1050 Brussels, Belgium
t: +32 (0)2 533 3800 I f: +32 (0)2 533 3890
office@cost.eu I www.cost.eu

1. Purpose of the STSM

Within the ANR-GECKO project C. Maragna developed a thermal model of Pile Heat Exchangers (Maragna and Rachez, 2015) (PHE). The model is based on semi-analytical methods. It is designed to deal with inner thermal inertia and equipment of PHE with large sections (typical diameters up to 1-2 m and up to 8 pipes) and heat transport (advection) through underground water flow. The model is based on two technical innovations. First, specific step-responses have been developed to better describe the large diameter and short length of PHEs and take into account underground water flow. Second, an innovative resistive-capacitive (RC) circuit is developed to account for the thermal inertia of the concrete in a large pile equipped with multiple U pipes. The RC circuit is then combined with a heat balance over the heat carrier fluid and with the developed step responses to obtain the semi-analytical PHE model. The model has been verified against a finite element code and was presented at the World Geothermal Congress 2015 in Melbourne, Australia. However, it was not yet validated against experimental data. The University of Southampton has access to Thermal Responses Tests carried out on several PHE with various geometries and equipment. The STSM is included in WP 2 "Energy Performance assessment" of the COST-GABI Action.

2. Summary of the work carried out during the STSM

The aim of the Mission was to validate the semi-analytical model of pile heat exchangers developed by BRGM in ANR-GECKO project against the Thermal Response Test (TRT) data sets available at the University of Southampton.

Some further work was carried out to develop a "black box" model where the heat transfer in the PHE is described by a simple RC model, which requires only 3 parameters, namely 2 resistances describing the pile internal heat transfer and one ground thermal conductivity. The internal resistances are not computed based on geometrical considerations but can be determined by curve-fitting on thermal response tests data (TRT). The influence of the TRT duration on the reliability of the estimated parameters and the long-term evolution of the fluid temperature was investigated.

The "black-box" model is indeed complementary to the GECKO model: The GECKO model can be used to compute the evolution of PHE fluid temperature while designing an energetic system, when no TRT has been performed but when the pile equipment (number and position of pipes, etc.) is known. The "black-box" model may have potential applications to TRT interpretation; furthermore it may provide a consistent framework for both the TRT interpretation and the computation of the long-term evolution of the fluid temperature. Application of this model for TRT interpretation suggests that for PHE with a diameter of 60 cm the TRT duration should not be below 200 to 250 h, and that for PHE with a diameter of 45 cm TRT duration of 100 h allows an adequate determination of the PHE and ground parameters.

3. Description of the main results obtained

1. <u>Selection of data sets to be used for the validation</u>

BRGM model was designed to handle PHE with 4 to 8 pipes. It was compared to a Finite Element model for PHE with a diameter from 0.30 m up to 1.00 m with up to 8 pipes and performed well.

The table below indicates the characteristics of 3 TRT data sets available at the University of Southampton. The data sets cover the range of diameters from 0.30 to 0.60 m and pipe equipment from 2 to 4 pipes (cf. Table 1).

Data Set	Depth	Geology	Diameter (m)	Number of Pipes	Test Length	Heating Type	Complementary Data
A	26m	London Clay	0.30	2	6 days	Multi-stage	Pile and external pipe temperatures
B	18.3m	Sands, silts and clays	0.45	2 or 4	4 days	Injection	Pile and adjacent borehole temperature
C	31m	London Clay	0.60	4	15 days	Injection	

Table 1: Characteristics of the 3 datasets

Note that the GECKO model was developed for configurations with 4, 6 or 8 pipes since the configuration with 2 pipes seemed to be unusual in France. Furthermore in the GECKO model the pipes are assumed to be equally spaced (i.e. at the edges of a regular polygon). Both conditions were only met for set C (cf. Figure 1).

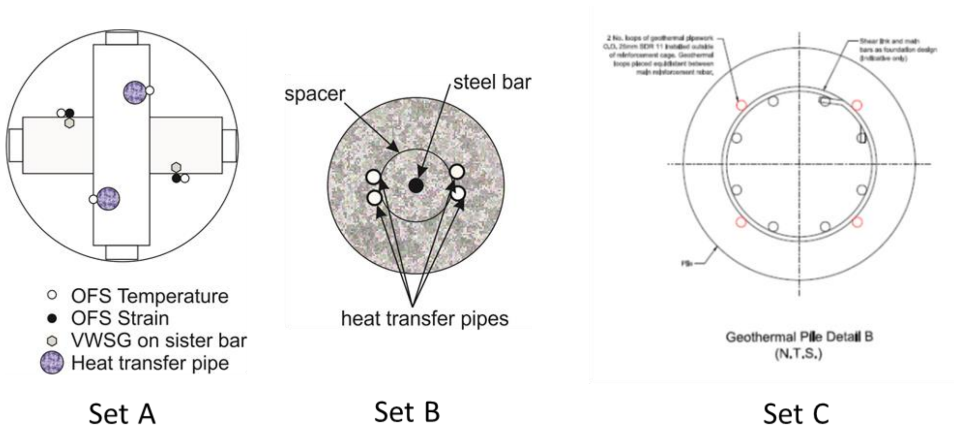

Figure 1: Pipe disposal within the concrete for set A, B and C.

For the validation the temperatures measured were averaged by periods of 15 min, so that to keep the computation time of both GECKO and "black-box" models low (in the ra).

Set A exhibited some discrepancies between the temperatures measured and the temperature computed once the parameters of the GECKO or "black-box" model have been fitted. Loveridge et al. observed similar effects (Loveridge et al., 2014). The reasons for it these discrepancies are unclear, but may be linked to some thermo-mechanical couplings leading to an increased contact resistance at the pile-soil boundary when the pile is cooled. Investigating these couplings is far out of the scope of this STSM; and set B will not be mentioned in what follows.

2. Experimental verification of the GECKO model

For set C the conductivities of the grouting material and ground had not been measured in laboratories, which made the validation of the GECKO model uneasy.

We adopted another approach: the GECKO model was used to determine the ground and concrete (grouting) thermal conductivities, respectively denoted λ_m and λ_g (cf. Figure 2). It was done by minimizing a "root mean square error" (RMSE or misfit) between the experimental and modelled curves by fitting λ_m and λ_g. The modelled gets fitted for a time interval ranging from a minimum duration t_{min} (1 h to 40 h) and a maximum duration t_{max} (100 to 250 h). The estimated value of λ_m decrease when t_{max} increases. For t_{max} = 250 h, λ_m converges to values between 1.45 and 1.55 $W.K^{-1}.m^{-1}$.

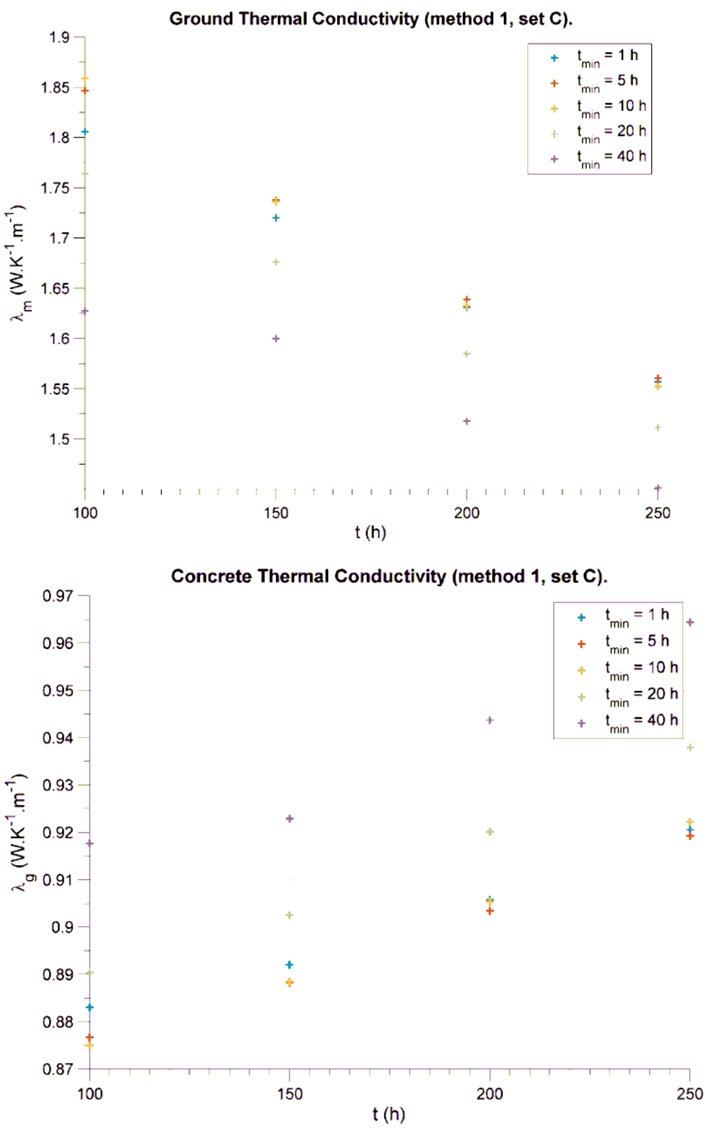

Figure 2: Set C. Thermal conductivities of ground λ_m and concrete (grout) λ_g as a function of t_{max} for several values of t_{min} (GECKO model)

From a practical point of view, the operator of a PHE is interested in the evolution of the fluid temperature to the extent that this temperature will determine the efficiency of the heat pump. The ability of the GECKO model to correctly describe the evolution of the fluid temperature after the TRT shutdown was investigated for several values of t_{max} ranging from 100 h to 250 h (cf. Figure 3). The temperature discrepancy (i.e. the difference between the measured and interpolated temperatures) is in the range 0.4 to 0.8 °C for a TRT duration t_{max} = 100 h. Such TRT duration seems to be too low to correctly describe the evolution of the fluid temperature after the TRT shutdown. As t_{max} increases, the discrepancy reduces: longer TRT duration allows a better prediction of the fluid temperature evolution.

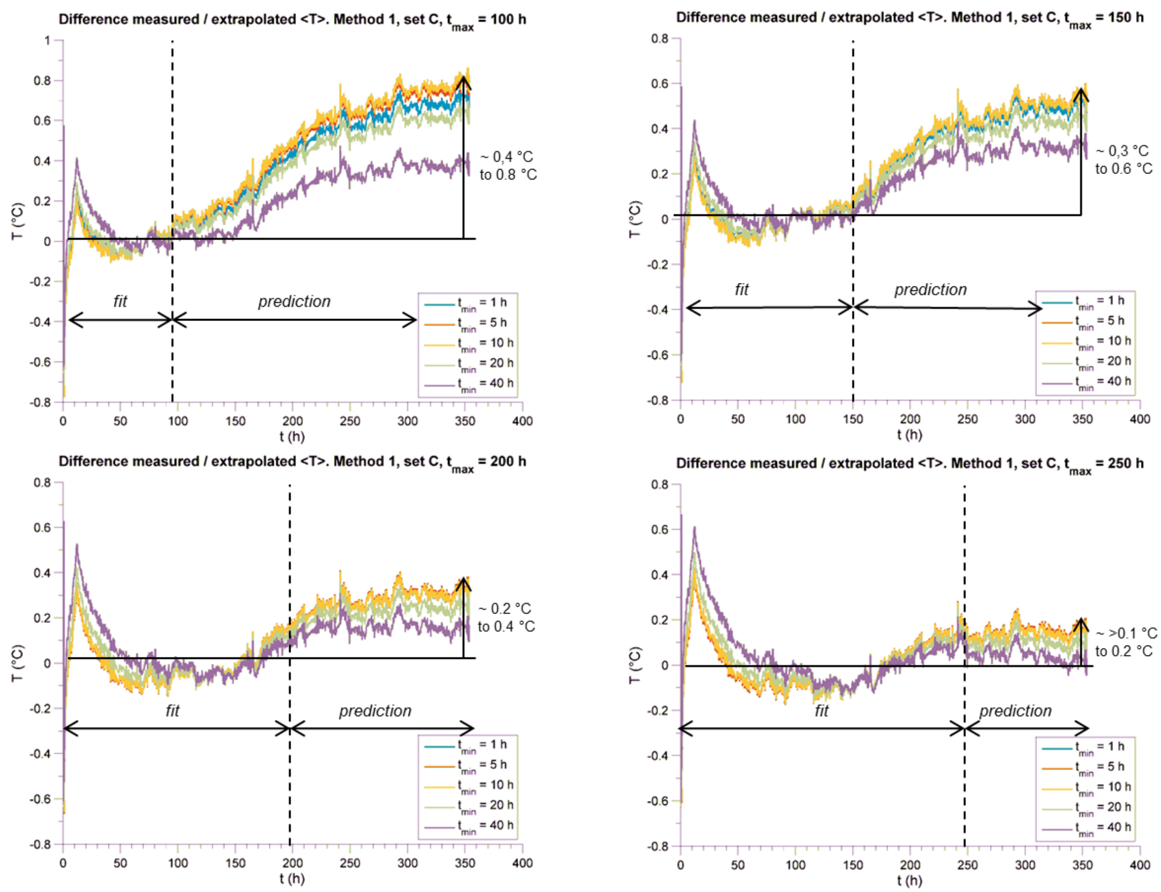

Figure 3: Set C. Discrepancy between computed values of temperatures with fitted parameters and measured temperatures for t_{max} = 100 h (upper left) to 250 h (lower right) and different values of t_{min}.

3. Development of a model for TRT interpretation

a. *Methodology*

Some further work was carried out to develop a "black box" model where the heat transfer in the PHE is described by a simple RC model with a goal to use it for the interpretation of thermal responses tests.

The "State-of-the-art" model for TRT analysis on borehole heat exchangers simplifies the borehole geometry to a line emitting thermal power at a constant rate *p* in the surrounding media characterized by a conductivity λ_m immediately delivered to the ground through a resistance R, neglecting the thermal inertia of the grouting material (cf. Figure 4) (Gehlin, 2002). During a

TRT the fluid circulates with constant power and flow rate; the interpretation consists in fitting two parameters λ_m and R on the measured evolution of the fluid temperature. However some recent works raise the question of the reliability of this model for the interpretation on PHE, especially due to the large section of the pile (Loveridge et al., 2014).

The "black-box" model is designed to tackle the limitation of the "state-of-the-art" model by taking into account the cylindrical shape of the borehole and the thermal inertia of the concrete. The power delivered by the fluid p_{fl} is stored in a capacity affected to a central node C_2, and a part of the thermal power p_b is delivered to the borehole wall. Two resistances R_2 and R_3 ($W.K^{-1}.m^{-1}$) connected to a capacity C_2 ($J.K.m^{-1}$) accounts for the pile internal heat transfer. C_2 is determined by multiplying on the section of concrete in the borehole with the specific heat capacity of the borehole $(\rho C)_g$. In the whole work a value of $(\rho C)_g$ = 2.32 $MJ.K.m^{-3}$ was assumed. The heat transfer in the ground is accounted for by an infinite cylindrical heat source. The underlying equation lies upon two parameters: the ground thermal conductivity λ_m ($W.K^{-1}.m^{-1}$) and the heat capacity of the ground $(\rho C)_m$ ($J.K.m^{-3}$). In the whole work a value for the heat capacity of the ground $(\rho C)_m$ = 3.45 $MJ.K.m^{-3}$ was assumed.

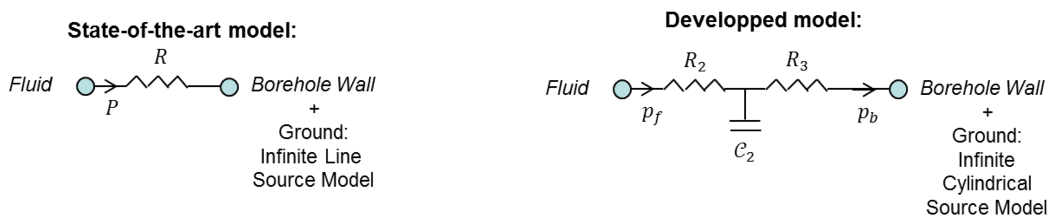

Figure 4: Left: State-of-the-art model for the interpretation of TRT, based on the assumption of steady-state heat transfer in the ground heat exchanger and the infinite line source model. Right: Developed "black-box" model for the interpretation of TRT.

The black-box model has 5 temperatures:

- T_f : mean temperature of the heat-carrier fluid
- T_c : temperature at the capacity node
- T_p : temperature at the borehole wall (interface between the concrete and the ground)
- T_{in} : PHE inlet fluid temperature
- T_{out} : PHE outlet fluid temperature

A heat balance describes the evolution of the 5 temperatures:

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \frac{d}{dt} \begin{Bmatrix} T_f \\ T_c \\ T_p \\ T_{in} \\ T_{out} \end{Bmatrix} + \begin{bmatrix} \frac{1}{R_2} & -\frac{1}{R_2} & 0 & 0 & 0 \\ -\frac{1}{R_2} & \frac{1}{R_2} + \frac{1}{R_3} & -\frac{1}{R_3} & 0 & 0 \\ 0 & 0 & -\frac{G^1}{R_3} & -\frac{G^1}{R_3} + \lambda_m & 0 \\ 2\lambda_m & 0 & 0 & -\lambda_m & -\lambda_m \\ 0 & 0 & 0 & \frac{\dot{m}(t) C_{p,f}}{H} & \frac{\dot{m}(t) C_{p,f}}{H} \end{bmatrix} \begin{Bmatrix} T_f \\ T_c \\ T_p \\ T_{in} \\ T_{out} \end{Bmatrix} = \begin{Bmatrix} p_f(t) \\ 0 \\ \lambda_m T_0 + p_b^*(t) \\ 0 \\ p_f(t) \end{Bmatrix} \quad (1)$$

p_b* accounts for the power transferred to the borehole wall convoluted with G, the step response of the cylindrical heat source model. At every time step t_n (i.e here every 15 minutes) the system is solved by an Euler implicit scheme.

When applied to the interpretation of TRT, three parameters are estimated from the "black-box model":

- The resistance R_2
- The resistance R_3
- The ground thermal conductivity λ_m

For sets B and C we investigated the influence of the TRT duration on:

- The determined values for R_2, R_3 and λ_m
- The long-term evolution of the fluid temperature.

For set C we draw some "iso-misfit" curves, one per couple of model parameters: {R_2, λ_m}, {R_3, λ_m}, {R_3, R_2}. These curves allow estimating the uncertainty on one determined parameter (Wagner et al., 2013).

b. *Application to Set C*

At small TRT duration t_{max} (i.e. 100 h) the determined ground thermal conductivity exhibits large discrepancies depending upon t_{min}. As t_{max} increases, λ_m starts to converge to a value in the range 1.2 to 1.4 $W.K^{-1}.m^{-1}$ (cf. Figure 5). For t_{max} = 200 h, the value is in the range 1.2 to 1.4 $W.K^{-1}.m^{-1}$; for t_{max} = 350 h it ranges between 1.25 and 1.35 $W.K^{-1}.m^{-1}$.

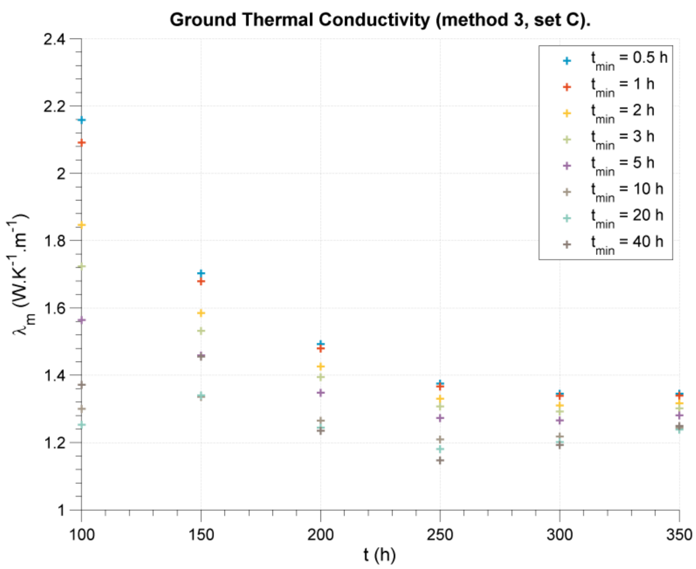

Figure 5 : Set C. Estimation of the ground thermal conductivity λ_m as a function of TRT duration t_{max}

The value of the thermal resistance R_2 is quite constant and ranges from 0.092 to 0.117 K.m.W^{-1}, no matter the minimum time t_{min} and maximum time t_{max}. R_3 exhibits a larger dependence on both t_{min} and t_{max}. R_3 tends to decrease when t_{max} or t_{min} increases. For t_{max} = 350 hours R_3 converges to a value comprised between 0.02 K.m.W^{-1} (t_{min} = 0.5 h) and 0.04 K.m.W^{-1} (t_{min} = 20 h).

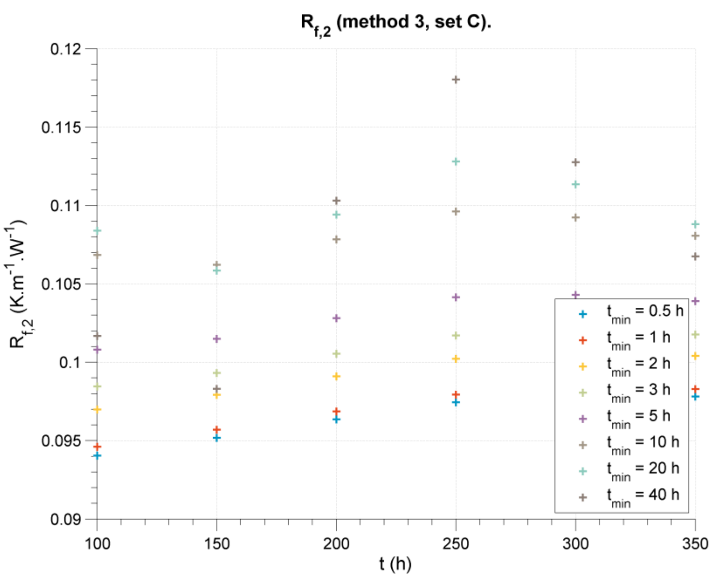

Figure 6 : Set C. Estimation of the resistance R_2 as a function of TRT duration t_{max}

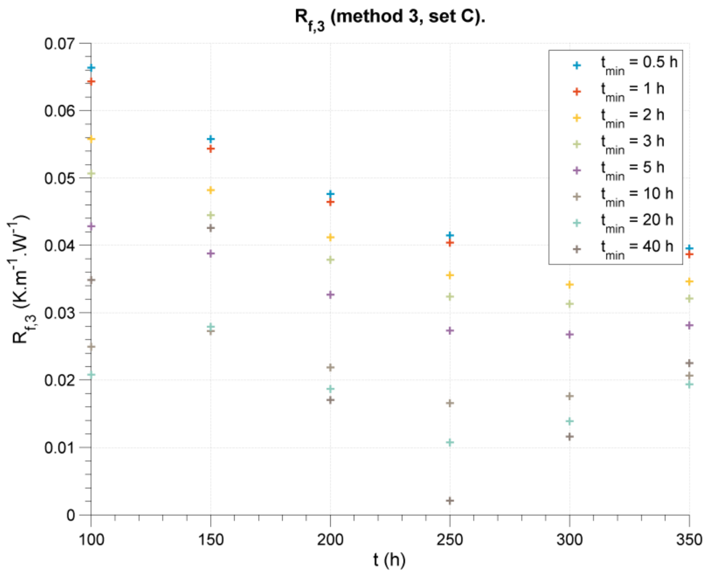

Figure 7 : Set C. Estimation of the resistance R_3 as a function of TRT duration t_{max}

When it comes to the predictability of the fluid temperature, the use of the black-box model with parameters computed on a 100-hour TRT results in large discrepancies in the fluid temperature evolution past 100 h (cf. **Error! Reference source not found.**). The discrepancy reaches c.a. 1.1 °C after 250 h of additional solicitation (corresponding to t = 350 h), and keeps on rising (not shown here). The discrepancy reduces when one uses the parameters fitted on a longer TRT. The comparison of the effect of t_{max} is uneasy since as t_{max} increases, the remaining time interval decreases (the test duration is 350 h). However, it can be noted that with values estimated from a 200-h TRT the agreement is better, the discrepancy is almost constant at 0.2°C. When the TRT duration is increased to 250 h, the discrepancy is in the range 0.1 to 0.2 °C. Qualitatively this seems to be in line with the fact that the value of the ground thermal conductivity starts to converge (to a value in the range 1.2 to 1.4 $W.K^{-1}.m^{-1}$) as t_{max} reaches c.a. 200 to 250 h.

Consequently, for this PHE with a diameter of 60 cm, a minimum duration of the TRT c.a. 200 to 250 hours ensures an appropriate estimation of the ground thermal conductivity, “appropriate” meaning “which can, once used in the model, properly described the fluid temperature evolution”.

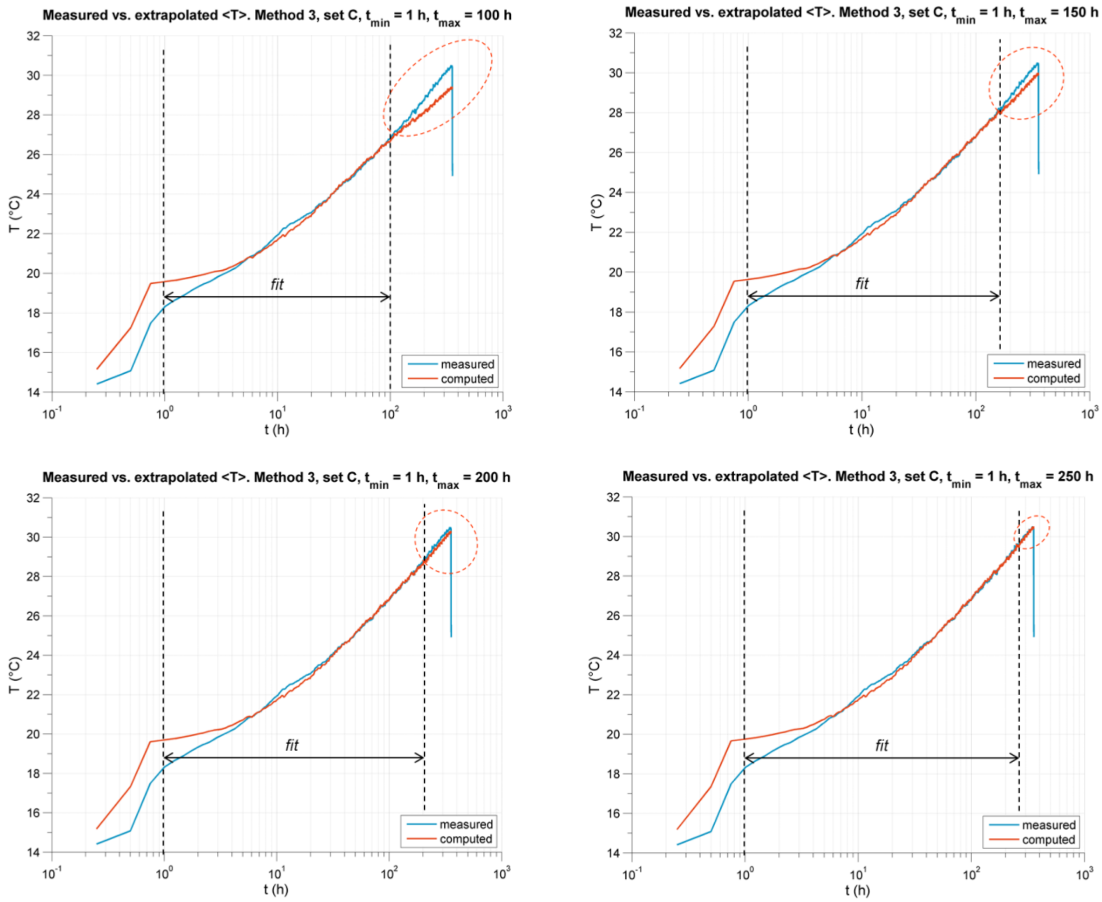

Figure 8 : Set C. Computed values of temperatures with fitted parameters vs. measured temperatures for t_{min} = 1 h and t_{max} = 100 h (upper left) to 250 h (lower right).

Some "iso-misfit" curves, one per couple of model parameters ({R_2, λ_m}, {R_3, λ_m}, {R_3, R_2}) were drawn. Such curves represent the value for which the misfit between experimental and fitted curves (root mean square error RMSE) is equal to a threshold value. These curves allow estimating the uncertainty on one determined parameter and that been used for "start-of-the-art" interpretation of TRT (Witte, 2013) (Wagner et al., 2013). Narrower curves indicate reliable estimation of a parameter.

The curves for a threshold value = 0.1 °C are shown on **Error! Reference source not found.** to **Error! Reference source not found.** for t_{min} = 1 h and t_{max} = 100 h, 200 h and 300 h. The set with values t_{min} = 1 h and t_{max} = 100 h, 200 h and 300 h does not appear, since it resulted in RMSE greater than 0.1 °C, whatever the values of the parameters. This was due to the fact that the difference between computed and measured temperatures is higher at the early solicitation, which is reflected in Figure 8. As expected, the uncertainty on λ_m decreases when t_{max} increases (see Figure 9 and Figure 10).

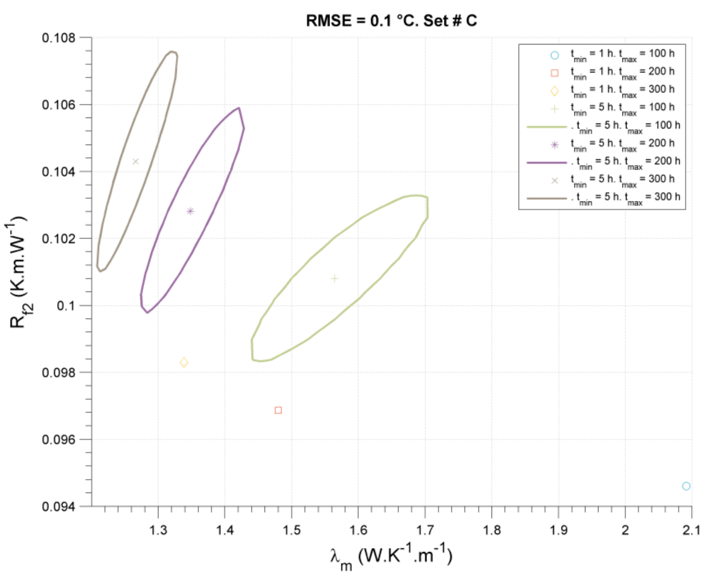

Figure 9 : Set C. Values of the iso-misfit = 0.1 °C for R_2 and λ_m

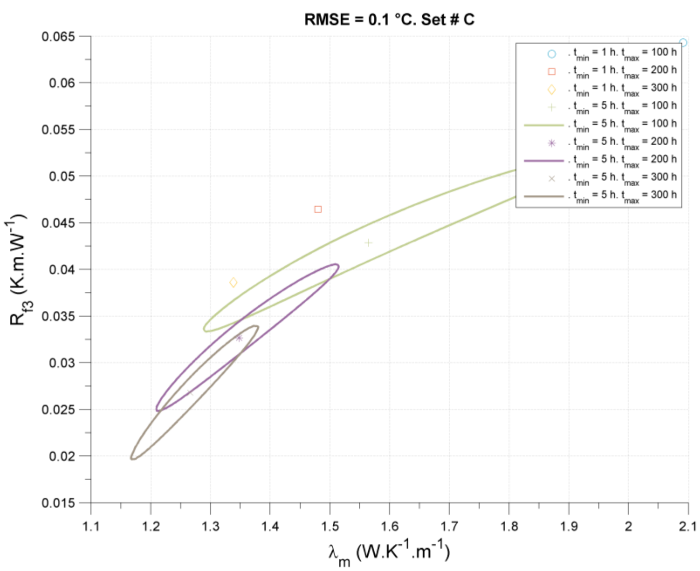

Figure 10 : Set C. Values of the iso-misfit = 0.2 °C for R_3 and λ_m

c. *Application to Set B*

As for set C, the sensibility of the ground thermal conductivity to t_{min} decreases when t_{max} decreases. For t_{max} = 100 h, λ_m ranges between 3.0 and 3.5 W.K^{-1}.m^{-1}. This in line with some laboratory measurements which indicated 2.98 W.K^{-1}.m^{-1}.

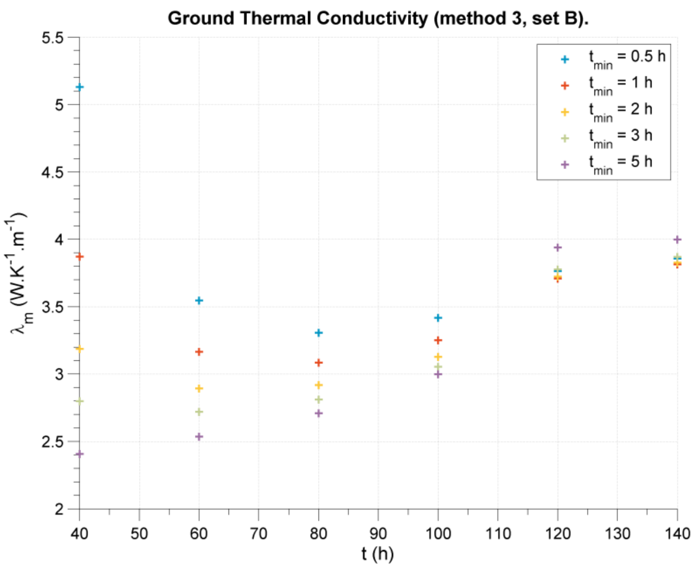

Figure 11: Set B. Estimation of the ground thermal conductivity λ_m as a function of TRT duration t_{max}

4. Future collaboration with host institution and foreseen publications/articles to result from the STSM

It is foreseen to publish the results in the peer-review Geothermics journal. This will include the description of the GECKO model.

5. Bibliography

Gehlin, S., 2002. Thermal Response Test - Method, Development and Evaluation [Doctoral Thesis]. Luleå University of Technology.

Loveridge, F., Powrie, W., Nicholson, D., 2014. Comparison of two different models for pile thermal response test interpretation. Acta Geotech. 9, 367–384. doi:10.1007/s11440-014-0306-3

Maragna, C., Rachez, X., 2015. Innovative Methodology to Compute the Temperature Evolution of Pile Heat Exchangers, in: Proceedings World Geothermal Congress 2015. Melbourne, Australia, 19-25 April 2015.

Wagner, V., Blum, P., Kübert, M., Bayer, P., 2013. Analytical approach to groundwater-influenced thermal response tests of grouted borehole heat exchangers. Geothermics 46, 22–31. doi:10.1016/j.geothermics.2012.10.005

Witte, H.J.L., 2013. Error analysis of thermal response tests. Appl. Energy 109, 302–311. doi:10.1016/j.apenergy.2012.11.060