Prototype development to conduct oscillatory thermal response tests (OTRT) and evaluate the subsurface heat capacity when designing ground-source heat pump systems

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List of symbols

A_t = amplitude of the thermal response [K]
A_h = amplitude of the heat injection [W/m]
i = complex function
d_p = depth of penetration [m]
D = hydraulic diffusivity [m^2/s]
K_0 = Bessel function
P = oscillation period [s]
q = heat injection/extraction rate [W/m]
Q = flow rate [m^3/s]
r = distance [m]
r_b = borehole radius [m]
r_{eq} = equivalent radius [m]
r_{pb} = dimensionless factor [-] defined in Eq. [10]
R_b = borehole thermal resistance [mK/W]
R_p = oscillatory resistance [mK/W]
s = drawdown [m]
S = storativity [-]
t = time [s]
T = transmissivity [m^2/s] (Eqs. [1] and [2])
T = temperature [K] [°C] (elsewhere)

Greek symbols

α = thermal diffusivity [m^2/s]
γ = Euler-Mascheroni constant [-]
λ = thermal conductivity [W/mK]
λ_{gt} = thermal conductivity of the grout [W/mK]
ϕ_p = phase shift/lag [-]
ω = oscillation frequency [s^{-1}]

ABSTRACT

Thermal response test (TRT) is the standard field method to estimate the subsurface thermal conductivity and the borehole thermal resistance to design ground-source heat pump systems. However, the conventional methods and analysis of TRTs do not allow the evaluation of the subsurface heat capacity, which is commonly fixed via literature values. Even though the range of variability of this property among geologic media is quite narrow, it impacts both on thermal diffusivity and the estimation of the borehole thermal resistance via conventional TRT. In turn, this can affect the evaluation of the total drilling length of borehole heat exchangers (BHEs), with obvious related financial and technical drawbacks. To date, methods for in-situ subsurface heat capacity estimation are: (1) laboratory analysis of rock/soil samples; or (2) measure the diffusion of the heat with temperature sensors in an observation well. However, both methods imply economical and logistical issues that can rarely be applied in the scope of geothermal heat pump system design. A third option might be possible by means of so-called oscillatory tests as sometimes performed in hydrogeology to evaluate the hydraulic diffusivity. The aim of this research project was therefore to prove the effectiveness of an oscillatory thermal response test (OTRT) as a tool to infer the subsurface thermal diffusivity (and hence the heat capacity) in addition to thermal conductivity and borehole thermal resistance, without the need of an observation well. Eskilson (1987) described the oscillatory thermal response induced by an oscillatory (sinusoidal) heat injection rate, and he provided the expressions to infer the amplitude attenuation (R_p) and the phase lag (ϕ_p) of the induced thermal response. These parameters are function of the subsurface thermal conductivity and diffusivity. To achieve the prefixed goal, the work involved parametric study, numerical simulations, and field testing. OTRTs with both a water circulation unit and a low-power heating cable unit were successfully carried out. The total duration of injection was 4 to 7 days, with oscillation periods of 12 h and amplitudes of 5 to 10 W/m. The subsurface heat capacity was first estimated via the method (2), with an observation well drilled at 1.2 m distance from the BHE. Results show that OTRT carried out with the low-power heating cable unit struggled to provide low-noise thermal response that can be analysed to properly estimate the subsurface heat capacity. Noise sources are mainly related to the BHE configuration, i.e. storage effect, pipe layout, borehole diameter. However, the OTRT performed with a conventional water circulation succeeded to infer the expected subsurface heat capacity. It also demonstrated that the thermal conductivity can concurrently be assessed with similar accuracy compared to conventional TRTs, whereas it failed to display the correct borehole thermal resistance. OTRT appears a promising tool to evaluate the heat capacity, but more field testing and mathematical interpretation of the sinusoidal response are necessary to better isolate the subsurface contribution to this response.

1. INTRODUCTION AND AIMS OF THE STUDY

This research is funded by the Natural Science and Engineering Research Council of Canada (NSERC) through an Idea to Innovation grant awarded to J. Raymond and L. Lamarche. The project started in May 2019 and lasted until December 2020. The consortium is made of two university partners, the Institut national de la recherche scientifique – Centre Eau Terre Environnement in Québec (INRS, https://inrs.ca/) and the École de Technologie Supérieure in Montréal (ETS, https://www.etsmtl.ca/), and the industrial partner Energie-Stat in Montréal (ES, http://www.energy-stat.com/).

Previous projects dealt with the drilling, installation and testing of 1-U grouted (Ballard et al., 2016) and 2-U water-filled (Ballard et al., 2018) borehole heat exchangers (BHEs) in the Laboratoires pour l'innovation scientifique et technologique de l'environnement of the INRS in Québec. A following project focussed on the experimentation of a heating cable unit to perform thermal response tests (TRTs) in BHEs (Vélez Márquez et al., 2018).

To date, TRT is the most common in-situ method for thermal conductivity evaluation of the subsurface. The technique also allows estimating the borehole thermal resistance. Both parameters are crucial elements to properly design shallow geothermal energy installations. However, TRTs do not allow the evaluation of subsurface heat capacity, which is normally fixed via literature values. Even though the range of variability of this parameter among geologic media is quite limited, a change from 1.5 to 3.2 MJ/m^{3}K influences the thermal diffusivity (± 40 %) and thus the evaluation of the borehole thermal resistance (± 10 - 23 %, with high and low thermal conductivity, respectively) via conventional TRTs. In turn, this can affect the evaluation of the total drilling length of BHEs by ± 6-7 %, with an impact of 3-4 % on the total cost of the system.

To date, subsurface heat capacity can be evaluated via:

(1) Laboratory analysis of rock/soil samples;

(2) Measurement of the heat diffusion with temperature sensors in an observation well;

Option 1 ensures quite accurate results (± 10 %), but several samples need to be collected in order to thoroughly characterize the subsurface. Option 2 can provide more spatially distributed information, but it needs a second well that will unlikely be useful after the tests. Moreover, a long-lasting heat injection (4 days at least for a well 1 m apart) is necessary to induce a significant thermal disturbance to be measured. A third option might be possible by means of so-called oscillatory tests as sometimes performed in hydrogeology to evaluate the hydraulic diffusivity. Option 3 can be carried out in the BHE itself without the need of samples or observation wells. However, the analysis of the thermal response can be quite challenging due to the potential noise provided by the backfilling, whether it is geothermal grout or groundwater.

This project aims to evaluate the effectiveness of so-called oscillatory thermal response tests (OTRTs) as a tool to estimate the subsurface heat capacity. To achieve this goal, a 1-U 154-m-deep grouted BHE was subject to several tests. An observation well was drilled at 1.2 m apart in order to evaluate the subsurface heat capacity and assess the accuracy of the estimation. A secondary objective is to define if the OTRT can be carried out with the standard duration of TRTs (ca. 50 h, Kavanaugh, 2001) while assessing thermal conductivity and borehole thermal resistance with the same accuracy of conventional TRTs. These objectives were addressed by performing OTRTs with both a conventional water circulation unit, provided by the industrial partner Energie-Stat, and a low-power heating cable unit, developed by the INRS. The heating cable apparatus and OTRT method are matter of a provisional patent application to the Canadian Intellectual Property Office - CIPO (**Appendix A**).

After briefly presenting the state of the art (**Section 2**) and the research hypothesis (**Section 3**), the report describes the site and all the experiments carried out to demonstrate the hypothesis and reach the objectives (**Section 4**). The outcomes are then shown (**Section 5**) and discussed (**Section 6**) before drawing the conclusions and future perspectives (**Section 7**).

2. STATE OF THE ART ON THERMAL RESPONSE TEST (TRT)

Thermal response test (TRT) is the most common field method to estimate the subsurface thermal conductivity and the borehole thermal resistance for ground-source heat pump systems. Hot water is circulated within the borehole heat exchanger (BHE) in order to inject 50 to 80 W/m (Kavanaugh, 2001; Spitler and Gehlin, 2015) during conventional TRTs. Low-power tests (10-25 W/m) can also be conducted with heating cables and demonstrated to provide as accurate results of thermal conductivity, whereas borehole thermal resistance cannot be properly assessed (Raymond et al., 2015). Other than being very compact and needing only 120 V power, the heating cable unit can provide thermal conductivity stratigraphy with several T sensors at depth or a fiber optic cable. Moreover, it does not require a BHE since it can be performed in open wells, provided that water is present to ensure proper thermal contact with the subsurface. Electric cable with heating and non-heating sections were also tested, but significant free convection occurs in the pipe (or well) according to the Rayleigh number stability criterion, thus allowing only 15 % accuracy in thermal conductivity estimation (Vélez Márquez et al., 2018). TRTs are commonly carried out for 48 to 72 h with a constant power. TRTs with step heat injection have also been proposed to determine optimal heat rejection/extraction rates (Kurevija et al., 2018).

Oscillatory pumping tests (OPTs) have been used in hydrogeology as a practical and effective technique for establishing local scale spatial variability in hydraulic parameters (Cardiff et al., 2013; Guiltinan and Becker, 2015). The phase shift and the amplitude attenuation of the recorded signal are functions of the transmissivity and storativity of the aquifer. Analogously, oscillatory thermal response tests (OTRTs) can be performed by inducing a heat sinusoid in a BHE or a well and measuring the sinusoidal thermal response of the system (Oberdorfer, 2014). The use of an oscillatory heat source in replacement of a common constant power induces a sinusoidal signal whose phase and amplitude are affected by the storage of heat into the subsurface, thus providing more information about the subsurface and borehole thermal properties when compared to conventional TRTs. It is in the authors' opinion that an OTRT might be useful to assess the subsurface thermal diffusivity (thermal analogue of the hydraulic diffusivity) and hence to estimate the heat capacity, property which can not be evaluated via conventional TRTs.

3. RESEARCH HYPHOTHESIS

According to Guiltinan and Becker (2015, and references therein), periodic hydraulic testing (also called harmonic, oscillatory, sinusoidal) is a quite old measurement technique. It was used in the oil industry as early as 1966 and it was used in oil production wells using alternating periods of flow and shut-in during the 1970s. At the beginning, naturally occurring periodic oscillations such as earth tides or barometric changes were used. The advantage is that these natural periodic variations impact the groundwater field over many kilometers. However, they might be difficult to isolate and interpret due to the complexity of these systems and the superposition of different processes. Once performed on purpose, periodic tests can provide local hydraulic information about the aquifer, in particular about the spatial variability of transmissivity and storativity of the aquifer. By varying the oscillation frequency, different regions of the aquifer can be tested, and the properties estimated. While being valid for any type of groundwater system, they are particularly effective in bedrock systems because the small storage coefficient means a longer propagation of the signal from the test well compared to higher storage coefficient (porous media).

The solution of an OPT is given by the following Eq. [1] (Guiltinan and Becker, 2015):

$$s(r,t) = \frac{Q}{2\pi T} K_0\left(r\sqrt{\frac{i\omega}{D}}\right) \qquad \text{Eq. [1]}$$

where s [m] is the drawdown, r [m] is the distance from the pumping well, t [s] is time, Q [m^3/s] is the flow rate injected in or extracted from the well, T [m^2/s] is the transmissivity, K_0 is the zero-order modified Bessel function of the second kind, i is the complex variable, ω [s^{-1}] is the frequency of the oscillation, and D [m^2/s] is the hydraulic diffusivity.

The amplitude of the oscillation $|s|$ in the observation well is given by Eq. [2]:

$$|s| = \frac{Q}{2\pi T}\left|K_0\left(r\sqrt{\frac{i\omega}{D}}\right)\right| \qquad \text{Eq. [2]}$$

and the phase shift (rad) between the source (test well) and the drawdown recorded in the observation well is given by Eq. [3]:

$$phase\ shift = \arg\left\{K_0\left(r\sqrt{\frac{i\omega}{D}}\right)\right\} \qquad \text{Eq. [3]}$$

These expressions provide a mean to estimate the hydraulic properties *T* and *D* (and therefore the storativity *S* [-] = *T/D*) independently.

Since the analogues of *T* and *D* in the heat problem are the thermal conductivity and diffusivity, the hypothesis is that the oscillatory thermal response induced by an OTRT might bring information about the subsurface thermal diffusivity, and thus the heat capacity (ratio of conductivity and diffusivity, **Figure 1**). Differently from the hydraulic tests, we do not want to use observation wells due to both technical and financial reasons: the subsurface is a very poor heat conductor, therefore the duration of the test would be excessively long in order to induce a signal clear enough to be effectively analysed; the distance of the supposed observation well (small enough to reduce the duration of the test) would not be compatible with the conventional spacing adopted in bore fields of ground-coupled heat pump (6-8 m) or underground storage (3-5 m) systems, therefore making the observation well barely useful for the installation.

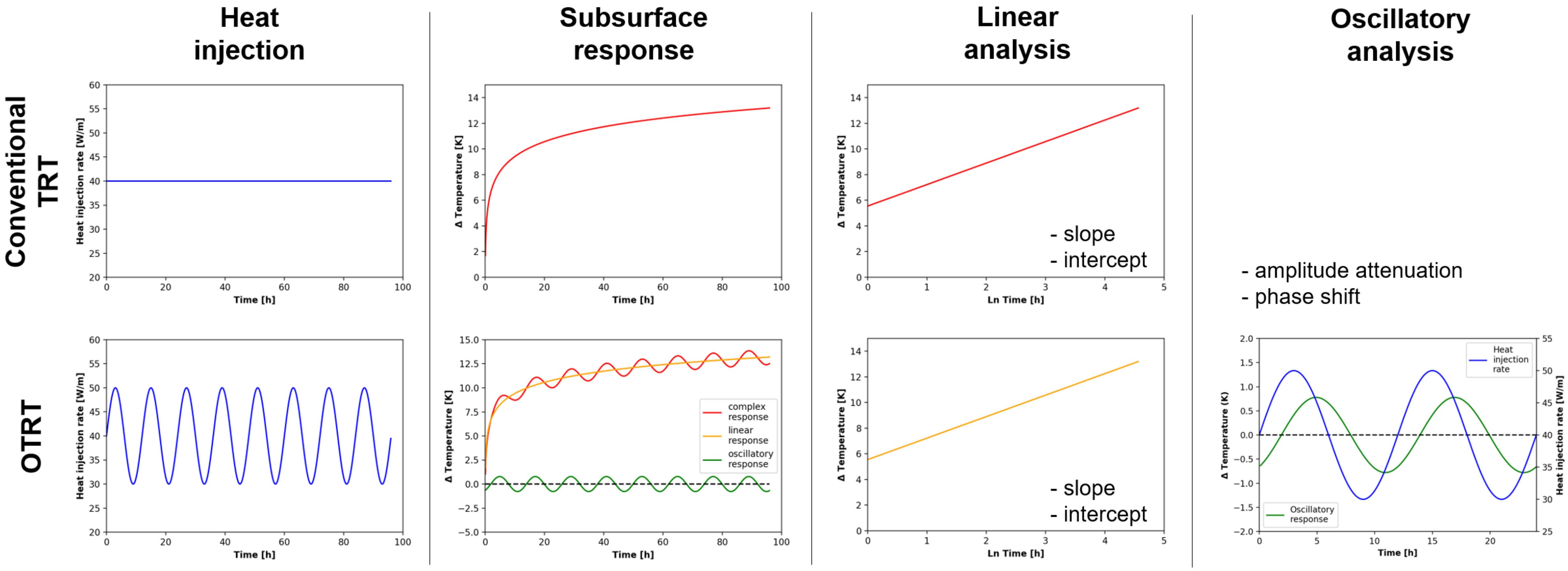


Figure 1 – Comparison between conventional and oscillatory TRT (modified from Oberdorfer, 2014)

The main challenge is the influence of the backfilling of the BHE, commonly made of sand-bentonite mixtures, thermally enhanced grouts, or groundwater where there is no risk of cross contamination of aquifers. The storage effect due to the heat capacity of the backfilling plays a key role in the oscillatory signal propagation, thus limiting the depth of investigation of the OTRT. This has also been highlighted in hydraulic periodic tests, that are proved to be more effective in low-storativity settings as bedrock aquifers (Guiltinan and Becker, 2015). The oscillation frequency of the OTRT is therefore a crucial parameter to choose the right trade-off between the investigation depth and the length of the test. To the best of our knowledge, Oberdorfer (2014) is the first and only study that performed OTRTs showing that high-frequency tests have small penetration depths and can highlight anomalous borehole thermal resistance due to flaws of the geothermal grouting. On the other hand, high-period tests (low frequencies) are necessary to increase the penetration depth to more than 10 cm and significantly affect the subsurface. A comprehensive description about the theory and analytical approach adopted to analyse the OTRT in this study are provided in Section 4.2.

The hypothesis of the research being stated, the following steps of the study were defined to prove the effectiveness of OTRT for the estimation of the subsurface heat capacity (HC):

(1) To highlight the most influencing parameters of an OTRT through a parametric numerical study in order to define the optimal heat injection protocol to conduct field experiments (not shown here, but reported in **Appendix E**);

(2) To perform a conventional TRT while recording the thermal response in a nearby observation well such to estimate the subsurface heat capacity with the dual needle technique and compare it to the OTRT results (**Sections 4.4** and **5.1**);

(3) To carry out an OTRT with both the water circulation and heating cable units and analyse the results to estimate the heat capacity.

4. MATERIALS AND METHODS

4.1 Test site

The test site is located at the *Laboratoires pour l'innovation scientifique et technologique de l'environnement* of the INRS, in the *Parc technologique du Québec métropolitain* (2605 blvd. du Parc-Technologique, Québec City, G1P 4S5, QC; Canada). Geographical coordinates are N 46°47’44.58’’ W 71°18’09.97’’.

Works at this site started in September 2015 with the drilling and installation of the a 154-m-deep single-U (1-U in **Figure 2**) borehole heat exchanger (BHE) and two 42-m-deep observation wells (obs1 and obs2) at 10 m on each side along a NW direction parallel to the hydraulic channel nearby (Ballard et al., 2016). In November 2017, a double-U BHE was installed in a 165-m-deep borehole together with a 49-m-deep observation well (Ballard et al., 2018). The two boreholes were made at 10 m distance along the same direction towards NW (2-U and obs3 in **Figure 3**).

In June 2019, a fourth observation well (obs4, **Appendix B**) was drilled at 1.2 m distance from the 1-U BHE in order to evaluate the thermal diffusivity of the subsurface through a conventional test. It is a 2-inch well drilled to a depth of 26 m. A fifth well (obs5) was finally drilled at the eastern limit of the site in order to evaluate the local potentiometric field and estimate the groundwater flow (GW) direction. It has a 1-inch diameter and a depth of 15 m.

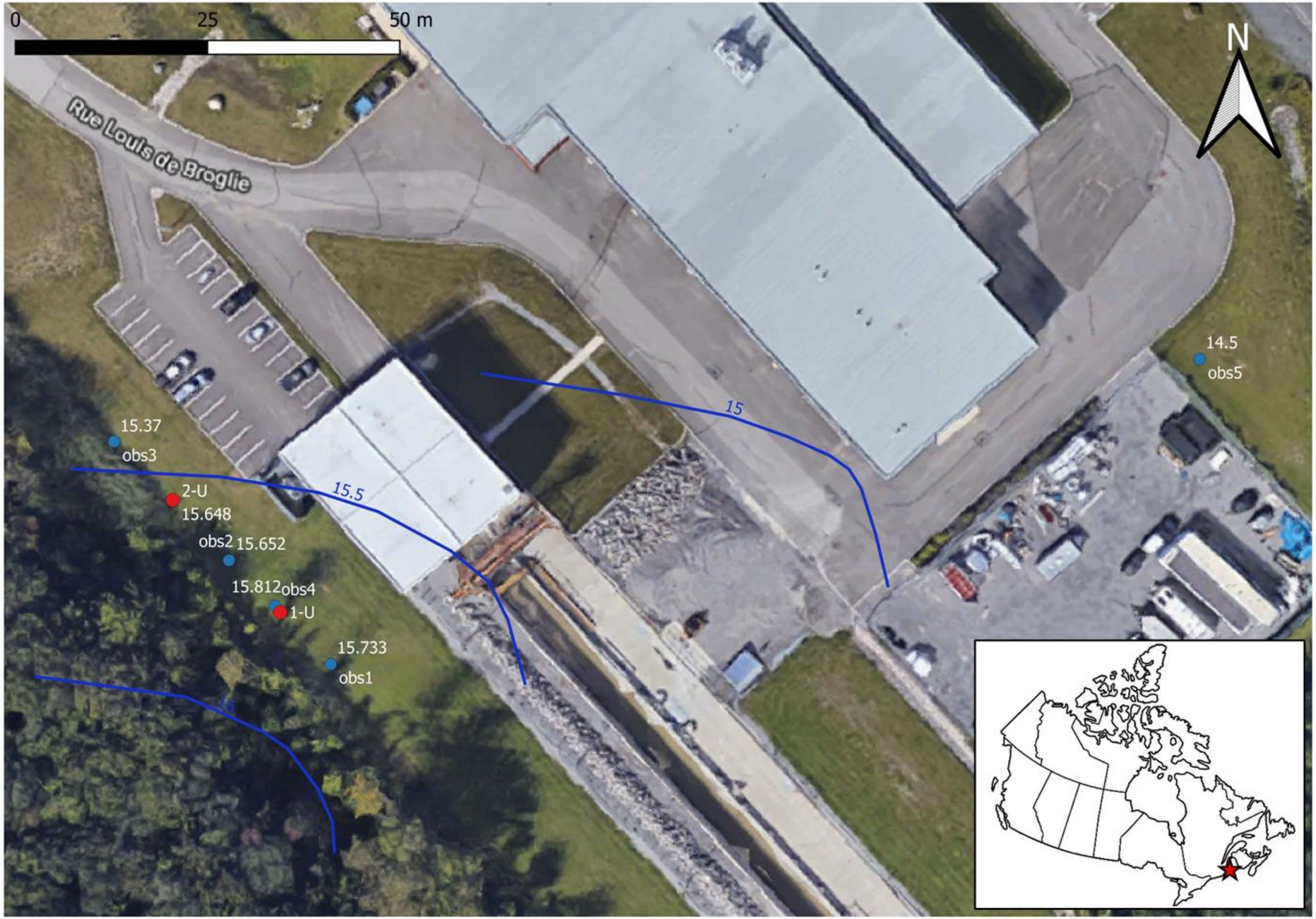


Figure 2 – Orthophoto of the study site. BHE and observation wells are pointed out by red and blue dots, respectively. Numbers indicate the water level in m a.s.l., blue lines represent the local potentiometric field.

From the geological point of view, the local stratigraphy presents 2 m of soil overlying 8 to 12 m of mixed till and pebbles, followed by clays over weathered rock (**Figure 3**). The bedrock is made of green and grey shales belonging to the "Les Fonds" Formation of the "Sainte Rosalie" Group of the Saint-Lawrence Lowlands sedimentary basin (Globensky, 1987; Koubikana Pambou et al., 2019). Major fracture zones were detected at depths of 20–25 m, 40–45 m, 95 m and 137 m during the drilling of the 1-U borehole. For more information about local geology and drilling information, please refer to the reports by Ballard et al. (2016) and Ballard et al. (2018), and the scientific paper by Koubikana Pambou et al. (2019).

The BHE used for the present study is the 1-U. The reason is that it is grouted as commonly done in north-America, while the 2-U BHE has been left open in contact with the GW in order to demonstrate that the borehole thermal resistance can be significantly reduced (Ballard et al., 2018). But, for the aims of this research project, the conventional grouted BHE represents the easiest situation, without possible further noise induced by the convection cells.

The observation well obs4 (**Appendix B**) was drilled on purpose to determine the thermal diffusivity by means of the well-established theory and methods of the dual needle probe (Raymond et al., 2017, http://log.ete.inrs.ca/laboratoire/), and then compare it with the OTRT results to validate its reliability. But, drilling a hole parallel to the BHE was quite challenging as expected, since generally deviations on the inclination of the drilling are in the range 1-10% of the depth. In order to have two parallel holes, it would have been necessary to drill them one after the other, with the same drilling machine and same operator, but drilling another BHE was not possible due to budget constraints. However, the inclination of obs4 was measured in order to have a better idea of the actual distance between the line heat source (1-U BHE, assumed vertical) and the reference well (obs4). Results of this analysis, made with the GyroMaster probe by SPT SemmLogging (inclination accuracy ± 0.05°), are shown in (**Figure 4**). Horizontal deviations with respect to the vertical are 0.05, 0.2, 0.9, and 2.1 m at depths of 5, 10, 15 and 21 m, respectively. The well is quite linear down to 10 m, with slight eastward inclination, then the deviation rate becomes bigger, and the inclination tends towards NNW. Distances to the BHE, assuming the latter to be perfectly vertical are approximately 1.2, 1.3, 2.0, 3.0 and 4.4 m at depths of 5, 10, 15, 20 and 25 m (projected), respectively.

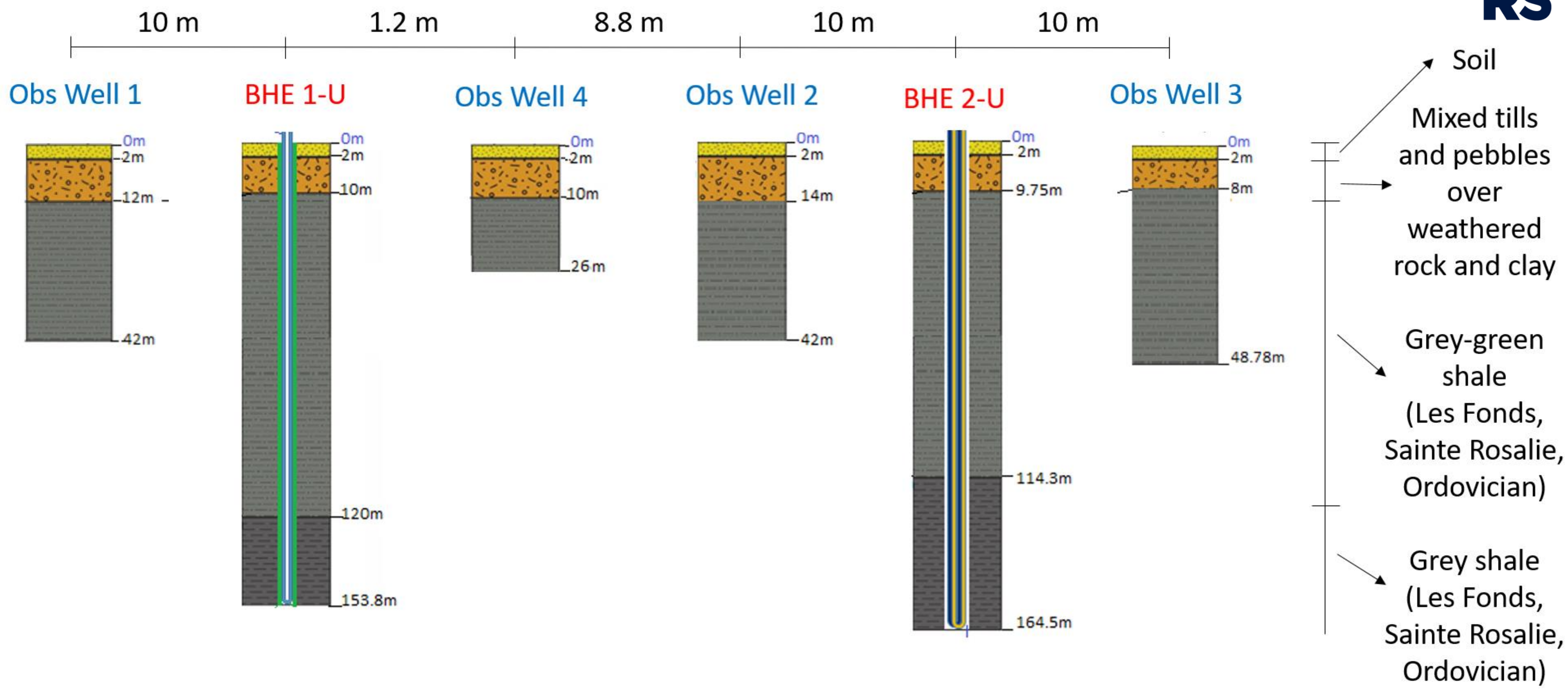


Figure 3 – Cross section of the study site between the observation wells 1 and 3.

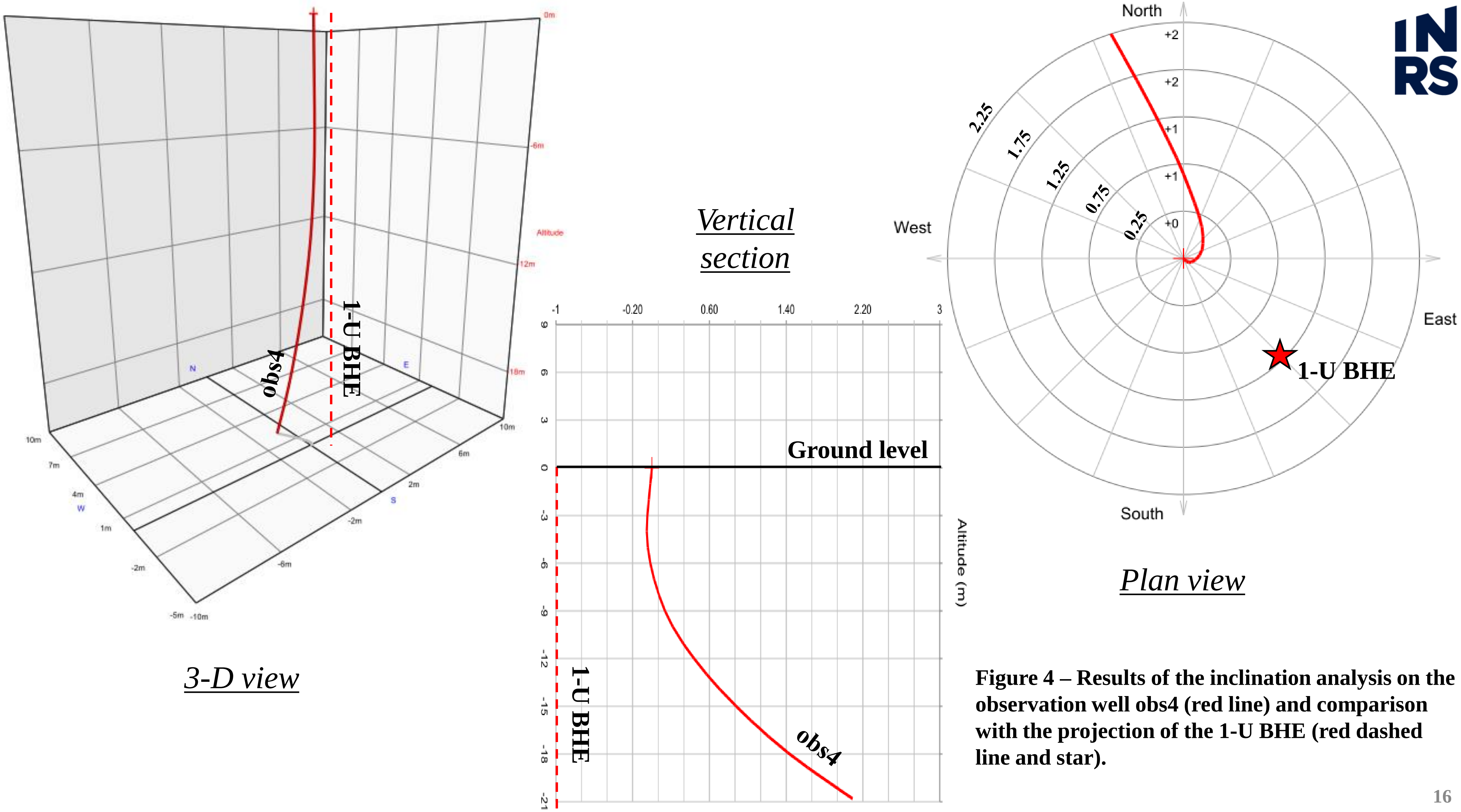


Figure 4 – Results of the inclination analysis on the observation well obs4 (red line) and comparison with the projection of the 1-U BHE (red dashed line and star).

4.2 Oscillatory heat injection theory and analytical approach for the evaluation of thermal diffusivity

An oscillatory (sinusoidal) heat injection carried out in a BHE has the following form:

$$q(t) = q_p \cdot \sin\left(\frac{2\pi}{P} \cdot t\right) \qquad \text{Eq. [4]}$$

where $q(t)$ [W/m] is the heat injected per unit length, q_p [W/m] is the offset of the sinusoidal function, P [h] is the period of the oscillation and t [h] is time. This induces an oscillatory thermal response in the same well ($r = r_b$) or in nearby observation wells which is described by the following equation given by Eskilson (1987):

$$T = -q_p \cdot R_p \cdot \sin\left(\frac{2\pi}{P} \cdot t - 2\pi\phi_p\right) \qquad \text{Eq. [5]}$$

where R_p [mK/W] denotes the resistance opposed by the surrounding medium and is therefore called oscillatory resistance, and ϕ_p [-] is the phase shift of the thermal response and is expressed as a fraction of P ($0 < \phi_p < 1$). R_p and ϕ_p can be evaluated by comparing the heat injection and thermal response as described by the following equations and presented in **Figure 5**:

$$R_p = \frac{A_t\ [K]}{A_h\ [W/m]} \qquad \text{Eq. [6]}$$

$$\phi_p = \frac{phase\ shift\ [h]}{P\ [h]} \qquad \text{Eq. [7]}$$

where A_t [K] and A_h [W/m] are the amplitudes of the thermal response and heat injection, respectively

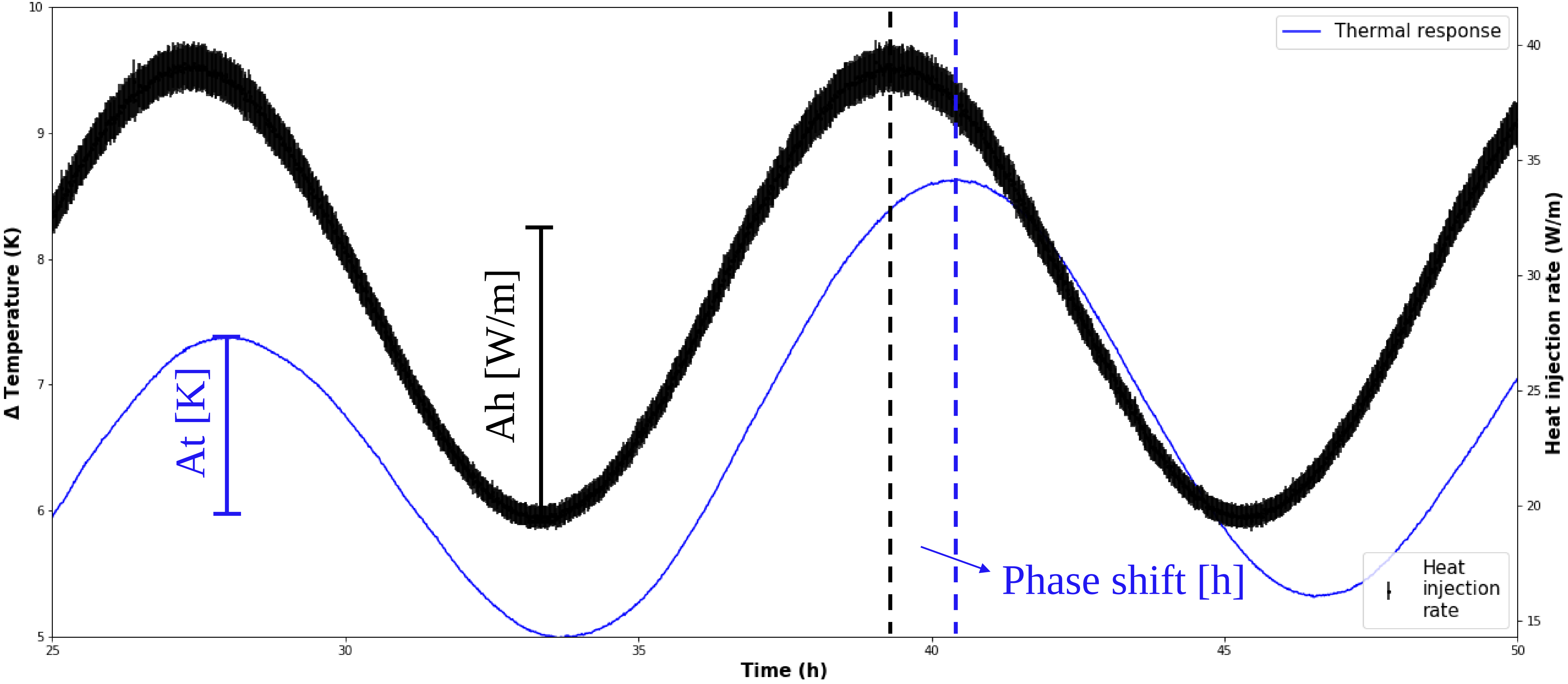


Figure 5 – Oscillatory heat injection (black line) and thermal response (blue line).

Eq. [5] is valid only if the system is Linear Time Invariant, i.e. the oscillation frequencies of the heat injection and thermal response are the same, as described and demonstrated by Oberdorfer (2014). If the heat source can be simplified to a heated line, there exists an analytical solution and Eskilson (1987) derived the expressions for R_p (Eq. [8]) and ϕ_p (Eq. [9]) as a function of r_{pb}, a dimensionless factor described in Eq. [10] that depends on the depth of investigation (d_p, Eq. [11]), that in turn varies according to the thermal diffusivity (α).

$$R_p(r_{pb}) = \frac{1}{2\pi\lambda} \cdot \sqrt{\left(\log\left(2/r_{pb}\right) - \gamma\right)^2 + \pi^2/16} \qquad \text{Eq. [8]}$$

$$\phi_p(r_{pb}) = \frac{1}{2\pi} \cdot \operatorname{atan}\left(\frac{\pi/4}{\log\left(2/r_{pb}\right) - \gamma}\right) \qquad \text{Eq. [9]}$$

$$r_{pb} = \frac{r_b\sqrt{2}}{d_p} \qquad \text{Eq. [10]}$$

$$d_p = \sqrt{\frac{\alpha \cdot P}{\pi}} \qquad \text{Eq. [11]}$$

where λ is thermal conductivity [W/mK], γ is Euler-Mascheroni constant 0.5772156649, r_b is the borehole radius [m], and α is thermal diffusivity [m^2/s] .

Eskilson suggests that these two expressions are valid provided that $r_{pb} < 0.1$, and thus $r_b < 0.07 \cdot d_p$. This means that an OTRT would have to last several days (Periods > 1000 h or 40 days), which is clearly not practical and economically feasible. But actually it was found here that the solution provides valid results until $r_{pb} < 1$ and $r_b < 0.7 \cdot d_p$. Periods of oscillations in the order of 10-12 h are still valid for 4-inch-diameter BHE (0.11 m) and of 18-20 h for 6-inch-diameter BHE (0.15 m). This allows us to carry out an OTRT lasting as a conventional TRT (i.e. 48-72 h). However, the subsurface volume investigated would be only in the close vicinity of the BHE, with $d_p = 10 - 15$ cm.

The analysis of the OTRT is done through the following main steps (**Figure 6**):

1. Evaluation of $\lambda_{heating}$ and R_b via the slope method;
2. Subtraction of the linear component $f(\lambda_{heating}, R_b)$ in order to get the oscillatory component of the OTRT response;
3. Comparison of the oscillatory heat injection and oscillatory thermal response to evaluate R_p and ϕ_p. Evaluation of α by means of the Equations [8-11];
4. Analysis of the recovery period to estimate $\lambda_{cooling}$, which we assume as the real subsurface thermal conductivity because it is not affected by the borehole thermal resistance. Evaluation of Cv via the ratio $\lambda_{cooling}/\alpha$

These steps are carried out via a Python script (**Appendices C** and **D**).

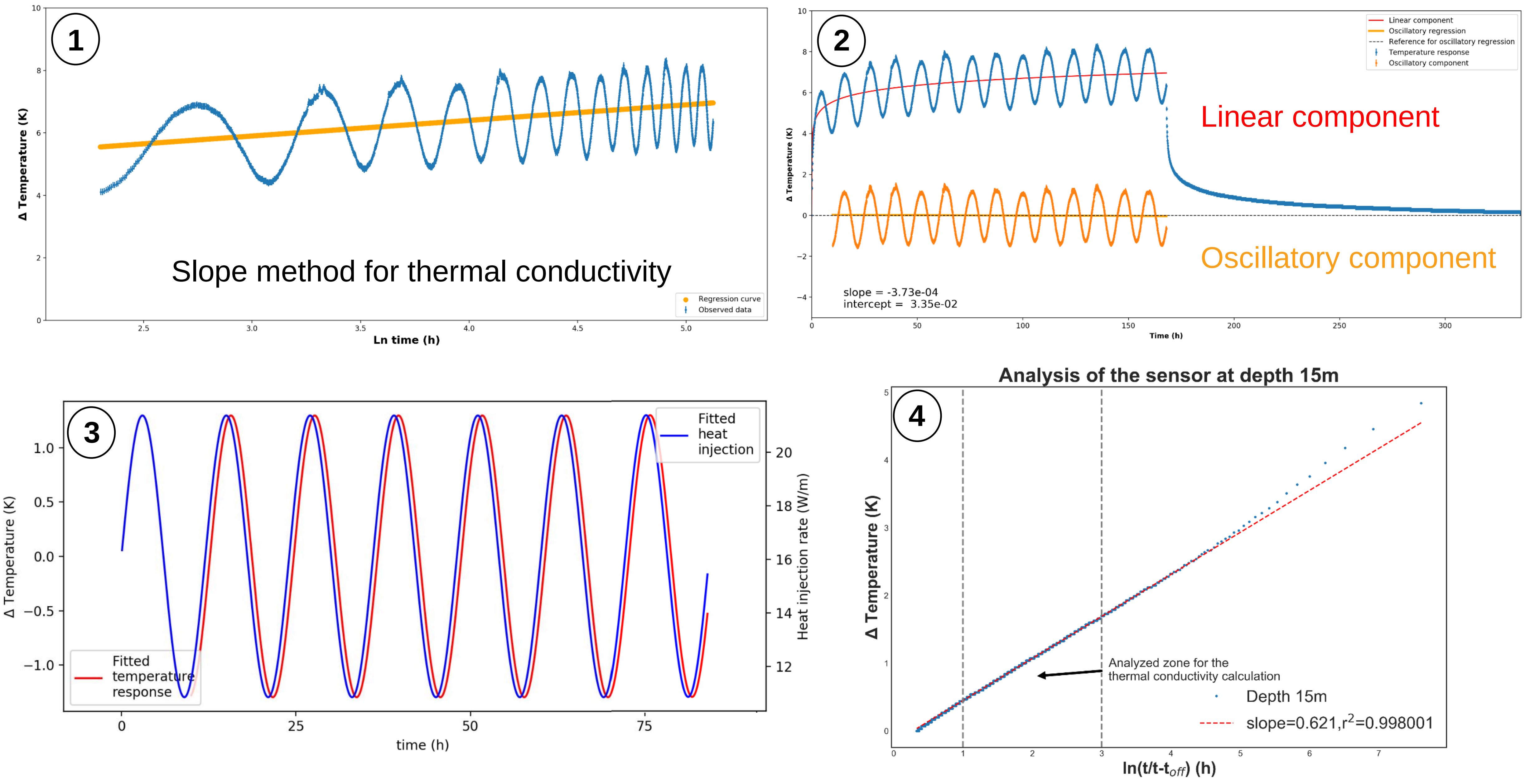


Figure 6 – Analysis of the OTRT

4.3 Parametric analysis

In order to decide the optimal injection protocol for the OTRTs, a parametric analysis was carried out with COMSOL Multiphysics. Details of the analysis are described in the report of Chapotard (2019, **Appendix E**), so this will not be repeated here. The main results are however briefly presented here because they have been a milestone for the field tests, and it would not be relevant to show them in the results section.

The analysis showed that the oscillation period has the highest influence (13.3%) on the results, which is expected since it directly impacts the investigation depth d_p (Giordano et al., 2019). The radius of the pipes follows with 11.1%. Other important result show that thermal conductivity (2.5 %) and heat capacity (0.8 %) of the backfilling material have a larger influence than the equivalent subsurface properties with 0.17 % and 0.2 %, respectively. In particular, increasing the grout HC by a factor of 2 will result in a larger signal difference on the phase shift than doubling the subsurface HC (**Figure 7**).

Therefore, as expected, the heat storage effect of the BHE is the largest obstacle to the evaluation of the subsurface HC. A longer oscillation period would result in a smaller BHE influence, thus reducing the "borehole noise". As highlighted by Oberdorfer (2014), high-frequency tests have small penetration depths and can highlight anomalous borehole thermal resistances due to flaws in the geothermal grouting. On the other hand, high-period tests (low frequencies) are necessary to increase the penetration depth to more than 10 cm and significantly affect the subsurface, but this would progressively make OTRT less and less practical in the field.

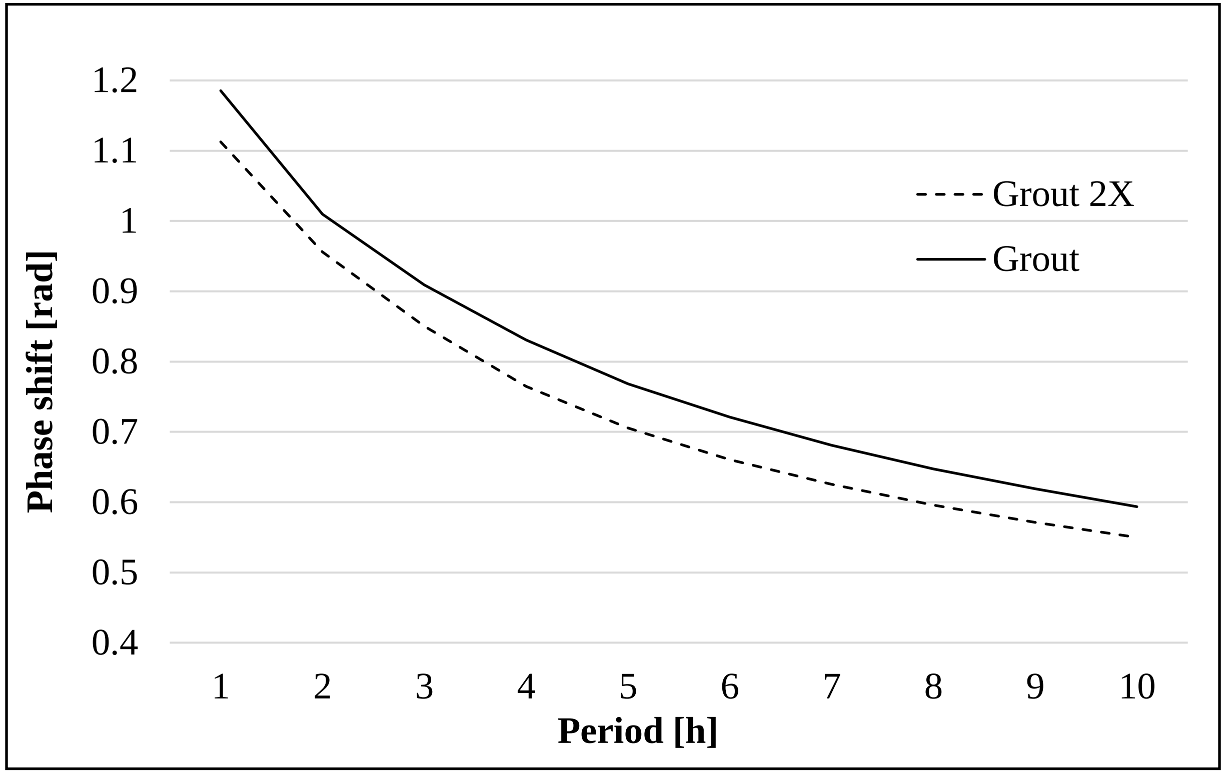
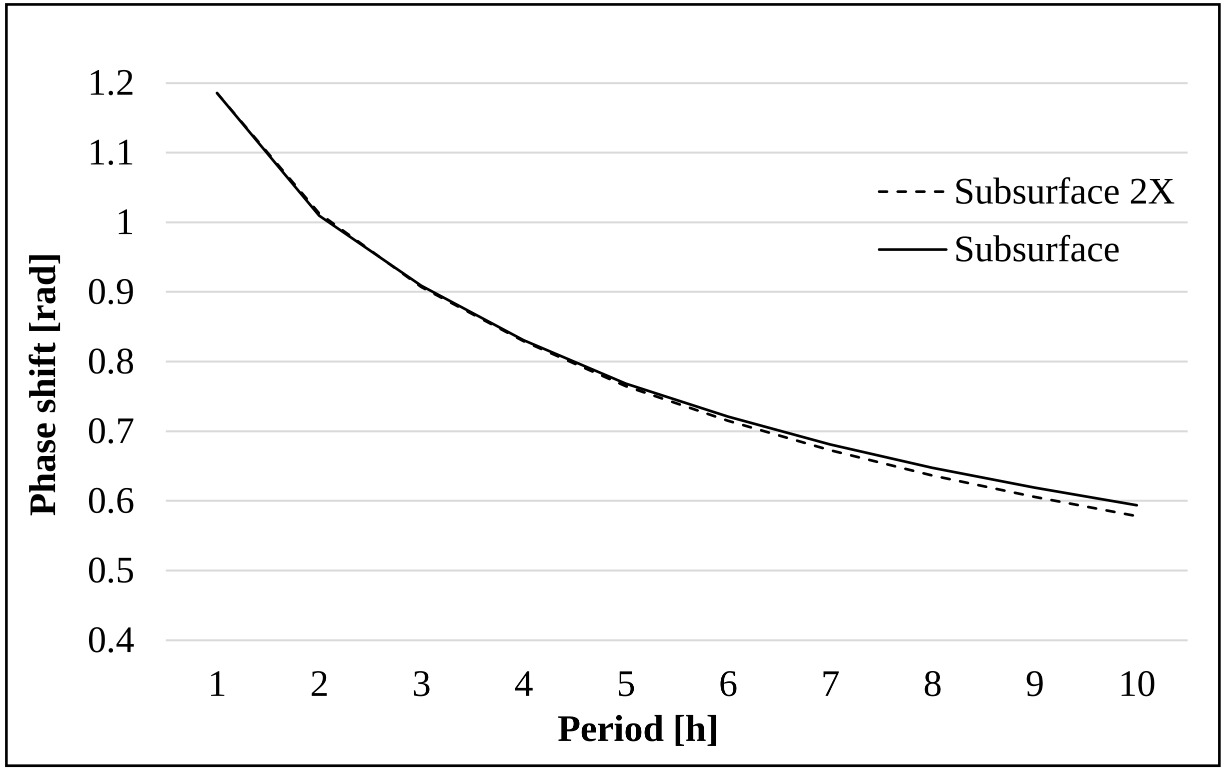


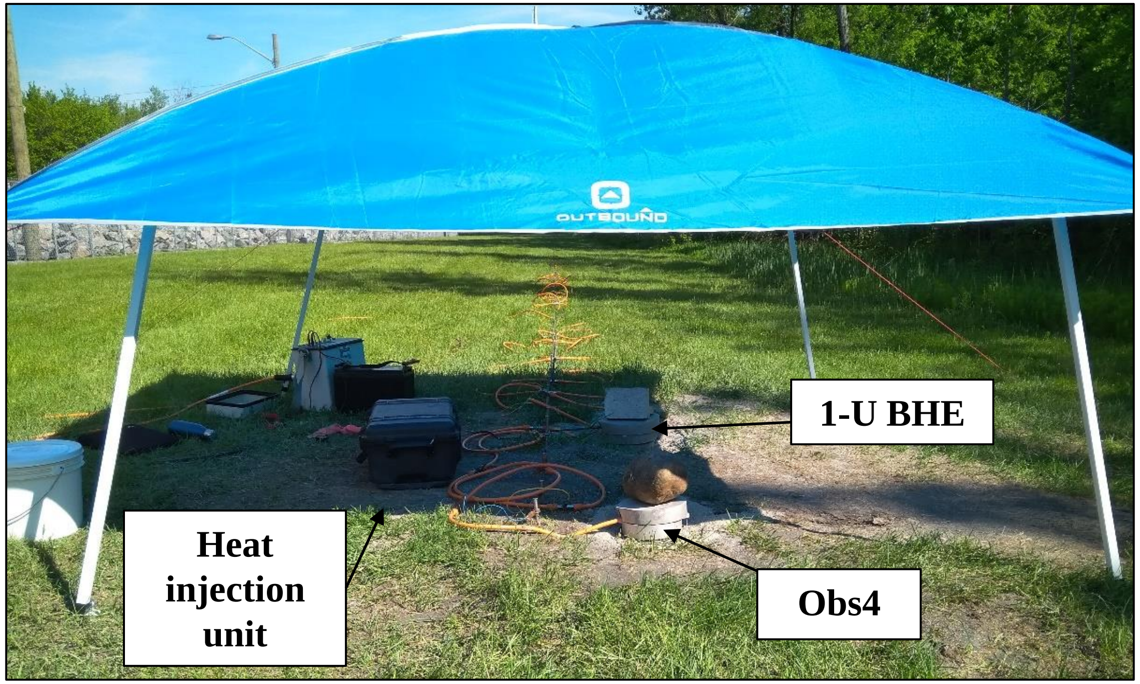
Figure 7 – Comparison between the phase lag of the thermal response when doubling the heat capacity of the BHE grout (upper-left graph) and the subsurface (lower-right graph)



A heat injection protocol with period of 12 h, offset of 35 W/m, amplitude of 15 W/m and duration of more than 48 h has been chosen to complete field testing with water circulation. Heating cables OTRT will have smaller offset (20 W/m) and amplitude (5 W/m); both parameters demonstrated to have no influence on the results anyway.

4.4 Conventional TRT with a heating cable unit

The test was carried out from 10 to 14 June 2019 (**Figure 8**), it lasted 97 h and the average power injected was 48 W/m along a cable of 45 m, doubled to reach a higher heat injection rate. DST Centi temperature sensors made by StarODDI (accuracy 0.1 °C, resolution 0.032 °C) were placed along the heating cable at depths of 2.5, 5, 10, 12.5, 15, 17.5, 20, and 22.5 m from the ground level. Sensors of the same type were installed in the observation well from 5 to 25 m with 2.5 m spacing (**Figure 9**). The drilling of the observation well Obs4 was carried out on the 28th of May, and temperature profiles were measured in the BHE and the well itself to wait for the undisturbed temperature to be recovered before starting the TRT (**Figure 10**).



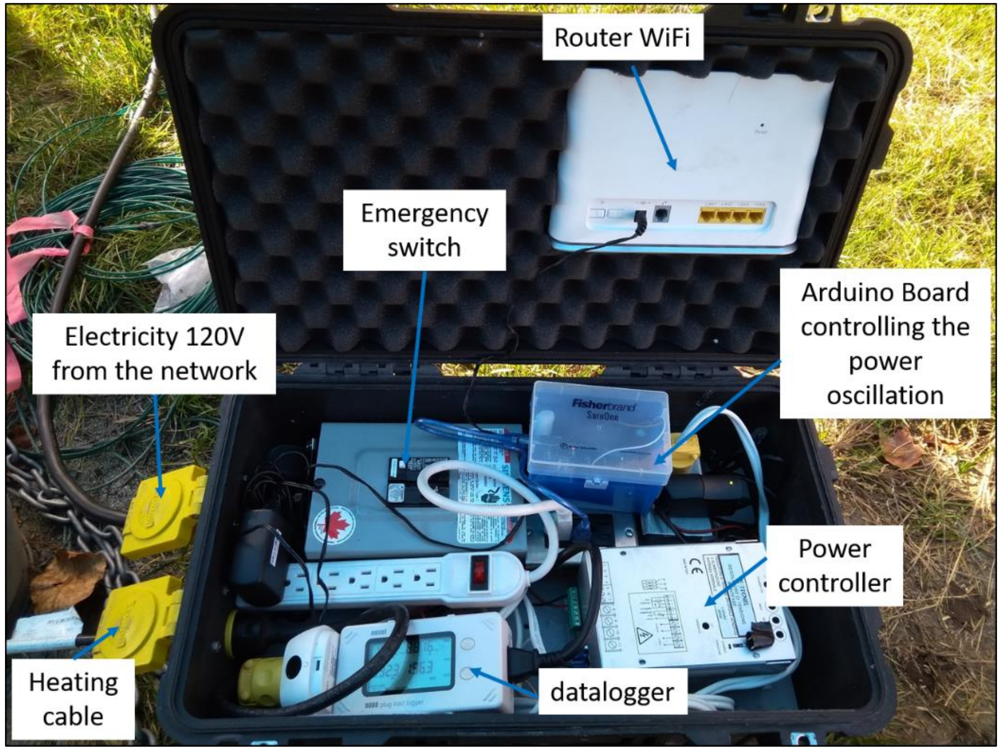


Figure 8 – Pictures of the field site during the TRT (left) and details about the heat injection unit (right).

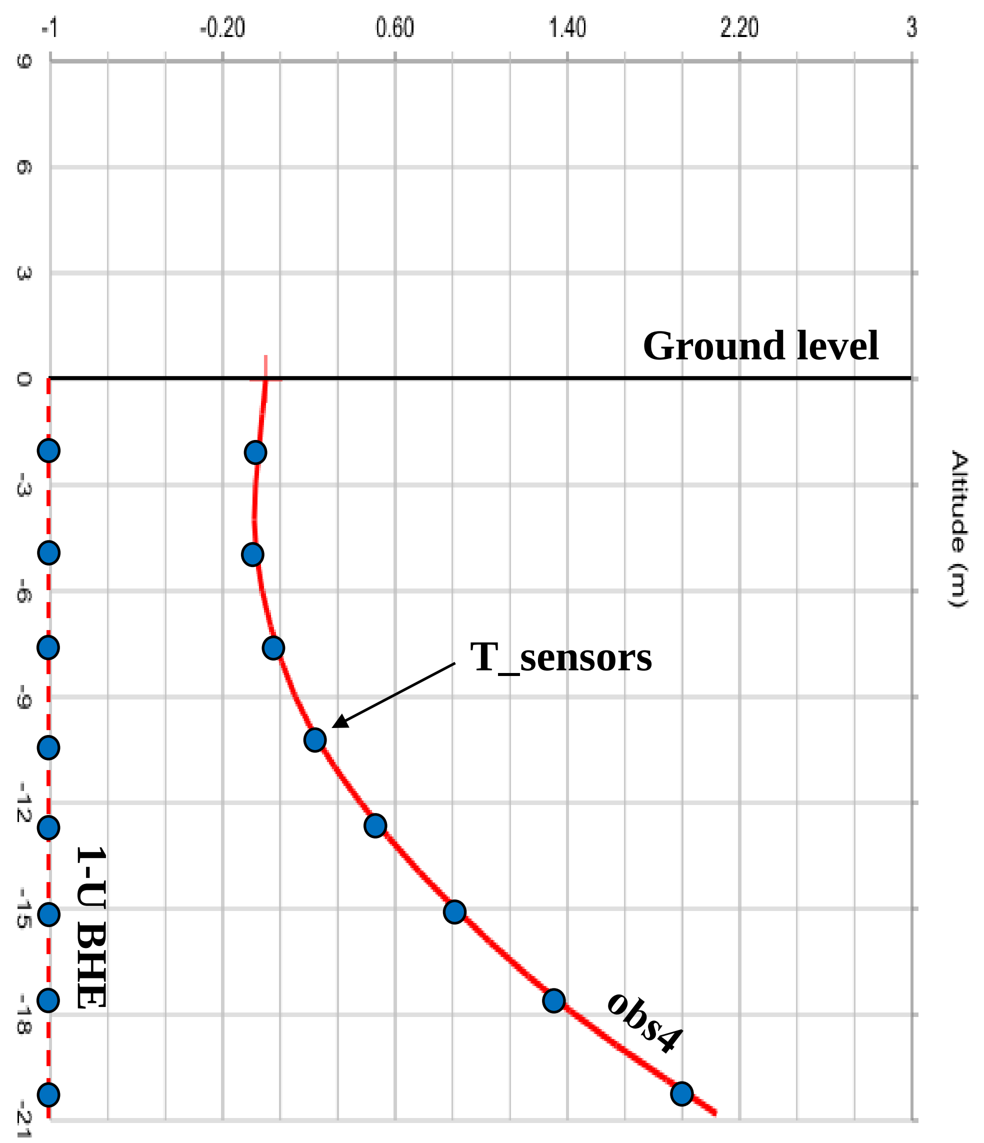


Figure 9 – Location of the BHE, the observation well and the temperature sensors within them down to 21 m.

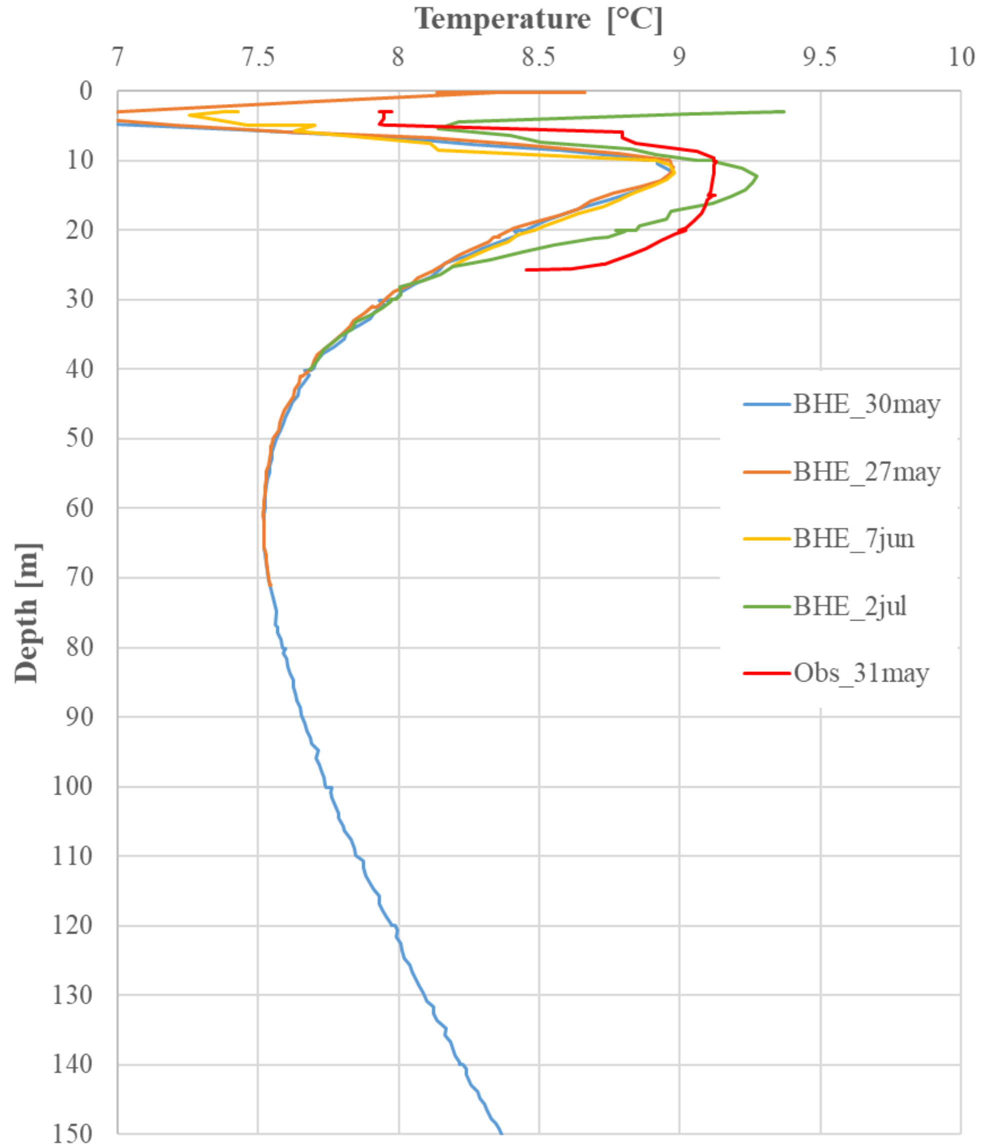


Figure 10 – Temperature profile in the BHE before (27 May) and after the drilling (30 May, 7 June) of the observation well, and after the TRT (2 July). In red the temperature profile made in the observation well few days after the drilling.

4.5 OTRT with a heating cable unit

Two OTRTs were performed with this unit. The first was carried out in the 4-inch and 42-m-deep open well called obs2, from 4 to 11 November 2019. It lasted 96 h with a period of 12 h and an amplitude of 10 W/m (35 to 55 W/m), with a median power rate of 47 W/m along a cable of 45 m, doubled to reach a higher power rate (**Figure 11**). DST Centi temperature sensors by Star ODDI (accuracy 0.1 °C, resolution 0.032 °C) were placed along the heating cable at depths of 5 m, 7.5 m, 10 m, 12.5 m, 15 m, 17.5 m, 20 m, 22.5 m, 25 m, and 27.5 m from the ground level.

The second test was carried out from 11 to 18 June 2020. It lasted 168 h with a period of 12 h and an amplitude of 5 W/m (11 to 21 W/m), with a median power rate of 15 W/m along a cable of 47.8 m (**Figure 12**). DST Centi temperature sensors by Star ODDI (accuracy 0.1 °C, resolution 0.032 °C) were placed along the heating cable at depths of 5 m, 10 m, 15 m, 20 m, 25 m, 30 m, 35 m, 40 m, 45 m, and 50 m from the ground level.

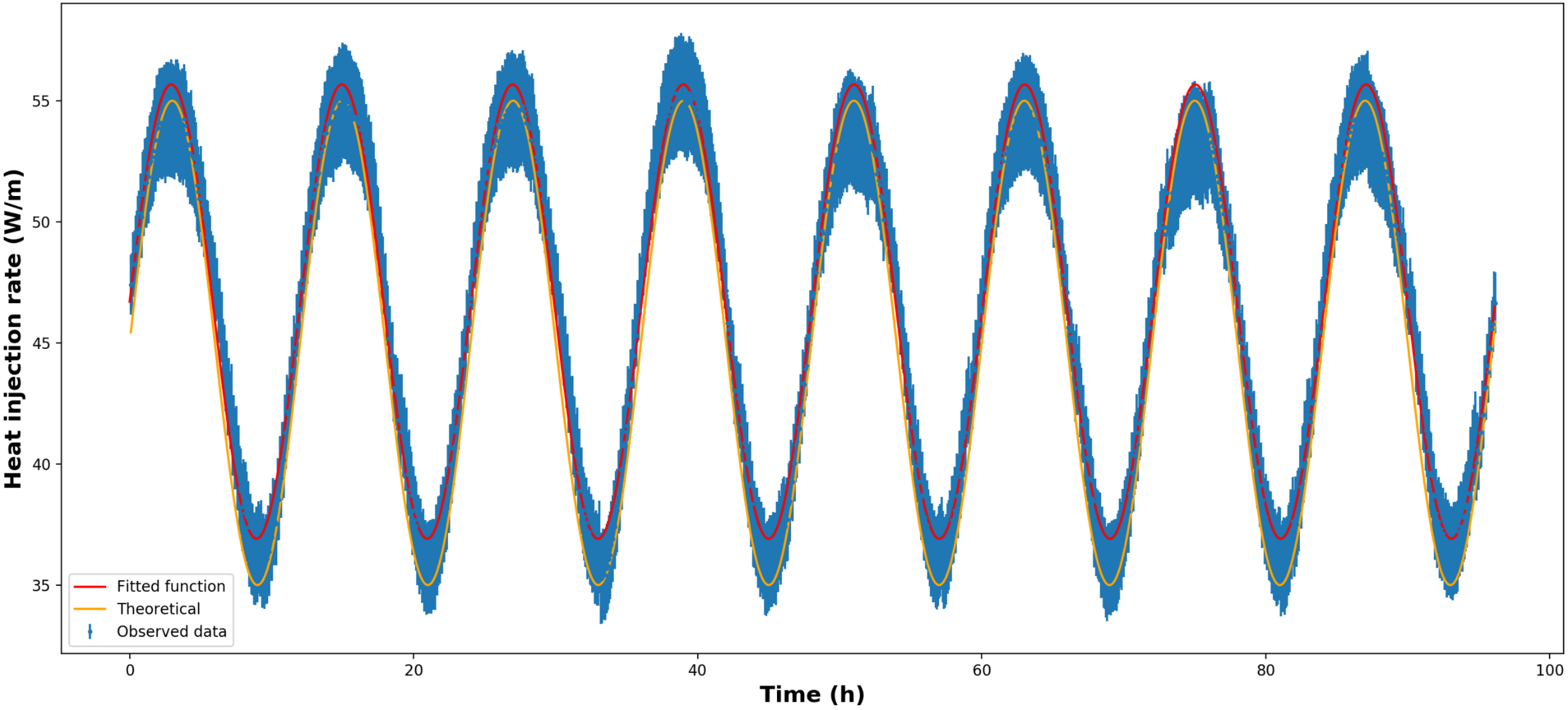


Figure 11 – Heat injection rate of the OTRT with heating cable performed in open well obs2. Comparison among observed data (blue), the mathematical fit following a perfect sinusoidal function (red), and the theoretical power imposed at the power controller.

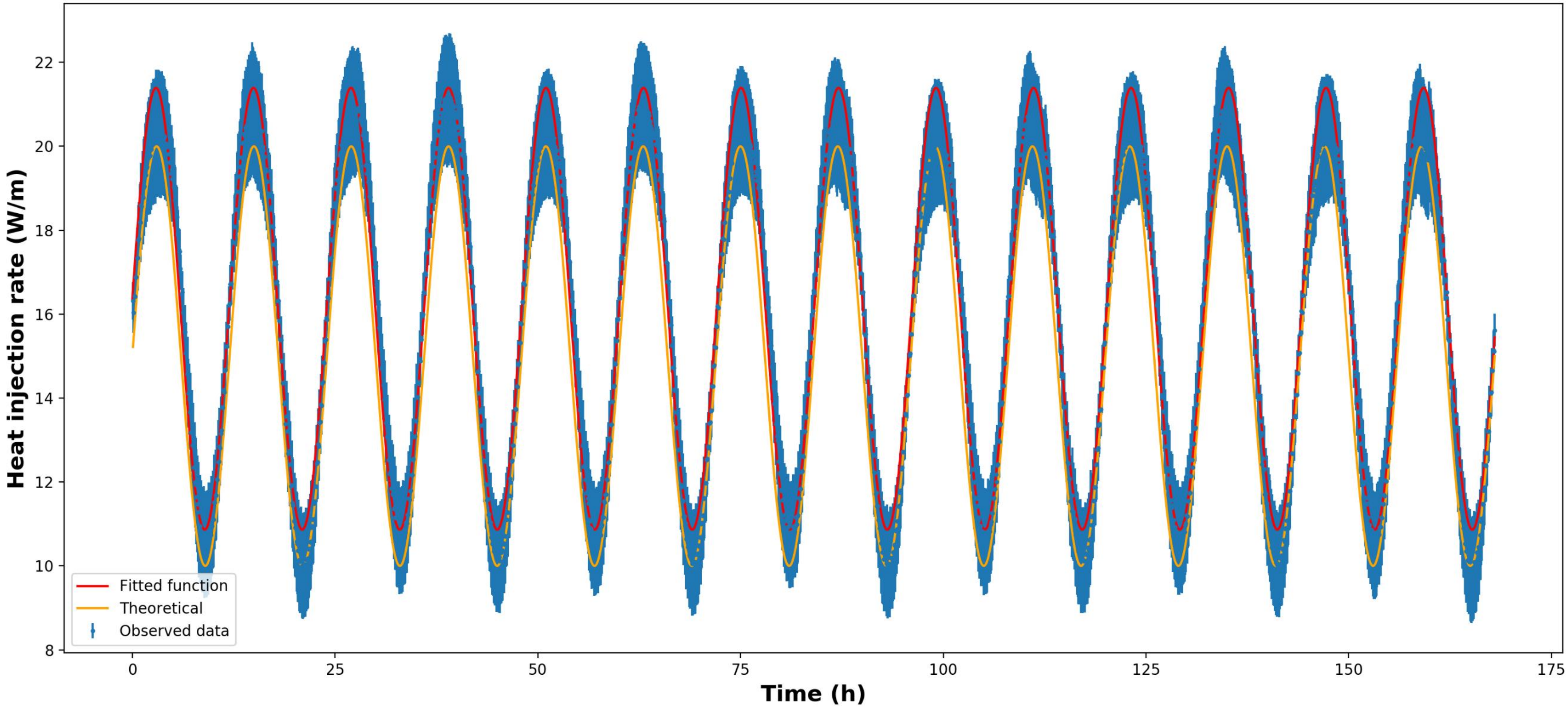


Figure 12 – Heat injection rate of the OTRT with heating cable performed in the BHE. Comparison among observed data (blue), the mathematical fit following a perfect sinusoidal function (red), and the theoretical power imposed at the power controller.

4.6 OTRT with water circulation

The test was carried out from 7 to 13 July 2020 (**Figure 13**). It lasted 147 h, with a period of 12 h and an amplitude of 10 W/m (19-20 to 39 W/m). The flowrate was constant at 6.1 ± 0.03 GPM (0.38 l/s) throughout the entire test. The median power injected was 29 W/m. The instrumentation of the partner Energie-Stat (ES) validly matched our request as shown in **Figure 14**. The equipment of ES is made of a heating element with max power of 7 kW, a flowmeter (0.5 % accuracy) and temperature sensors (0.15 °C accuracy, resolution 0.01 °C) to record the data. Two additional temperature sensors by Star ODDI (Starmon Mini, accuracy 0.1°C, resolution 0.025 °C) were placed by the INRS right at the entrance of the BHE (**Figure 13**).

Figure 13 – Picture of the instrumentation of the partner Energie-Stat.

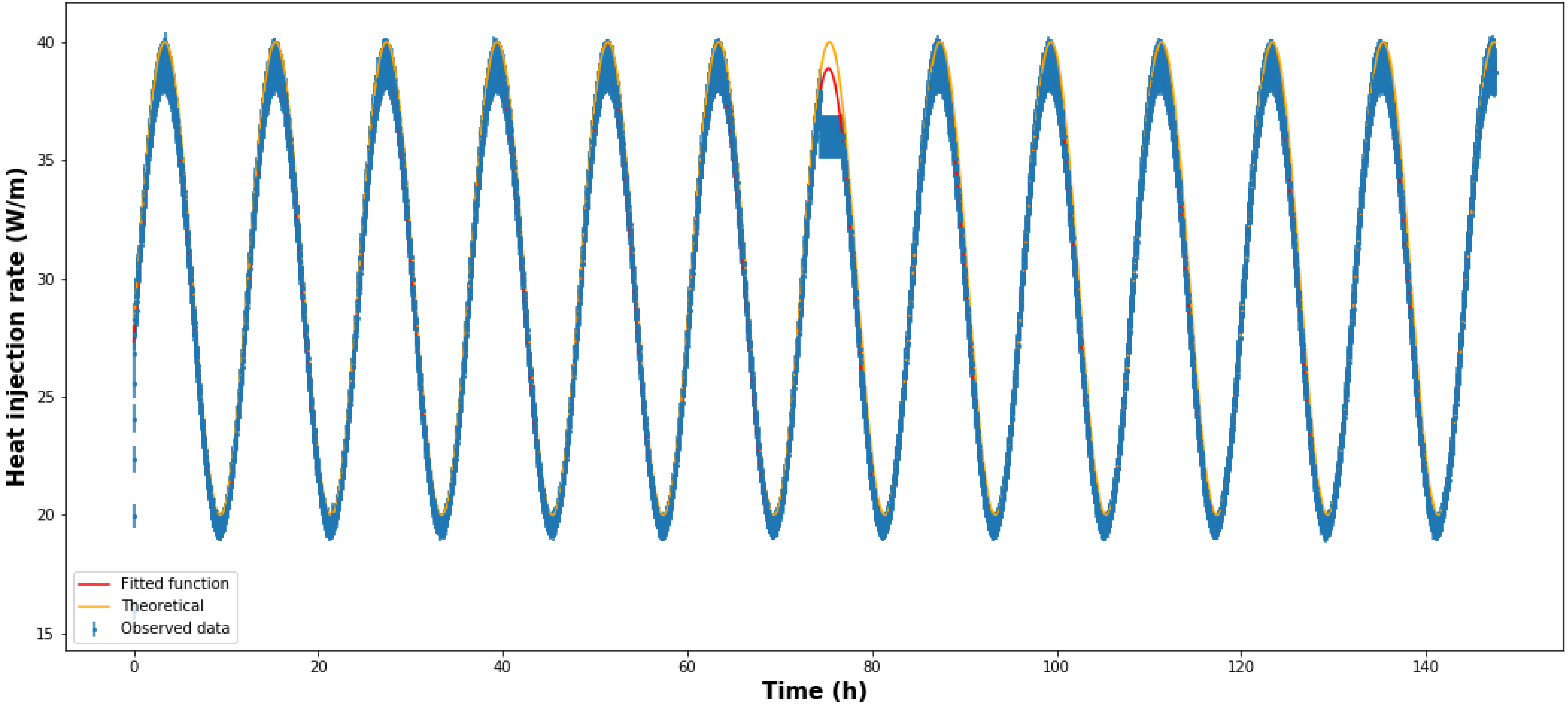


Figure 14 – Heat injection rate of the OTRT with water circulation. Comparison among observed data (blue), the mathematical fit following a perfect sinusoidal function (red), and the theoretical power we asked to Energie-Stat (yellow).

4.7 Numerical simulations

Numerical simulations with FEFLOW (Diersch, 2014) were carried out to simulate the OTRT and compare the results with the experimental observations (**Appendix F**). Both 2-D and 3-D models were built, and different heat transport boundary conditions (BC) were used in different scenarios while changing the heat capacity of the subsurface.

In particular, 4 different scenarios with HC of 1.5, 2.0, 2.5, 3.0 MJ/m^{3}K, named SC1, SC2, SC3, and SC4, respectively. The following model simulations were run:

- 3-D model and BHE tool with both numerical Al Khoury et al. (2005) solution and analytical Eskilson and Claesson (1988);
- 3-D model and BHE tool by setting the heat injection in [W];
- 3-D model and BHE tool by setting the inlet temperature in [°C];
- 2-D model with 4th type BC in [W].

Figure 15 shows a detail of the mesh and the material properties input nearby and inside the BHE for the 2-D model, made of 2000 triangular elements to discretize a 100 x 100 m subsurface volume. The time discretization follows an automatic scheme to minimize the errors and reach the convergence.

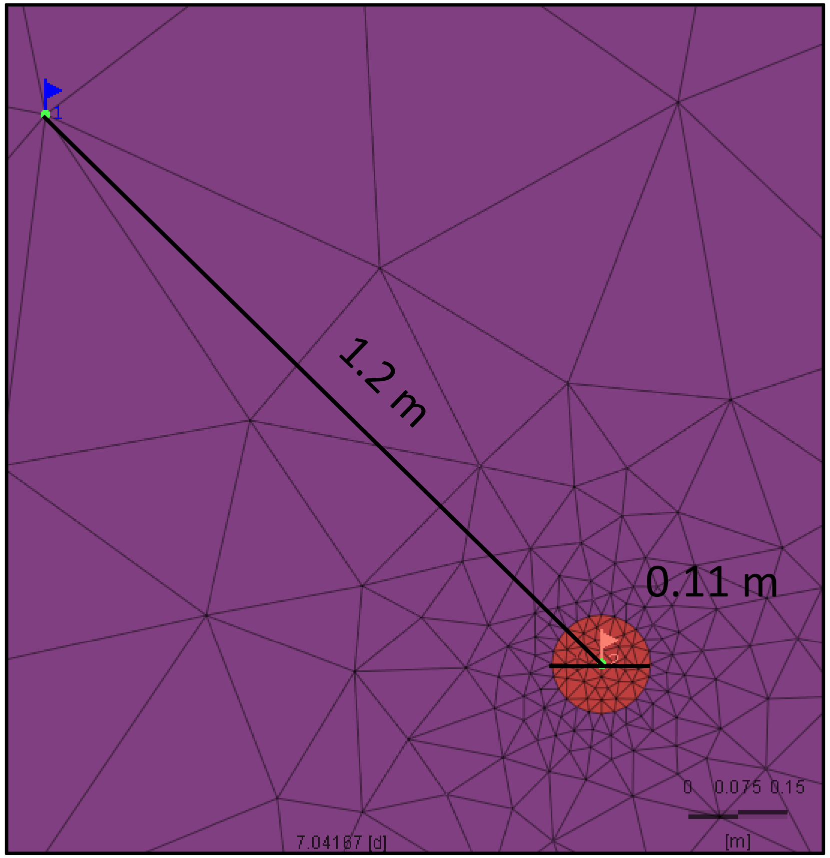
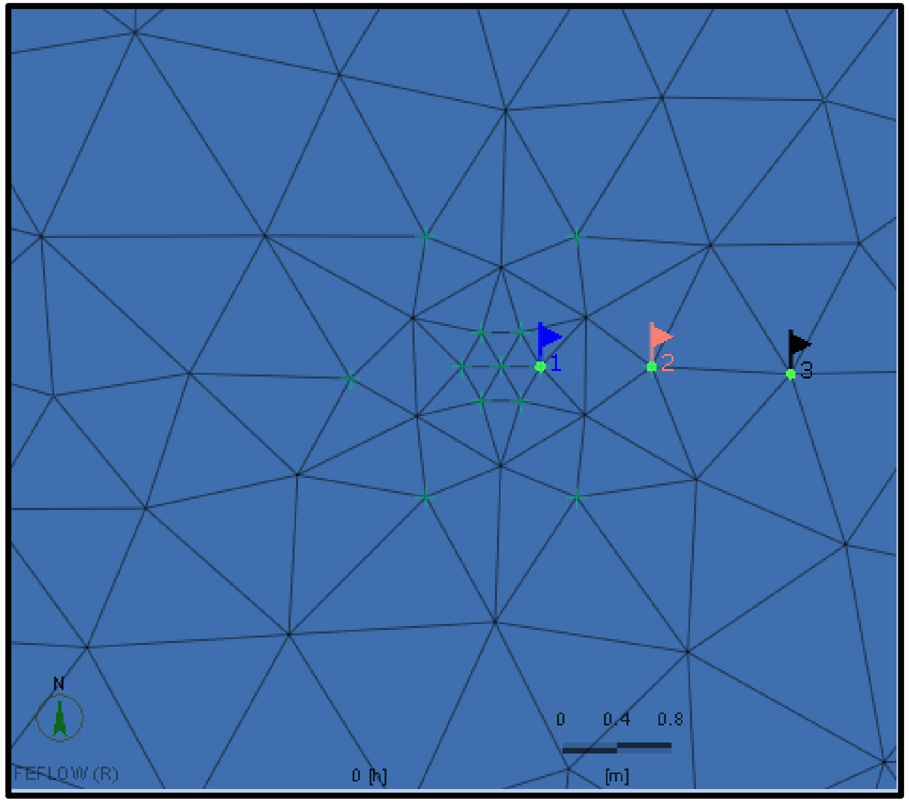


Figure 15 – Details of the mesh and material property selection of the 2-D model. The subsurface is represented in purple and assumes the HC mentioned above; the grout of the BHE is represented in red. The observation well at 1.2 m distance from the BHE has been modelled as an observation point.



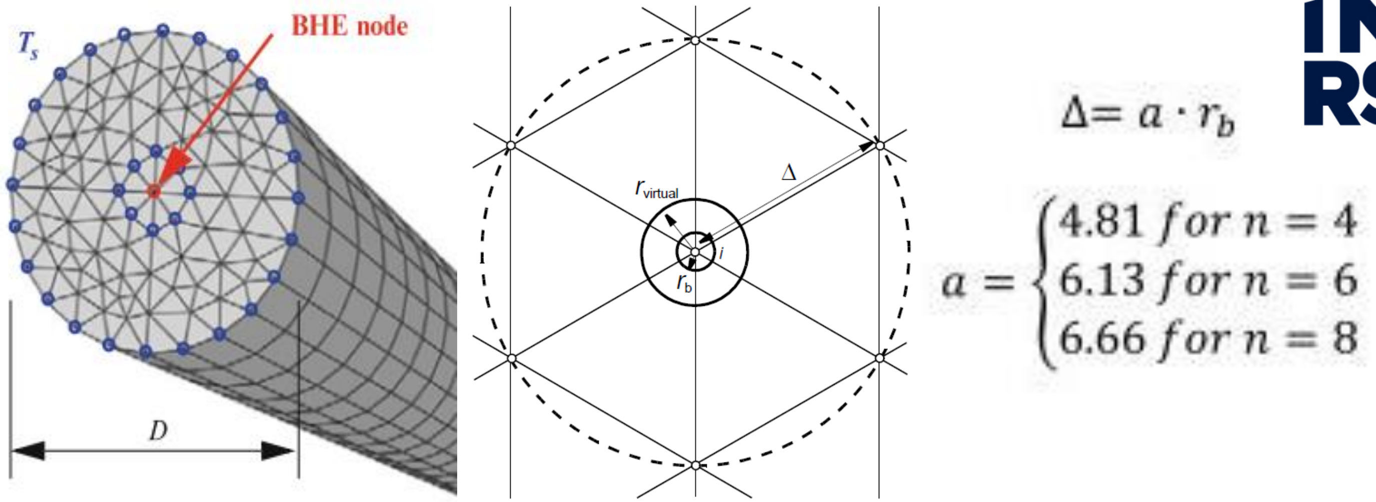
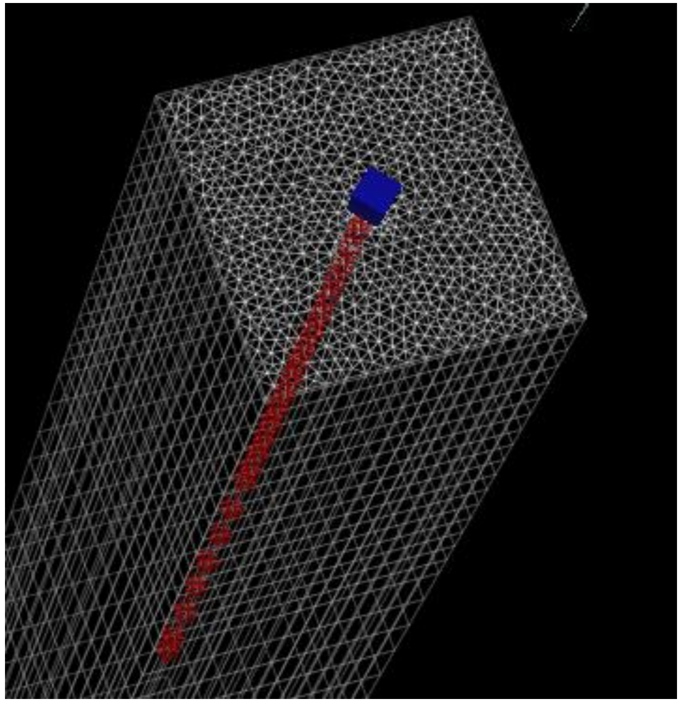


Figure 17 – Critical radius and mesh refinement criteria for BHE (modified from Diersch et al., 2011)

Figure 16 – Details of the mesh of the 3-D model.

Figure 18 – Details of the 3-D mesh of the model, the BHE is highlighted in red.



The 3-D model has 66,600 triangular prismatic elements (details in **Figure 16**) to discretize a 100 x 100 x 350 m subsurface volume. The mesh refinement respects the critical radius described by Diersch et al. (2011) in order to account for the real size of the BHE and ensure numerical stability (**Figure 17**). Indeed, the BHE is assigned to the element edge and is simulated as a linear element (1-D) immersed in the 3-D mesh (**Figure 18**), and solved analytically (Eskilson and Claesson, 1988) or numerically (Al Khoury et al., 2005). The time discretization follows an automatic scheme to minimize the errors and reach the convergence.

5. RESULTS

5.1 Conventional TRT with a heating cable unit

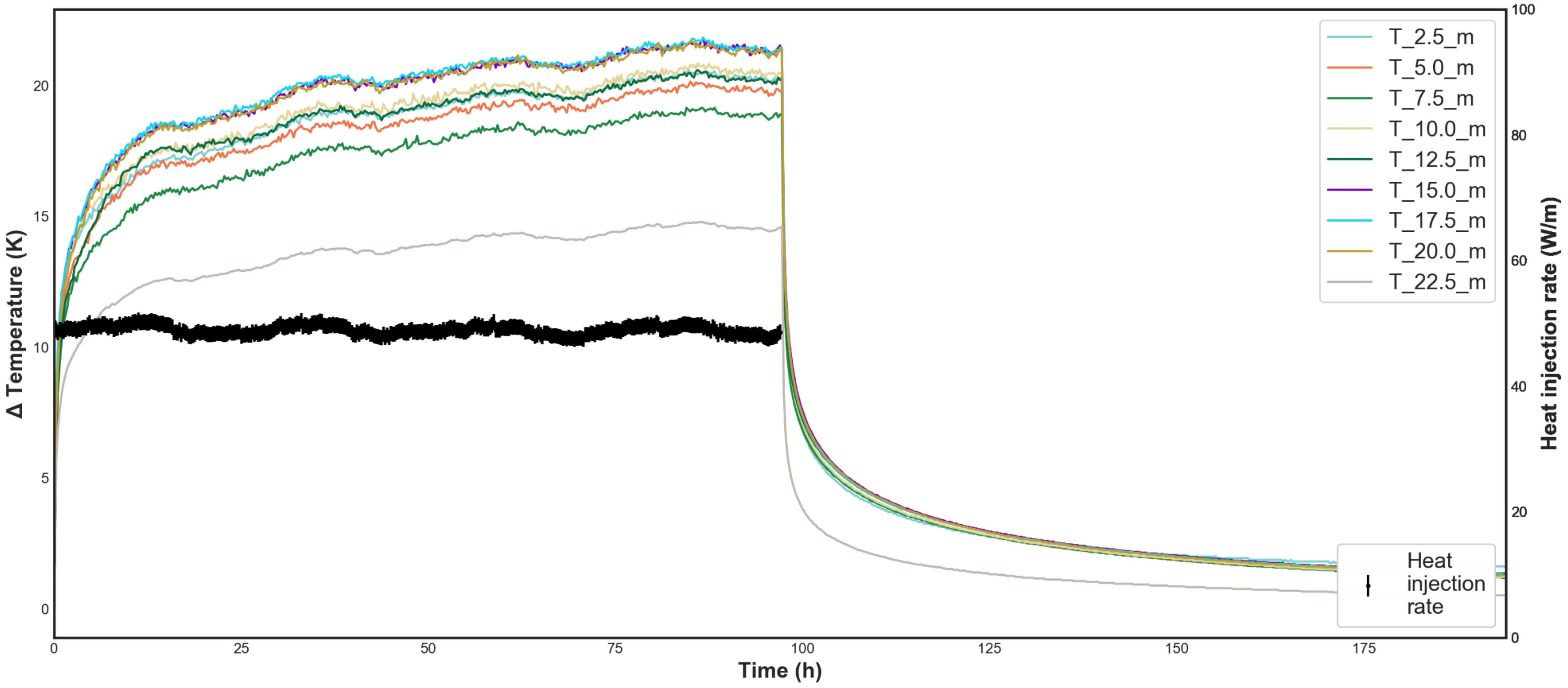


Figure 19 – Results of the conventional TRT with heating cable in the 1-U BHE.

The conventional TRT (**Figure 19**) was carried out to evaluate the subsurface thermal diffusivity via the temperature signal recorded in the observation well obs4. First the thermal conductivity was evaluated by both the heating and recovery period via the slope method. R_b was also estimated with the heating period (**Table 1**). The recovery period is more reliable because there isn't any effect of R_b, that in the heating cable method is particularly noisy. This is due to the fact that the source of heating (cable) is placed in one of the BHE pipes and thus its position in the hole unknown. Indeed, the R_b values are in the order of 0.2 mK/W, while the expected one is 0.09 (Ballard et al., 2016), and thermal conductivity is higher than expected (2.2-2.3 W/mK). The slope analysis of the recovery period outputs thermal conductivity of 1.8-2.0 W/mK (**Figure 20**), which is in the range of previous TRTs with water circulation at 1.75 W/mK (Ballard et al., 2016). Differences can be related to the shorter length investigated by this study (22.5 m), while water circulation TRTs investigate the whole length (154 m). Heating cable TRT can however give information about the heterogeneity of the stratigraphy. There is indeed a slight but clear difference in the first 10 m (λ > 1.95) compared to deeper portions (λ < 1.95), reflecting the local stratigraphy (**Figure 3**, cross section). First and last sensors do not give reliable results due to violation of line source assumptions and possible occurrence of convection cells.

Table 1 – Thermal conductivity and borehole thermal resistance deduced from the heating (left) and recovery (right) periods.

Depth (m)	λ (W/m/K)	λ err (%)	R_b (mK/W)	R_b err (%)
2.5	2.153	2.51	0.221	3.58
5	2.317	2.52	0.222	3.59
7.5	2.234	2.52	0.198	3.58
10	2.238	2.51	0.231	3.58
12.5	2.431	2.51	0.238	3.58
15	2.217	2.51	0.248	3.58
17.5	2.264	2.51	0.253	3.58
20	2.212	2.52	0.247	3.58
22.5	3.236	2.52	0.16	3.59

Depth (m)	λ (W/m/K)	λ err (%)
2.5	2.258	2.519
5	1.969	2.524
7.5	2.002	2.52
10	1.968	2.518
12.5	1.927	2.518
15	1.859	2.518
17.5	1.911	2.519
20	1.862	2.519
22.5	3.583	2.523

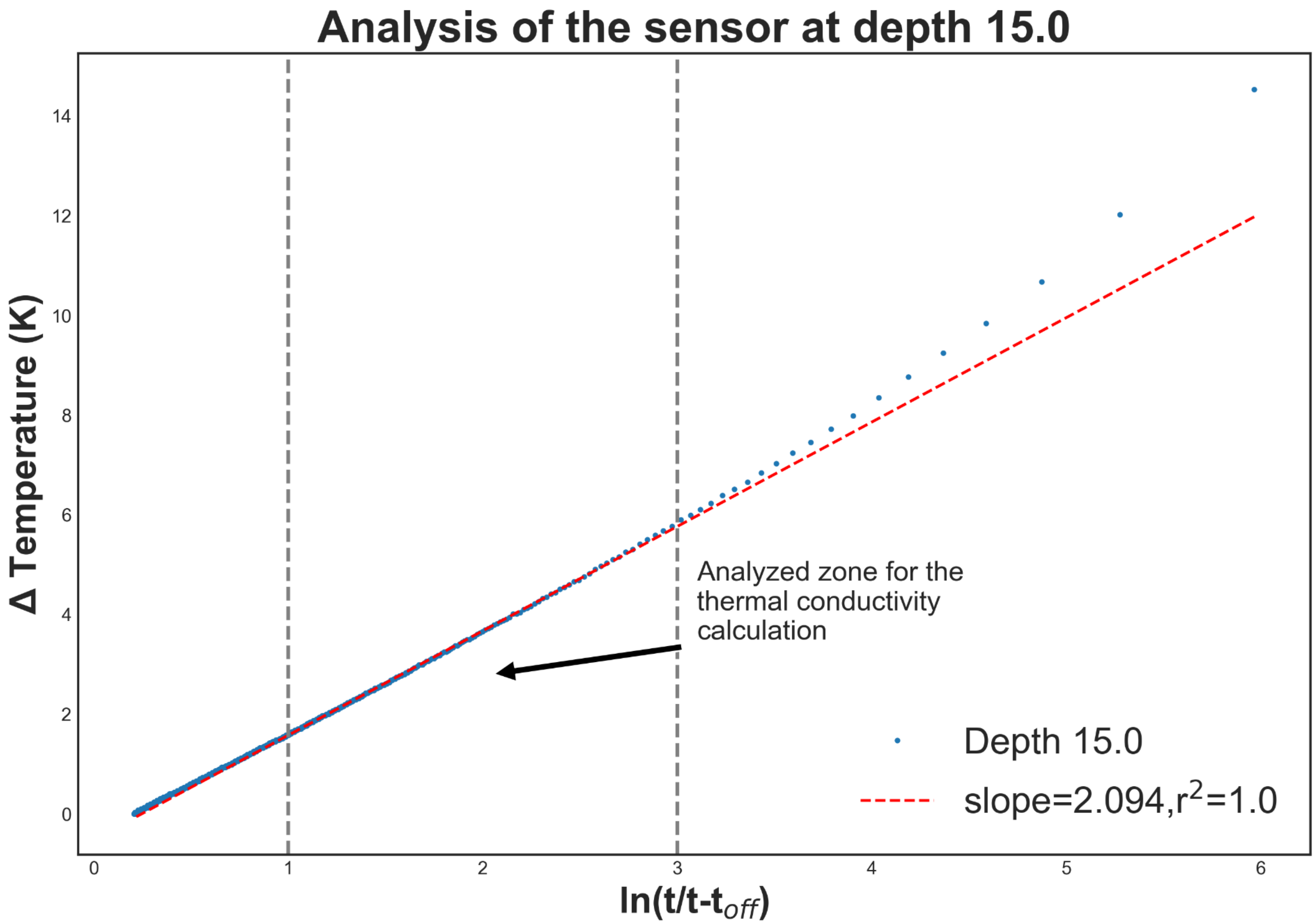


Figure 20 – Recovery period analysis for thermal conductivity estimation.

The thermal response recorded in the observation well was very low, with a maximum variation of 0.6 °C, but clear enough to analyse the data (**Figure 21**). Temperature recordings clearly represent the inclination of the well, with the signal getting smoother and smoother with increasing depth. Sensors below 15 m do not display a valid thermal response.

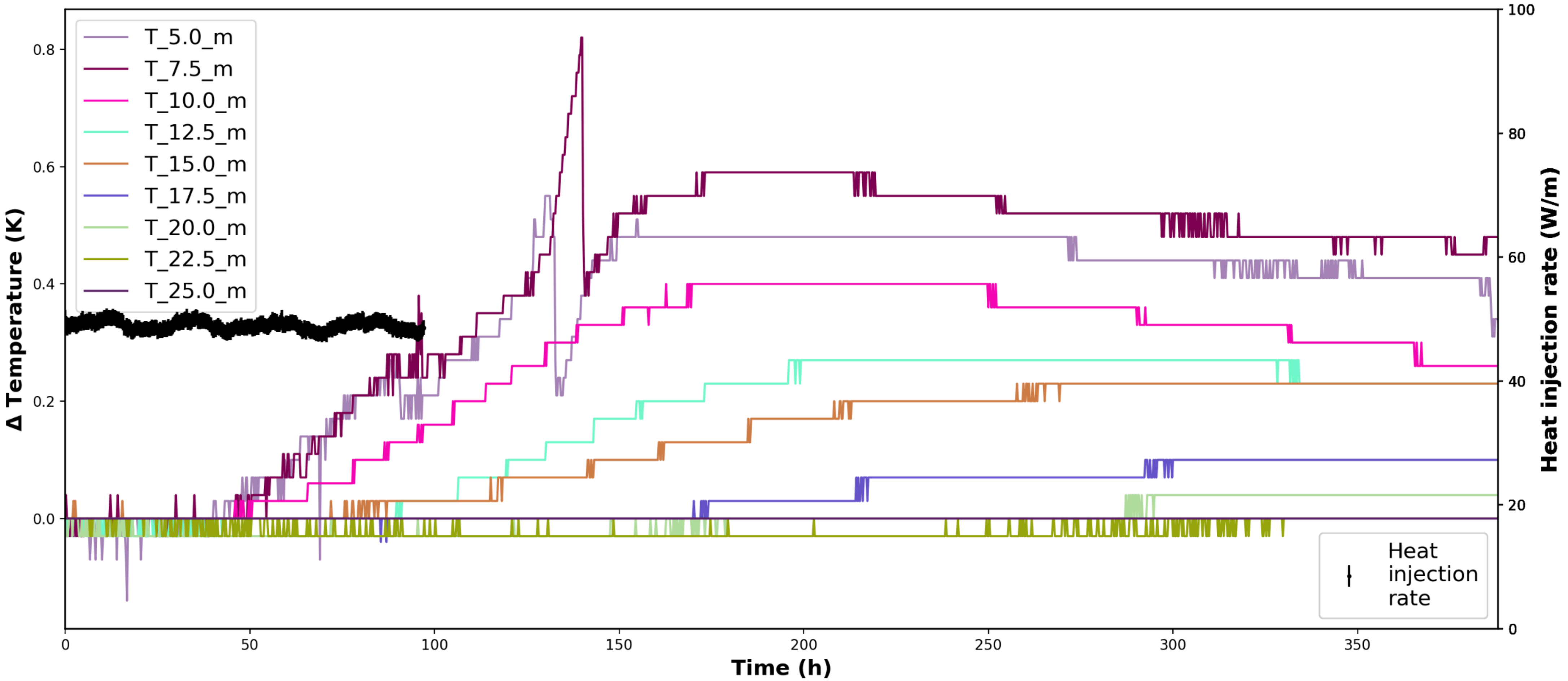


Figure 21 – Temperature response in the observation well obs4. The black line shows the duration and magnitude of the power injection, same as in Figure 17.

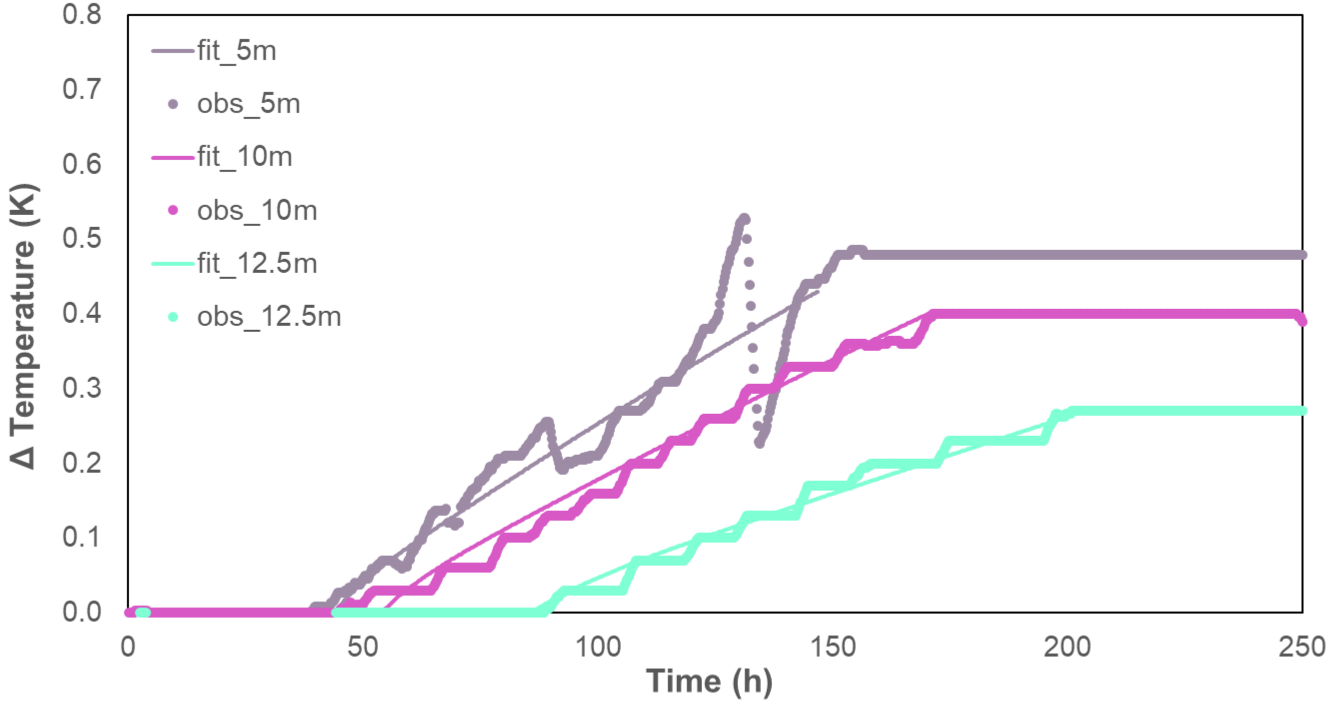


Figure 22 – Thermal response analysis fit in the observation well obs4.

Table 2 – Thermal conductivity and diffusivity values used to match the observed data shown in Figure 20

Depth (m)	5.0	10.0	12.5
r (m)	1.2	1.3	1.6
λ (W/mK)	4.0	4.0	4.0
α (mm2/s)	1.10	1.05	1.00

Table 3 – Heat capacity values

Depth (m)	5.0	10.0	12.5
r (m)	1.2	1.3	1.6
λ (W/mK)	1.969	1.968	1.927
α (mm2/s)	1.10	1.05	1.00
Cv (MJ/m3K)	1.79	1.87	1.93

Sensors at 5, 10 and 12.5 m were analysed to evaluate the thermal diffusivity (**Figure 22**). The pumping tests concept and superposition principles proposed by Raymond et al. (2011) were adopted. The observed data were manually matched with λ and α values reported in **Table 2**. Thermal conductivity is very high (4.0): this is due to a weak thermal response (0.5 °C magnitude) and maybe some influence of heat advection in the subsurface and within the well. Thermal diffusivity values are similar (1.0 - 1.1 mm^2/s) and the differences in the thermal response are therefore related only to the inclination of the observation well, i.e. the distance *r* (m). By applying the thermal conductivity obtained through the previous analysis, we therefore found the heat capacity at the analysed depths being ca. 1.8-1.9 MJ/m^3K (**Table 3**). The error of the estimation is expected to be within 5-10 %, without considering heterogeneity in the subsurface between the wells.

5.2 OTRT with a heating cable unit

Results of the OTRT in the open well are reported in **Figure 23** with a zoom in **Figure 24**. The analysis is shown in **Figure 25** with the values reported in **Tables 3, 4** and **5**. The results of the analysis are compared with a forward model of the analytical solution. R_p and ϕ_p are calculated via the Equations [5] and [6] with the expected subsurface thermal properties. This helps us to evaluate how far is the experimental estimation (inverse model) from the analytical solution (forward model).

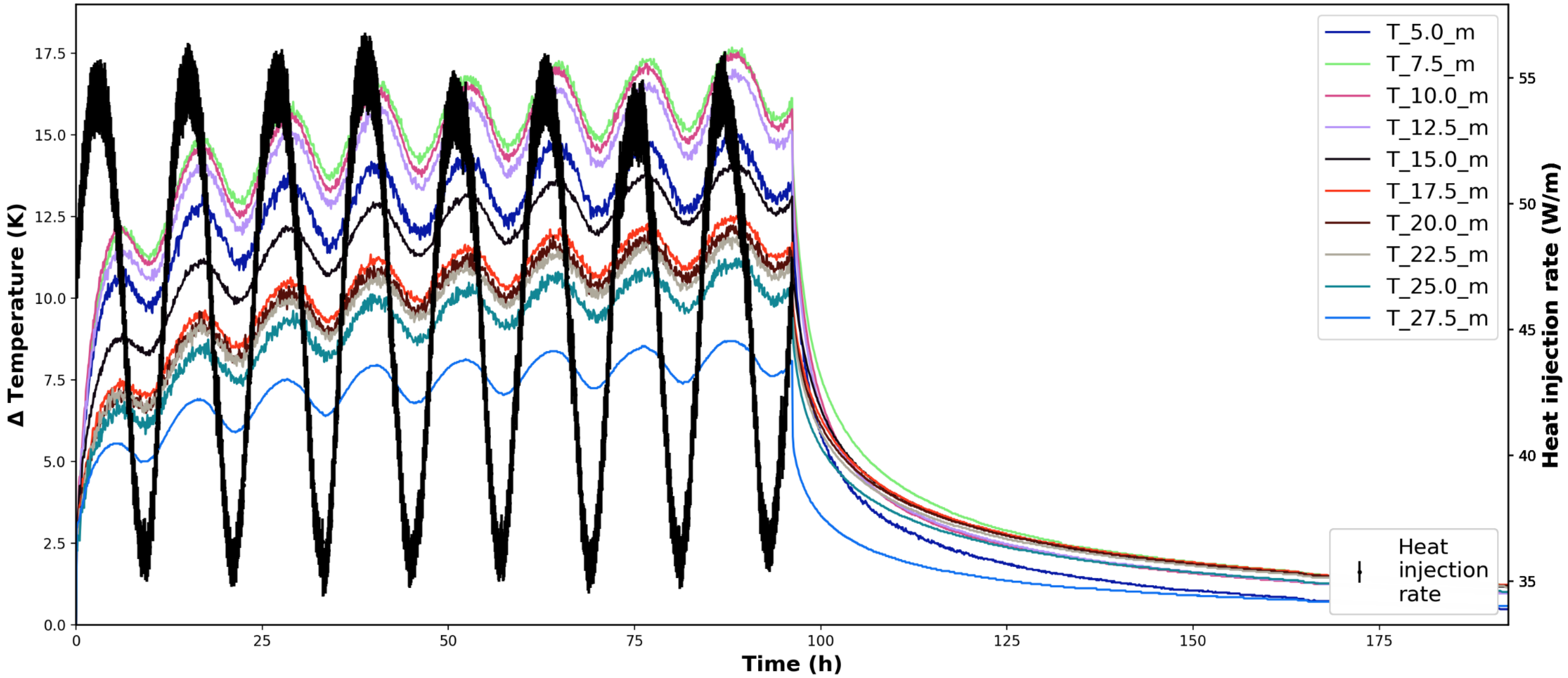


Figure 23 – Results of the OTRT in the open well obs2

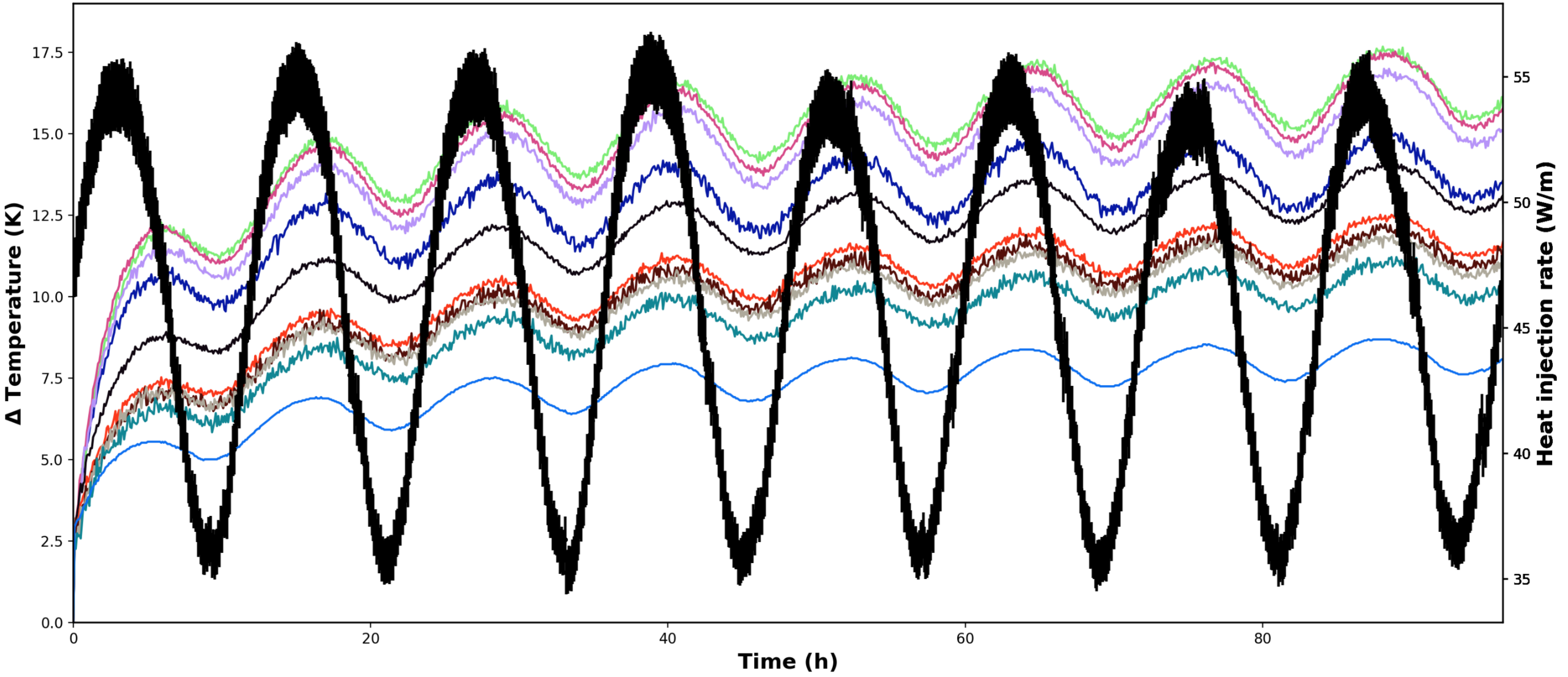


Figure 24 – Zoom of Figure 23, the colors are the same.

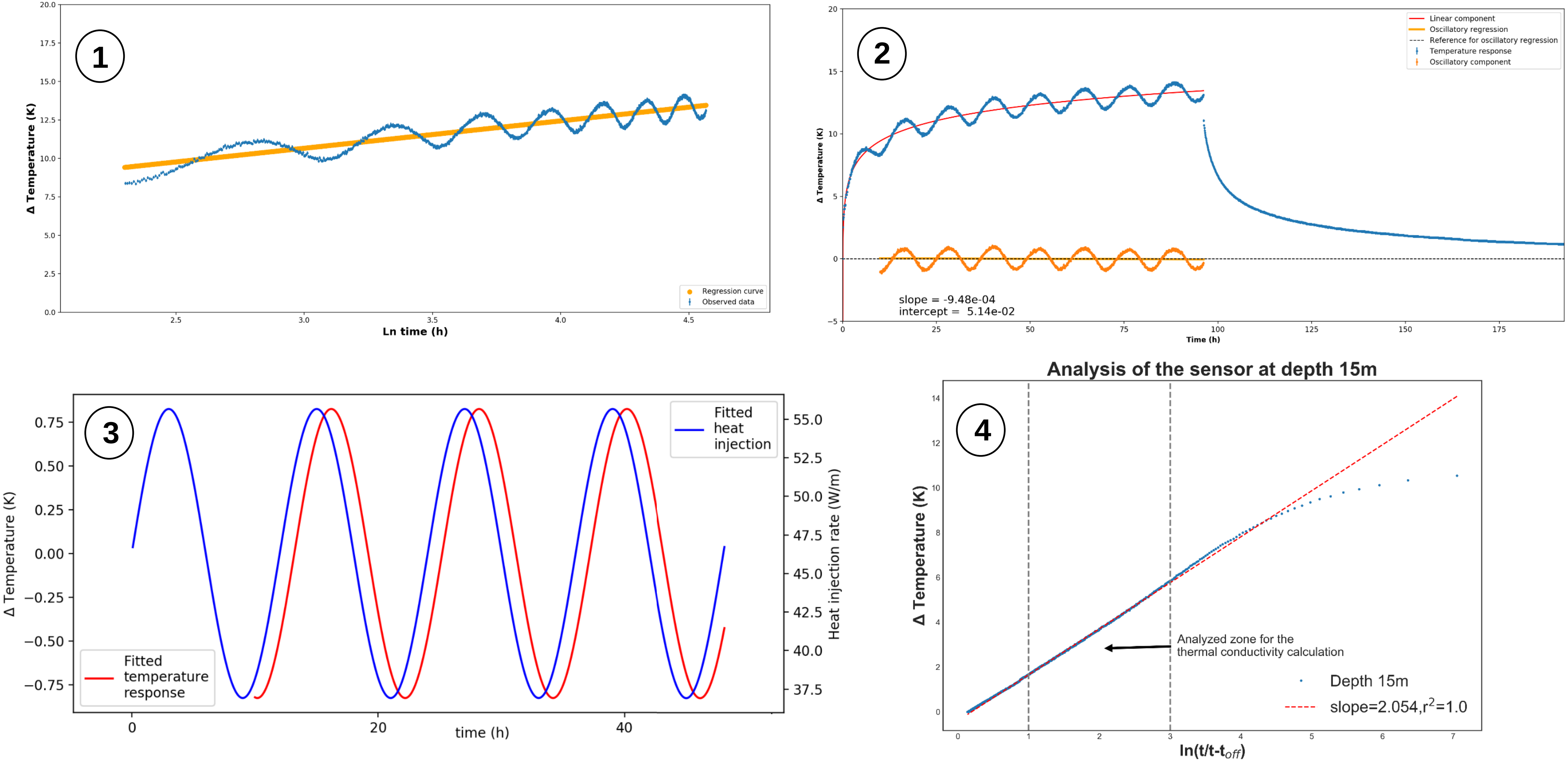


Figure 25 – OTRT analysis of the test in the open well obs2. Example from sensor placed at a depth of 15 m. Figure 3 is cut at ca. 50 h.

The results show R_p values decreasing with depth from 0.12-0.13 to 0.07 mK/W and ϕ_p decrasing from 0.11 to 0.09 (**Table 3**). By doing a forward analysis with thermal properties expected from the subsurface («an GROUND» with λ 1.9 W/mK and Cv 1.9 MJ/m^{3}K, r_{pb} 0.6), R_p and ϕ_p should be 0.083 and 0.145. Important to note the accuracy of the fit, that returns α values with 3-8 % error from the expected 1 mm^2/s (**Table 5**). The values we find from the OTRT are affected by a high variability which in turn is reflected on the final results of thermal diffusivity. Finally, the expected α is not correctly estimated by the OTRT.

Table 3 – OTRT analysis of the test in the open well obs2

Depth (m)	Rp (mK/W)	Rp err (%)	ϕp (-)	ϕp err (%)
5	0.113	3.26	0.113	1.49
7.5	0.123	3.25	0.117	1.34
10	0.132	3.26	0.109	1.36
12.5	0.127	3.27	0.115	1.32
15	0.088	3.30	0.099	2.10
17.5	0.074	3.34	0.093	2.64
20	0.071	3.54	0.089	2.86
22.5	0.071	3.38	0.091	2.80
25	0.07	3.49	0.093	2.77
27.5	0.065	3.37	0.062	4.43
an GROUND	0.083	0.29	0.144	0.76

Table 4 – Thermal conductivity results from recovery period

Depth (m)	λ (W/m/K)	λ err (%)
5	1.835	2.67
7.5	1.513	2.69
10	1.706	2.71
12.5	1.753	2.72
15	1.786	2.72
17.5	1.834	2.73
20	1.904	2.73
22.5	1.984	2.74
25	2.123	2.75
27.5	3.373	2.78

Table 5 – Thermal diffusivity from Eq. 8 (R_p) and Eq. 9 (ϕ_p)

Depth (m)	α_Rp (mm2/s)	α err (%)	α_ϕp (mm2/s)	α err (%)
5	2.398	4.22	1.867	1.49
7.5	1.694	4.22	1.706	1.34
10	3.131	4.24	2.058	1.36
12.5	3.026	4.26	1.752	1.32
15	0.989	4.27	2.627	2.10
17.5	0.578	4.31	3.223	2.64
20	0.580	4.47	3.707	2.86
22.5	0.657	4.35	3.361	2.80
25	0.824	4.44	3.206	2.77
27.5	2.814	4.37	13.346	4.43
an GROUND	0.919	0.29	1.028	0.76

Results of the OTRT in the BHE are reported in **Figure 26** with a zoom in **Figure 27**. The analysis is shown in **Figure 28** with the values reported in **Tables 6, 7** and **8**.

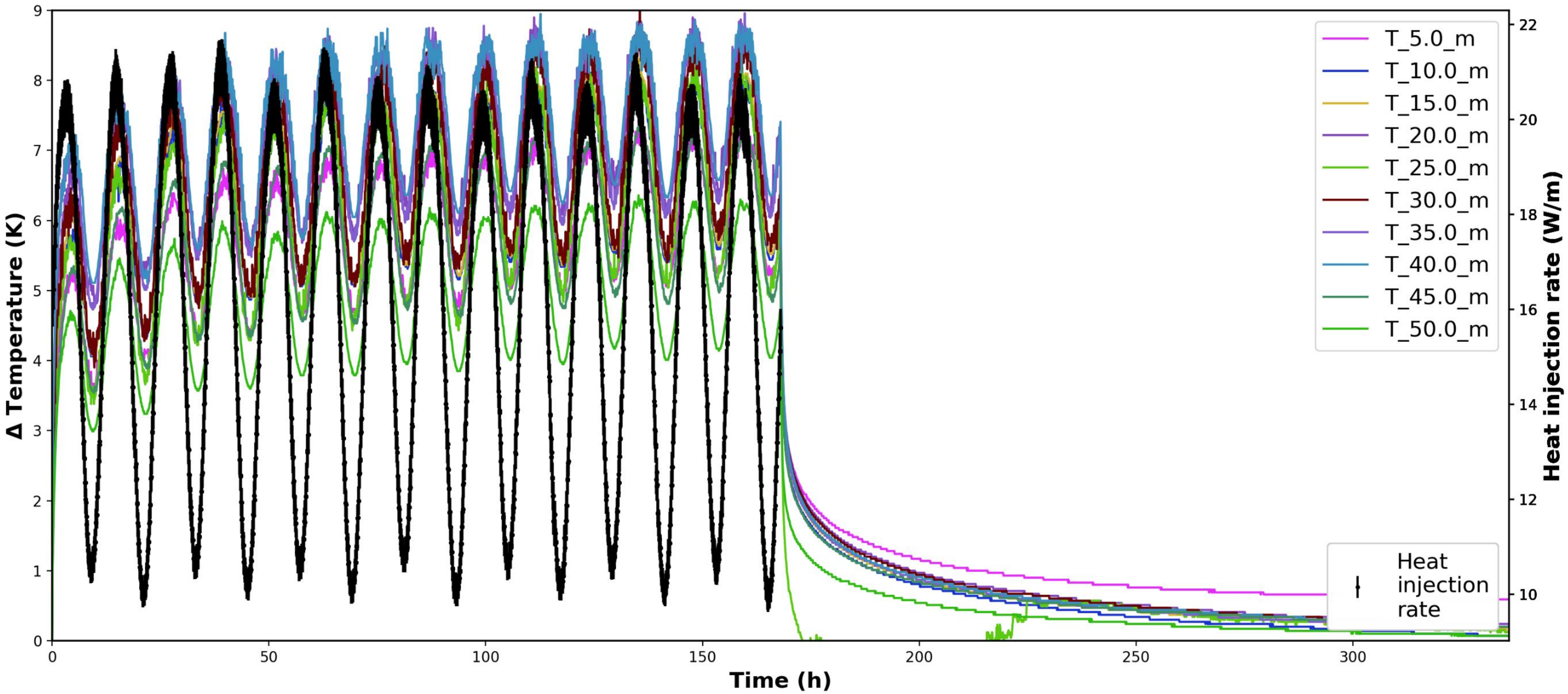


Figure 26 – OTRT analysis of the test in the BHE

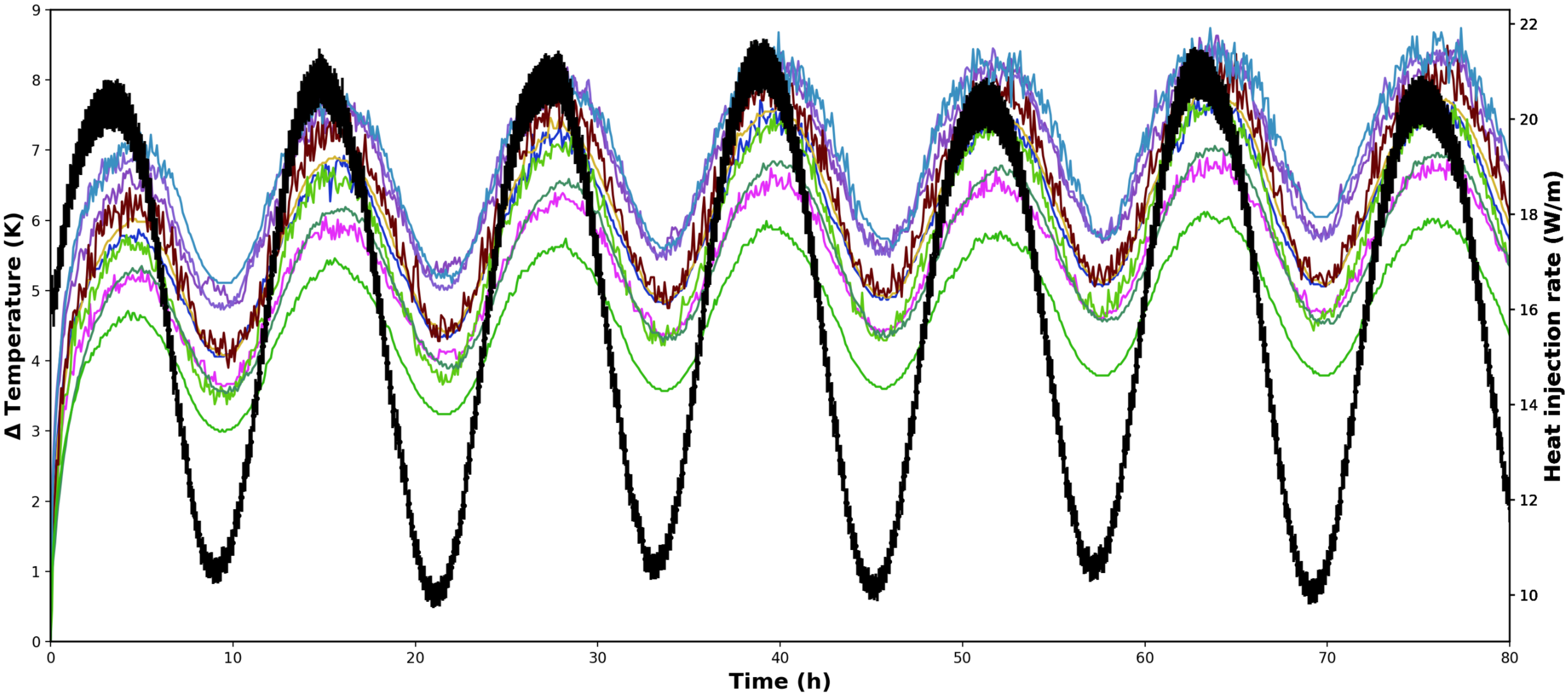


Figure 27 – Zoom of Figure 26, the colors are the same.

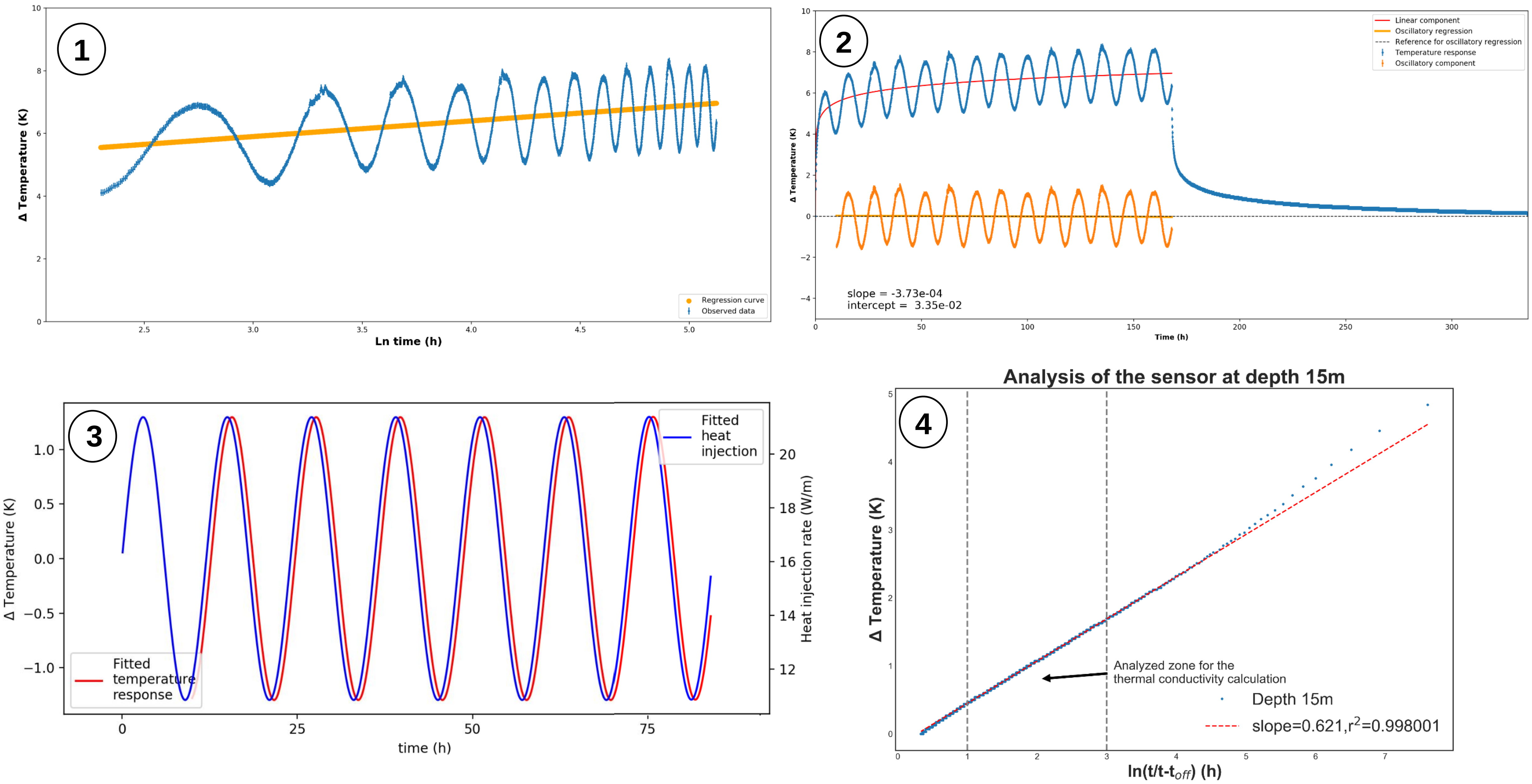


Figure 28 – OTRT analysis of the test in the BHE. Example from sensor placed at a depth of 15 m. Figure 3 is cut at ca. 80 h.

The results show R_p values of 0.22-0.27 mK/W and ϕ_p rather constant at 0.05, with only one outlier at 0.07 at 45 m (**Table 6**). A forward analysis with thermal properties expected from the subsurface (as before, r_{pb} 0.2) and the grout («an GROUT» with λ 1.5 W/mK and *Cv* 3.9 MJ/m^{3}K, r_{pb} 0.3) was also carried out. R_p and ϕ_p should be 0.162 and 0.167, and 0.067 and 0.087 for the ground and the grout, respectively. Important to note the deviation of the fit, that returns α values with 2-3 % difference from the expected 1 and 0.38 mm^2/s (**Table 8**). The variability along the depth seems related to the local stratigraphy, but, finally, the expected α is not correctly estimated by the OTRT.

Table 6 – OTRT analysis of the test in the BHE

Depth (m)	Rp (mK/W)	Rp err (%)	ϕp (-)	ϕp err (%)
5	0.194	3.55	0.053	2.44
10	0.234	3.45	0.052	2.15
15	0.246	3.44	0.056	1.93
20	0.228	3.49	0.058	1.96
25	0.279	3.87	0.047	2.17
30	0.271	3.73	0.054	1.90
35	0.239	3.55	0.047	2.37
40	0.220	3.68	0.054	2.18
45	0.226	3.47	0.072	1.59
50	0.209	3.49	0.049	2.46
an GROUND	0.162	0.20	0.067	1.05
an GROUT	0.160	0.21	0.087	0.82

Table 7 – Thermal conductivity results from recovery period

Depth (m)	λ (W/m/K)	λ err (%)
5	2.275	2.81
10	2.02	2.74
15	2.038	2.73
20	1.954	2.74
25	-1.937	2.9
30	1.993	2.76
35	2.05	2.77
40	2.047	2.78
45	2.278	2.79
50	2.964	2.8

Table 8 – Thermal diffusivity from Eq. 8 (R_p) and Eq. 9 (ϕ_p)

Depth (m)	α_Rp (mm2/s)	α err (%)	α_ϕp (mm2/s)	α err (%)
5	6.037	3.60	2.896	3.60
10	9.045	3.50	2.988	3.50
15	13.231	3.49	2.076	3.49
20	6.423	3.54	1.767	3.54
25	21.614	3.92	5.461	3.92
30	21.954	3.78	2.556	3.78
35	11.437	3.60	5.398	3.60
40	6.730	3.73	2.587	3.73
45	15.660	3.52	0.740	3.52
50	59.272	3.54	3.971	3.54
an GROUND	1.018	0.20	0.981	1.05
an GROUT	0.373	0.21	0.384	0.82

5.3 OTRT with water circulation

Results of the OTRT are reported in **Figure 29** with a zoom in **Figure 30**. The analysis is shown in **Figure 31** with the values reported in **Tables 9, 10** and **11**.

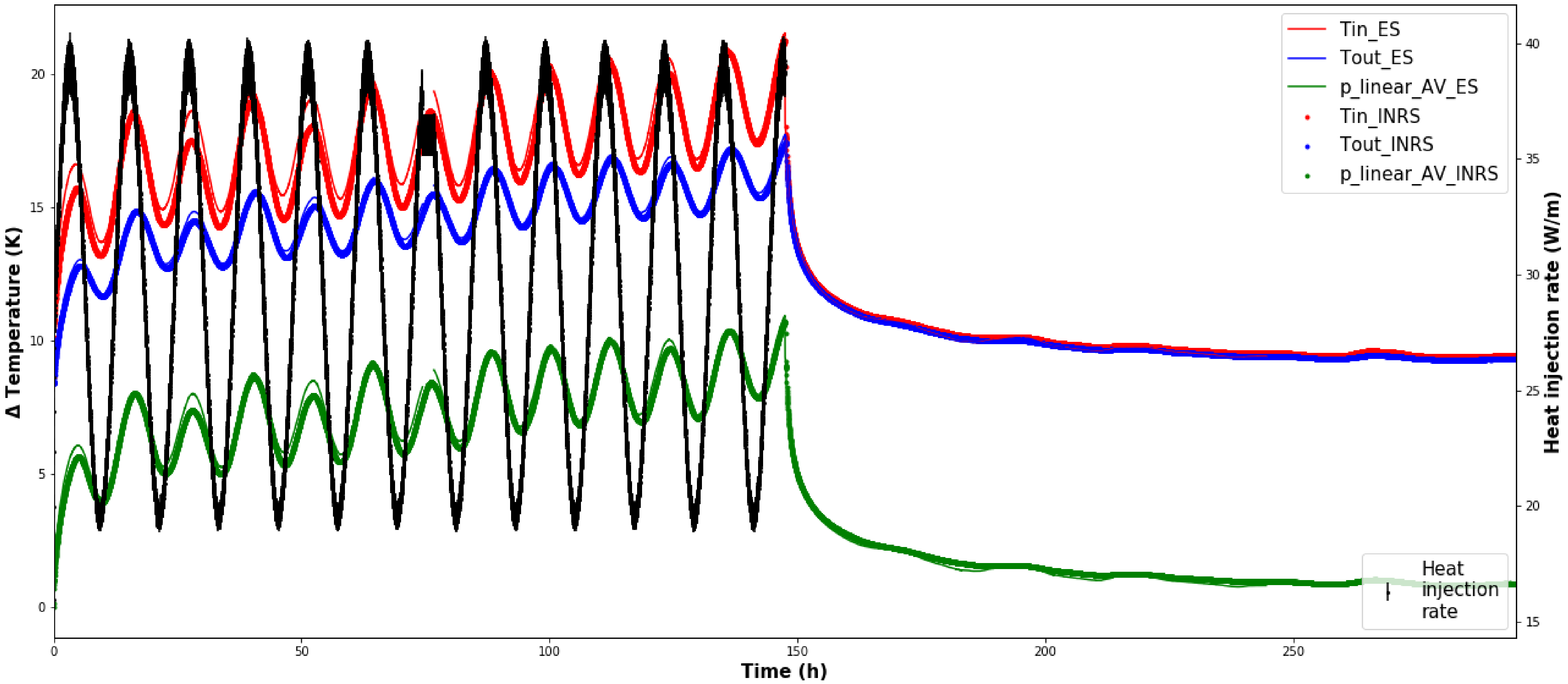


Figure 29 – OTRT analysis of the test with water circulation

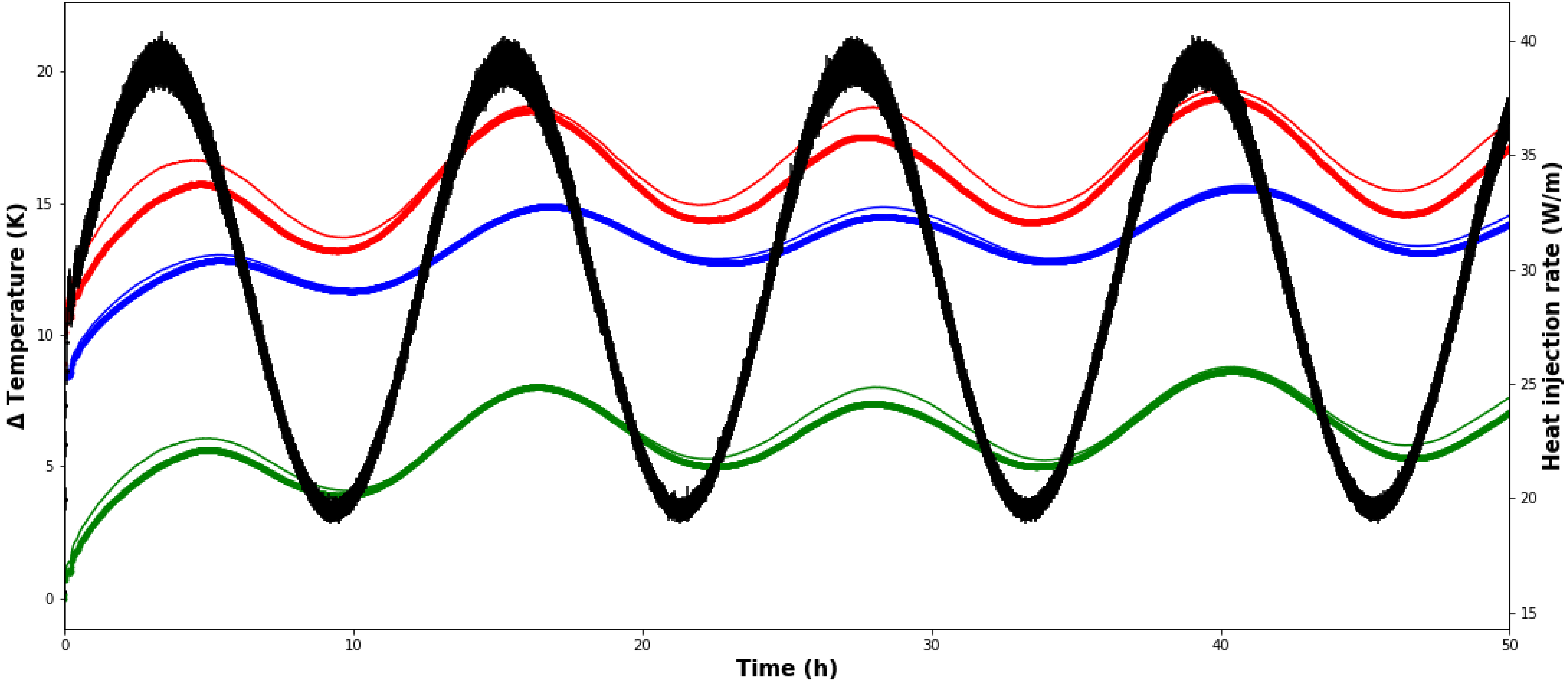


Figure 30 – Zoom of Figure 29, the colors are the same.

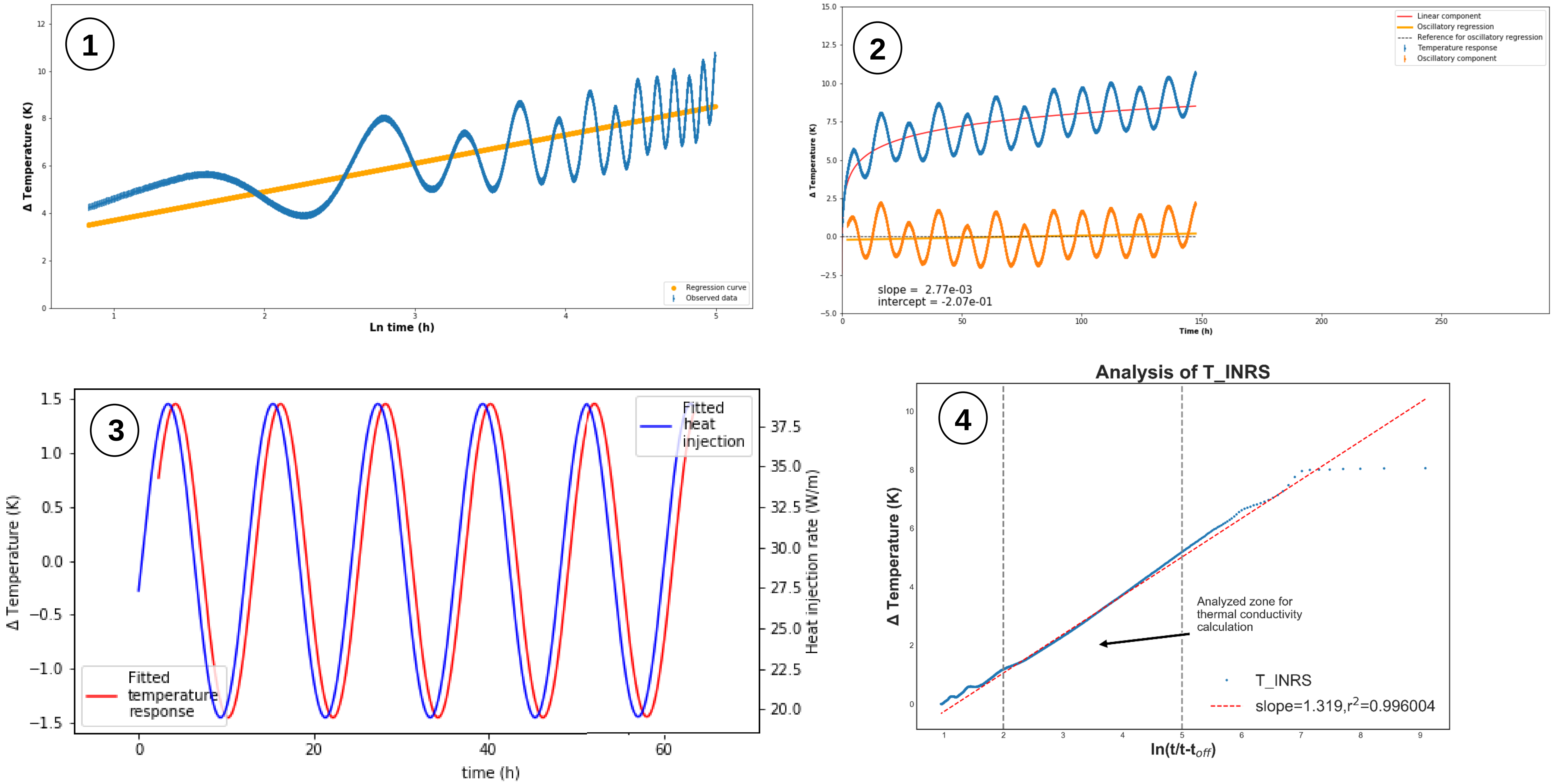


Figure 31 – OTRT analysis of the test with water circulation. Example from INRS sensors. Figure 3 is cut at ca. 60 h.

The p-linear average (with p = -0.99999) was used to analyse the data, because it better represents the profile along the BHE as described and proposed by Marcotte and Pasquier (2008). The thermal conductivity from the recovery period is very close to the one found in the previous conventional TRTs performed on the same BHE (**Table 9**). Ballard et al. (2016) indeed found 1.7-1.75 W/mK. However, the borehole thermal resistance is far smaller, with 0.06 and 0.05 according to ES and INRS sensors, respectively. Ballard et al. (2016) evaluated R_b at 0.09 mK/W, which seems reliable for a 1-U BHE.

The oscillatory results show R_p values of 0.151 mK/W and ϕ_p of 0.1, without any clear difference between ES and INRS couple of sensors (**Table 10**). A forward analysis with thermal properties expected from the subsurface (properties as before, r_{pb} 0.7) and the grout (properties as before, r_{pb} 0.7) was also carried out. R_p and ϕ_p should be 0.078 and 0.083, and 0.161 and 0.247 for the ground and the grout, respectively.

Important to note the deviation of the fit, that returns α values with 1-12% difference from the expected 1 and 0.38 mm^2/s, except for the grout, whose α_R_p has 40 % difference (**Table 11**).

Table 9 – Thermal conductivity results from recovery period

	λ (W/mK)	**λ err (%)**	**Rb (mK/W)**	**Rb err (%)**
ES	1.702	2.69	0.063	5.2
INRS	1.762	2.69	0.047	5.3

Table 10 – OTRT analysis of the test

	Rp (mK/W)	**Rp err (%)**	**ϕ*p* (-)**	**ϕ*p* err (%)**
ES	0.151	6.03	0.109	0.76
INRS	0.150	14.04	0.103	0.80
an GROUND	0.077	0.21	0.162	0.40
an GROUT	0.083	0.22	0.251	0.25

Table 11 – Thermal diffusivity from Eq. 8 (R_p) and Eq. 9 (ϕ_p)

	α_Rp (mm2/s)	**α err (%)**	**α_ϕ*p* (mm2/s)**	**α err (%)**
ES	6.334	6.60	2.564	2.80
INRS	7.041	14.29	2.977	2.81
an GROUND	1.123	0.21	0.994	0.40
an GROUT	0.544	0.22	0.372	0.25

5.4 Numerical simulations

Results of the numerical simulations were compared to the observed data shown in (**Section 5.3**). Results are reported in **Figure 32** with a zoom in **Figure 33**. The analysis is shown in **Figure 34** with the values reported in **Tables 12, 13,** and **14**.

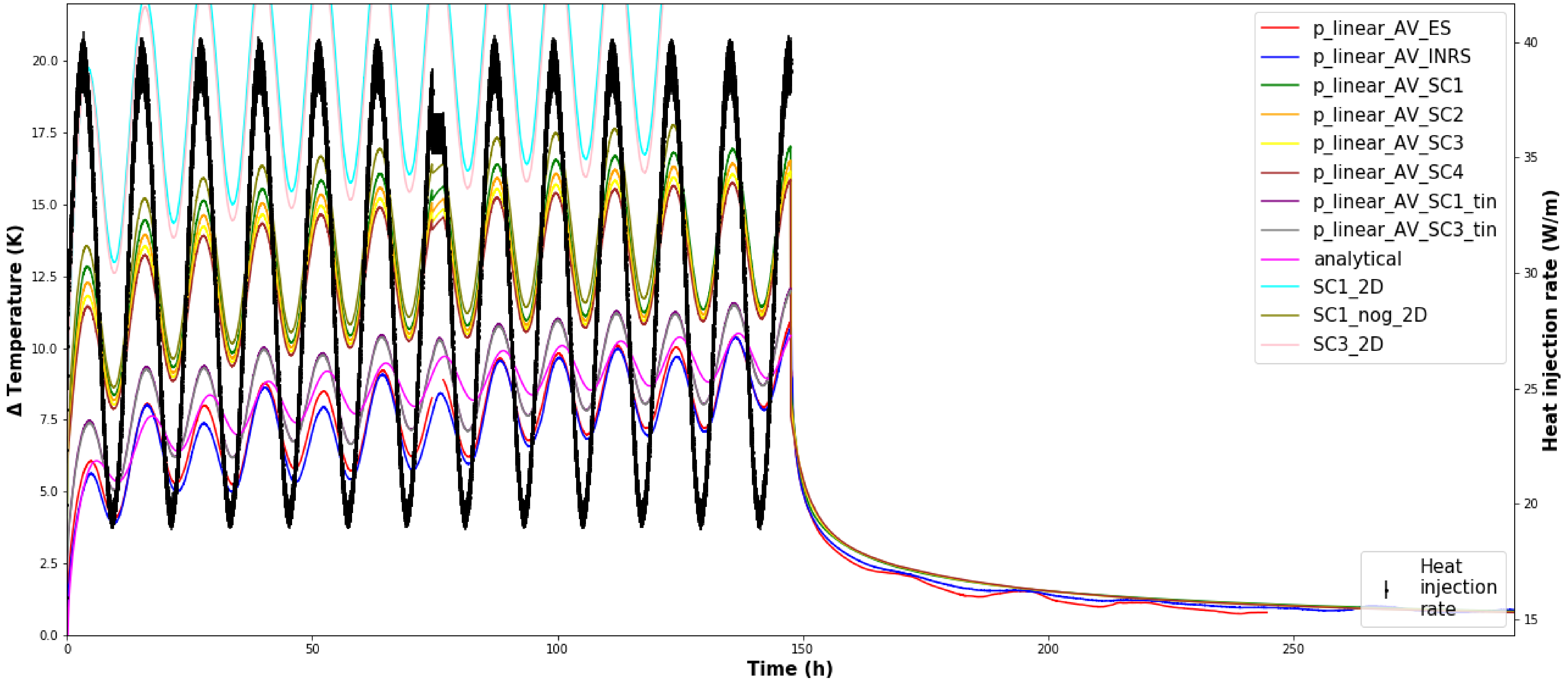


Figure 32 – OTRT numerical simulations compared to experimental water circulation OTRT.

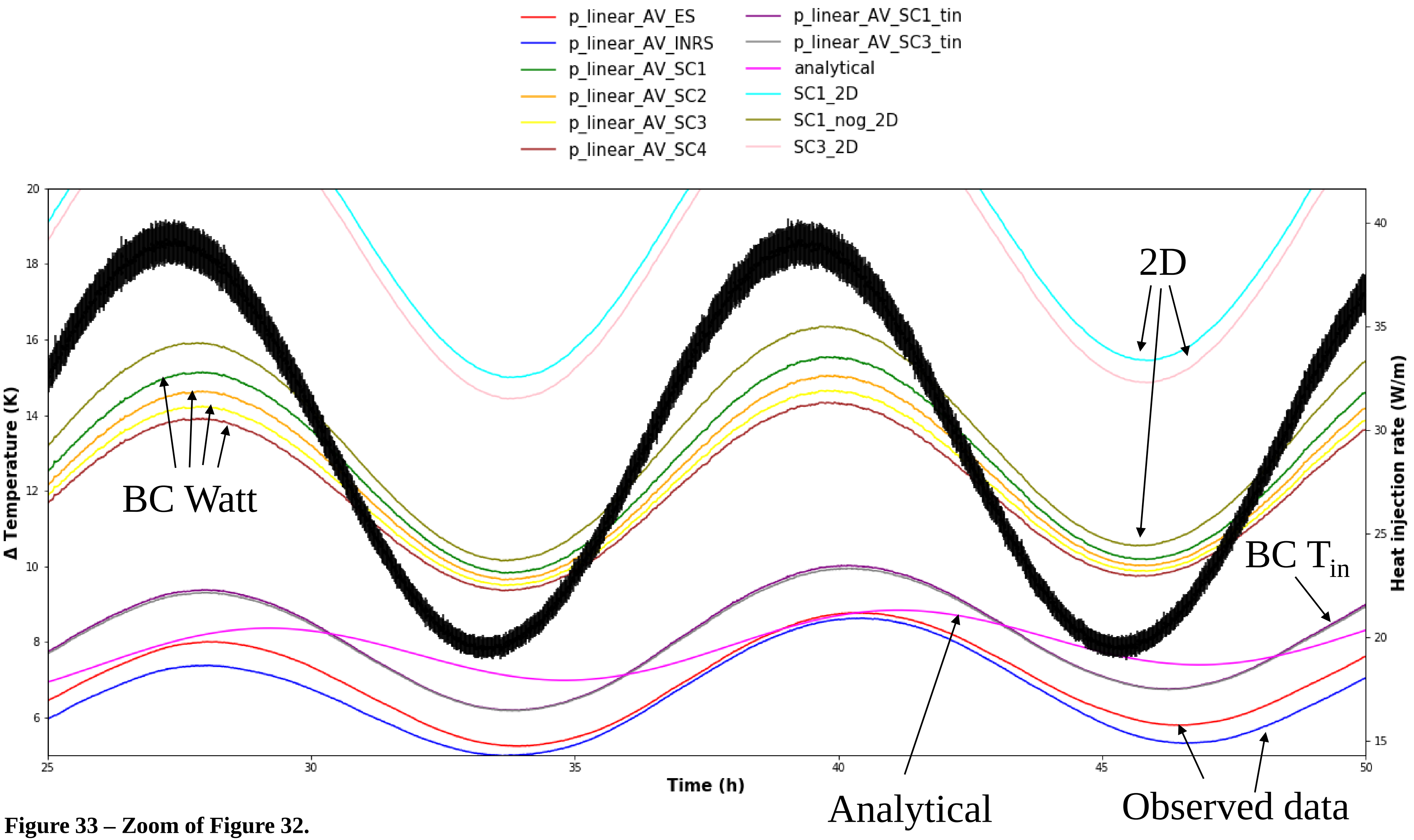


Figure 33 – Zoom of Figure 32.

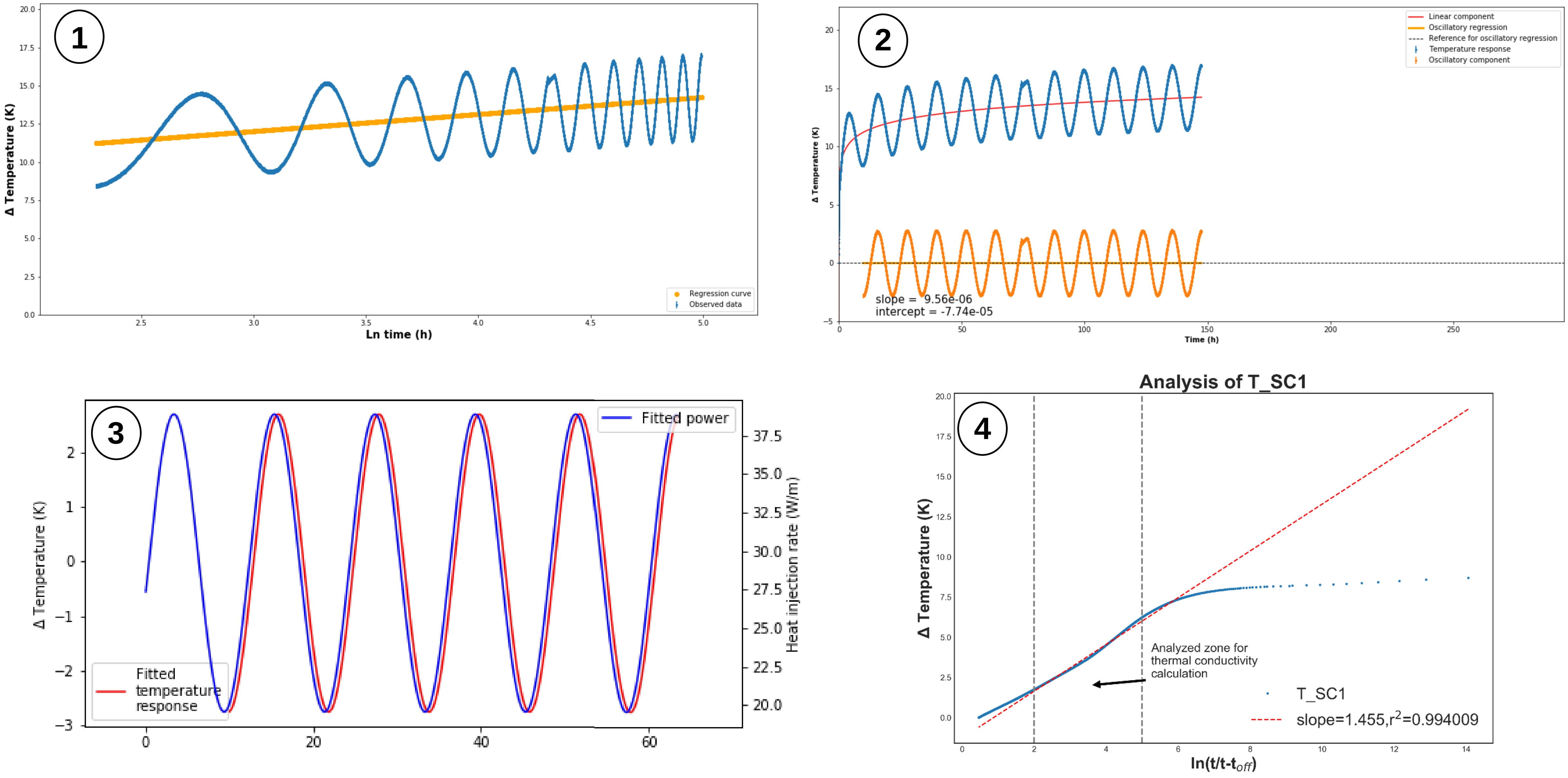


Figure 34 – OTRT analysis of the numerical simulations. Example from Scenario 1. Figure 3 is cut at ca. 70 h.

Table 12 – Thermal conductivity results from recovery period. From SC1_Tin to SC3_2D the thermal conductivity values are found from the heating period

	λ (W/mK)	λ err (%)	Rb (mK/W)	Rb err (%)
ES	1.702	2.69	0.063	5.20
INRS	1.762	2.69	0.047	5.30
SC1	1.598	5.95	0.266	3.98
SC2	1.432	2.97	0.253	4.05
SC3	1.557	6.05	0.243	4.08
SC4	1.553	6.13	0.235	4.13
SC1 Tin	1.976	2.96	0.106	4.75
SC3 Tin	1.962	3.05	0.104	4.98
SC1 2D	1.576	2.53	0.449	3.62
SC1 2D no grout	1.858	2.55	0.268	3.68
SC3 2D	1.667	2.50	0.439	3.55

Table 13 – OTRT analysis of the numerical simulations and comparison with observed data

	Rp (mK/W)	Rp err (%)	ϕp (-)	ϕp err (%)
ES	0.151	6.03	0.109	0.76
INRS	0.15	14.04	0.103	0.80
SC1	0.282	2.67	0.073	0.93
SC2	0.266	2.70	0.073	0.94
SC3	0.253	2.71	0.071	0.96
SC4	0.244	2.73	0.069	0.99
SC1 Tin	0.17	3.79	0.096	0.77
SC3 Tin	0.167	3.87	0.096	0.79
SC1 2D	0.434	2.54	0.078	0.87
SC1 2D no grout	0.307	2.56	0.067	1.03
SC3 2D	0.437	2.51	0.076	0.89
an GROUND	0.077	0.21	0.161	0.39
an GROUT	0.083	0.21	0.251	0.24

	α_Rp (mm2/s)	α err (%)	α_ϕp (mm2/s)	α err (%)
ES	6.334	6.60	2.564	2.80
INRS	7.041	14.29	2.977	2.81
SC1	86.93	6.52	9.152	6.02
SC2	34.206	4.01	9.15	3.11
SC3	41.019	6.63	9.857	6.13
SC4	33.493	6.71	11.062	6.21
SC1 Tin	6.785	8.97	3.647	8.17
SC3 Tin	6.358	9.00	3.658	8.17
SC1 2D	1465.001	8.52	7.218	8.18
SC1 2D no grout	115.224	8.52	12.545	8.20
SC3 2D	1524.663	8.51	7.799	8.18
an GROUND	1.063	0.21	0.996	0.39
an GROUT	0.472	0.21	0.371	0.24

Table 14 – Thermal diffusivity from Eq. 8 (R_p) and Eq. 9 (ϕ_p)

The thermal conductivity is lower than simulated when evaluated from the recovery period (1.4-1.5 W/mK) while it is bigger when estimated from the heating period (1.8-1.9 W/mK, **Table 12**). However it is in the 10 % range of error expected when using the slope method. The borehole thermal resistance is overestimated (doubled and more) when the BHE tool of Feflow was used (SC1 to SC4). It is closer to the observed when the inlet temperature was used as the boundary condition to the BHE.

The oscillatory results show R_p and ϕ_p values closer to the observed in scenarios SC1_Tin and SC3_Tin, with 0.17 mK/W and 0.1 (**Table 13**). Thermal diffusivity is therefore closer to the observed data in these scenarios, but, as expected, far from the forward analysis of the thermal properties of the ground and the grout (**Tables 14**). It is however interesting to note that an increase in the subsurface heat capacity generates a decrease of R_p by 13 % (from 0.282 to 0.244) and of ϕ_p by only 5 % (from 0.073 to 0.069), with no change of ϕ_p when Cv changes from 1.5 to 2.0 MJ/m^3K.

6. DISCUSSIONS

The heat capacity was reasonably estimated via the analysis of the temperature recorded in the observation well. To vary the thermal conductivity to match the observed slope does not impact the final estimation of the thermal diffusivity. The subsurface thermal conductivity is that obtained by the temperature response recorded in the BHE (1.9 W/mK), while the thermal diffusivity only affects the offset of the thermal response in the observation well (1.0-1.1 mm^2/s). Those two properties then allow us to evaluate a heat capacity of 1.8-1.9 MJ/m^3K, which is in the lower range of literature values for clays and shales (VDI 4640). However, this benchmark analysis has some limitations. It is valid only in the first 12 m of the local stratigraphy because the observation well is not perfectly vertical, and clear thermal responses are only available at depths < 15 m. Moreover, there is not any information about the inclination of the BHE, which has been assumed to be vertical for simplicity. Future research projects that aim at comparing OTRT with observation wells do have to think about drilling the wells one after the other, with the same drilling machine and operators. This will ensure to have, if not verticality in absolute terms, at least parallelism between them, such that the dual needle theory can be easily applicable.

The OTRT carried out in the open well showed significant noise related to water and possible convection cells occurring in the well around the heating cable. Convection cells are expected due to the period (12 h) and amplitude (10 W/m) of the heat rate oscillation, which are relatively high for the well configuration (radius) and geological setting (thermal properties). It appears indeed difficult to successfully perform an OTRT in an open well. However, reducing the well radius or the amplitude and magnitude of the heat injection might reduce the formation of convection cells, and thus the noise in the thermal response signal. The thermal conductivity is instead reasonably defined, with values close to the previous conventional TRTs performed in the nearby BHE. This means that the heating cable unit is a useful tool to perform in-situ thermal conductivity estimation when BHEs are not available. The analysis of the analytical thermal response, obtained via the forward evaluation of R_p and ϕ_p values from previously defined thermal properties (those expected), demonstrates that the Eskilson's Equations [8] and [9] provide valid estimations (3-8 % error) until $r_{pb} > 0.1$, in this case 0.6.

The OTRT performed with the heating cable in on of the pipes of the BHE outputs Rp and ϕ_p values closer to the expected ones compared to the open well tests. The variability with depth seems related to the local stratigraphy and there is not a clear noise due to the convection cells previously described. A bore radius of 0.016 m (that of the pipe) and amplitude of 5 W/m seems therefore small enough to avoid the occurrence of convection cells. However, these results do not allow to obtain reliable thermal diffusivity values, with higher oscillation resistance (+ 0.08 mK/W) and lower phase shift (-0.02). The thermal conductivity is reasonably defined. However, the borehole thermal resistance cannot be properly assessed due to the unknown position of the cable within the BHE. The analysis of the analytical thermal response, with the expected subsurface thermal properties (r_{pb} = 0.2), provides thermal diffusivity estimations with 2-3 % error. This clearly means that the higher r_{pb}, the higher the error of the final evaluation. This in turn confirms that the smaller the radius, the better (Eq. [10]).

The OTRT with water circulation demonstrated that subsurface thermal conductivity can be successfully evaluated even with an oscillatory heat injection. Thermal conductivity was reasonably estimated by both the recovery and heating periods via the slope method and the p-linear average (Marcotte and Pasquier, 2008). The complex thermal response can indeed be profitably split in a linear and an oscillatory component. Nevertheless, the analysis of a shorter period of the tests (50 h as the common duration of TRTs) did not provide valid results (λ < 3 W/mK). This can be due to the non-linearity of the thermal response (amplitude of the oscillation and slope of the linear component) occurring in the first 80 h of tests. Indeed, from 80 h on the amplitude and slope of the thermal response shows a perfect linearity. Further tests are necessary to investigate this aspect in detail. However, it is already quite clear that the linear regression can hardly provide the correct borehole thermal resistance R_b, which is highly dependent on the intercept of the linear fit. If the intercept is 0.5 °C, R_b increases by 30-40%. The non-linearity of the oscillation described before determines errors up to 14 % (INRS sensors), which is high when compared to the heating cable unit (2-3 %). Therefore, from this study it turns out that the linear regression coefficient of an oscillatory response can not be accurate enough to provide valid R_b values.

The numerical simulations performed with Feflow demonstrate that the Eskilson & Claesson (1988) analytical solutions used to solve the BHE problem overestimates the borehole temperature, which in turn overestimates R_b. Best match with the experiments is obtained by applying the inlet BHE temperature as boundary conditions (scenarios SC_Tin). Interestingly, the subsurface heat capacity was seen to impact the R_p (13 %) more than the ϕ_p (5 %) value over the range of variation under study. Both values are however far from the analytical forward estimation of the thermal diffusivity, demonstrating the significant impact of the BHE configuration.

However, we can consider an equivalent radius of the BHE calculated as follows (Aydin et al., 2017):

$$r_{eq} = r_b \cdot e^{-2\,\pi\lambda_{gt}R_b} \qquad \text{Eq. [12]}$$

where λ_{gt} is the thermal conductivity of the grout. By setting this to 1.7 W/mK as reported by Ballard et al. (2016), $r_{eq} = 0.022\,m$. If we carry out the calculation with this radius and we perform the forward analysis of the R_p and ϕ_p, we obtain the results reported in **Tables 15** and **16**. R_p is then close to the observed one, while ϕ_p shows a difference of about 0.02. This allows a valid estimation of the thermal diffusivity with Eq. [11], and thus a heat capacity closer to the expected value assessed via the dual needle method as shown in **Section 5.1**.

Table 15 – OTRT analysis of the test with r_{eq}

	Rp (mK/W)	Rp err (%)	ϕp (-)	ϕp err (%)
ES	0.151	6.03	0.109	0.76
INRS	0.150	14.04	0.103	0.80
an GROUND	0.152	0.12	0.079	0.41

Table 16 – Thermal diffusivity from Eq. 8 (R_p) and Eq. 9 (ϕ_p) with r_{eq}

	α_Rp (mm2/s)	α err (%)	α_ϕp (mm2/s)	α err (%)	Cv_Rp (mm2/s)	Cv err (%)
ES	0.926	6.60	0.375	2.80	1.838	7.13
INRS	1.030	14.29	0.435	2.81	1.711	14.54
an GROUND	1.142	0.12	0.985	0.43	1.489	1.42

The final thermal response of an OTRT in a BHE might then be represented by the following Eq. [13]:

$$T = -q_p \cdot R_p \cdot \sin\left(\frac{2\pi}{P} \cdot t - 2\pi(\phi_p + delay)\right) \qquad \text{Eq. [13]}$$

where the *delay* would be a factor due to the BHE configuration. In the authors' opinion, this deserves to be further investigated because it can be due to the fact that, in this case, the thermal conductivity of the subsurface and the grout are close values, 1.7 W/mK both.

7. CONCLUSIONS AND FUTURE PERSPECTIVES

Thermal response test (TRT) is the most common field method to infer the in-situ subsurface thermal conductivity. Borehole thermal resistance can also be inferred by means of TRT, and this makes it the standard technique for the design of heat pump systems fed by borehole heat exchanger (BHE) fields. However, the thermal response does not bring information about the subsurface heat capacity (HC), property which needs to be set via literature values. Even though the range of this parameter among geologic media is quite limited, a misinterpretation of it can impact the estimation of the total drilling length by 6-7%. The aim of this research project was therefore to prove the effectiveness of an oscillatory thermal response test (OTRT) as a tool to infer the subsurface thermal diffusivity (and hence the HC) in addition to thermal conductivity and borehole thermal resistance, without the need of an observation well. To achieve this goal, parametric study, numerical simulations, and field testing with both a water circulation and a low-power heating cable units were carried out. The main conclusions can be summed up as follows:

- As oscillatory pumping test (OPT) allows the evaluation of the subsurface hydraulic diffusivity, OTRT can be carried out to estimate the thermal diffusivity. Although having a smaller penetration depth than OPT, OTRT can induce an oscillatory thermal response in the same well/borehole whose smoothed amplitude and shifted phase contain information about the subsurface heat capacity;
- Dealing with abstraction and injection of heat from/to a BHE over a seasonal time scale, Eskilson (1987) described the oscillatory thermal response induced by an oscillatory (sinusoidal) heat injection rate, and he provided the expressions to infer the amplitude attenuation (R_p) and the phase lag (ϕ_p), parameters that are function of the subsurface thermal conductivity and diffusivity, and theoretically allow an independent estimation of the thermal properties;

- In the need of a trade-off between a sufficient penetration depth and a reasonable duration of the test, optimal periods of oscillation appear to be 12 to 24 h. To this regard, the BHE storage effect, i.e. the heat capacity of the backfilling material (grout or groundwater), constitutes the main obstacle to the OTRT analysis because the signal of the thermal response is significantly affected by the portions closer to the BHE pipes. As Eskilson (1987) already understood, and Oberdorfer (2014) reiterated, low frequencies (periods of tens of days) would be necessary to have information of a significant volume of the subsurface. Periods of 12-24 h can guarantee a penetration depth of 10-15 cm only;
- In order to verify the results of the OTRT, an observation well was drilled at 1.2 m apart from the BHE. A conventional constant heat injection TRT was carried out, and the heat capacity was inferred by means of the dual needle technique as commonly performed on laboratory samples. Despite some issues related to the parallelism between the BHE and the observation well, the subsurface heat capacity was estimated to be about 1.8-1.9 MJ/m^3K, in agreement with literature values for shales;
- Both the OTRTs carried out with the low-power heating cable unit (in the open well and the BHE) did not provide valid results of R_p and ϕ_p, that in turn did not allow us to accurately estimate the thermal diffusivity. The test performed in the open well experienced high noise due to the convection cells; the test completed in the BHE was most likely affected by the second pipe and the grout. However, it became clear that a smaller the pipe/well radius can help reduce the noise due to convection cells. This highlights that OTRT can possibly be successfully conducted in 1-inch to 2-inch wells. Moreover, we anticipate the profitable use of the heating cable unit for tests in direct contact with a porous medium, such that the radius of the heat source would be that of the cable (2.5 mm);

- The OTRT carried out with the conventional water circulation unit allowed us to infer the expected subsurface heat capacity by using the equivalent radius via the oscillatory resistance (R_p). It also demonstrated that the thermal conductivity can be assessed with similar accuracy compared to conventional TRTs. However, it failed to display the correct borehole thermal resistance, and it proved unable to achieve the expected thermal conductivity and heat capacity within the 50 h target (Kavanaugh, 2001);
- Finally, although OTRT seems a promising tool to evaluate the HC, more field testing (different geological settings, BHE configurations, temperature sensors, flow meters, etc.) and mathematical interpretation of the sinusoidal response are necessary to better isolate the subsurface contribution to this response in vertical BHEs. On the other hand we already see immediate potential for horizontal ground-coupled heat pumps (HGCHPs) with the heating cable unit (Giordano and Raymond, 2020). To the best of our knowledge, TRT is rarely performed for horizontal installations. OTRT with a heating cable in direct contact with the geologic medium (obviously unconsolidated sediments) completely eliminates the noise produced by the BHE itself (i.e. plastic pipes and grout), thus allowing the proper interpretation of the subsurface thermal properties. This fast and low-invasive technique would surely benefit the design of HGCHPs by the optimization of the total ground heat exchangers' length;
- Further experiments and studies are therefore necessary to implement the outcomes of this project. In particular, some questions remain open and need, in our opinion, to be further investigated. For example: is the OTRT method able to properly provide thermal conductivity and heat capacity within a common duration of 48-72 h? Can the BHE storage effect be neglected (e.g. delay factor in Eq. [13]) in order to isolate the subsurface contribution from the whole oscillatory response? Can the borehole thermal resistance be accurately (± 10 %) determined with an OTRT?

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Energie·Stat TECHNOLOGIES DU DÉVELOPPEMENT DURABLE

INRS Institut national de la recherche scientifique

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To Maria Isabel Vélez Márquez, the first Jasmin's student who worked on the heating cable unit, and taught Nicolò everything about it and the TRTs at the beginning of the project.

On February 21, 2020, the scientific community lost a rigorous, intelligent and promising researcher. We lost a friend whose place will never be replaced. Sorry for everything we might have done to hurt you. Thanks for anything you did for us. May your soul and smile rest in peace forever.

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