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# A Novel Approach to the Analysis of Thermal Response Test (TRT) with Interrupted Power Input

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**Abstract:** The quality of measuring datasets of the thermal response test (TRT) significantly influences the interpretation of borehole thermal parameters (BTP). A thermal response test with an unstable power input may induce an unacceptable error in the estimation of the borehole thermal parameters. This paper proposes a novel approach to treat the dataset with interrupted power input. In this approach, the test records were segmented into several subsections with a constant time interval of 100 min, 60 min, and 30 min, separately. The quality of each data section was assessed and analyzed. Then, two algorithms, including the continuous algorithm and semi-superposition algorithm, were developed. The results estimated by the linear source model (LSM) were compared with one Thermal response test datasets with a stable power input at the same testing site. It shows that the effects of power interruption during the test can be effectively mitigated by deploying both the continuous and semi-superposition methods. The lowest deviation of the calculated thermal conductivity to a thermal response test with stable power input was 2.8% in the continuous method and 0.9% using the semi-superposition method. Thus, the proposed approaches are effective measures to mitigate the effects of interrupted power input on the interpretation of the thermal properties of the ground.

**Keywords:** thermal response test (TRT); interrupted power input; measuring outputs; borehole thermal parameters

## 1. Introduction

Thermal response tests (TRT) are a common method to determine borehole thermal parameters, e.g., the effective ground conductivity and the borehole thermal resistance [1]. These thermal parameters were commonly interpreted by following the Linear source model (LSM) or the cylinder source model (CSM) [2,3]. For both the LSM and CSM, many datasets of fluid temperature, fluid flow rate, and power input must be recorded over the testing process [4]. A stable TRT process is a prerequisite to the proper estimation of the borehole thermal parameters [5,6]. However, in practice, it has been reported that the measured outputs of TRT can be influenced by a large number of factors, such as unstable power input or undesirable energy loss under extreme ambient climatic conditions [7,8]. Furthermore, if the heating power rises due to fluctuation, it was found that the higher heat injection rate results in a higher effective thermal conductivity being measured [9].

To understand the measuring uncertainties of TRT, many types of studies have been conducted. Signorelli et al. [10] showed that groundwater flows higher than 0.1 m/d ( $1.2 \times 10^{-6}$  m/s) strongly influenced the TRT data. Choi and Ooka applied the sol-air temperature to analyze convective and radiative heat transfer simultaneously in the TRT setup. They reported that weather parameters, such as wind speed solar irradiation and ambient temperature, significantly influence TRT outputs [11]. Sanner et al. indicate that the stable power input, pipe insulation, and extreme climate conditions can affect the TRT significantly [12]. Moreover, it has been reported that the estimation of borehole thermal parameters was affected by TRT outputs. Signorelli et al. published in 2007, that the calculated ground thermal conductivity based on LSM is sensitive to the heating power stability and the effects of ambient conditions on heat injection rates [13].

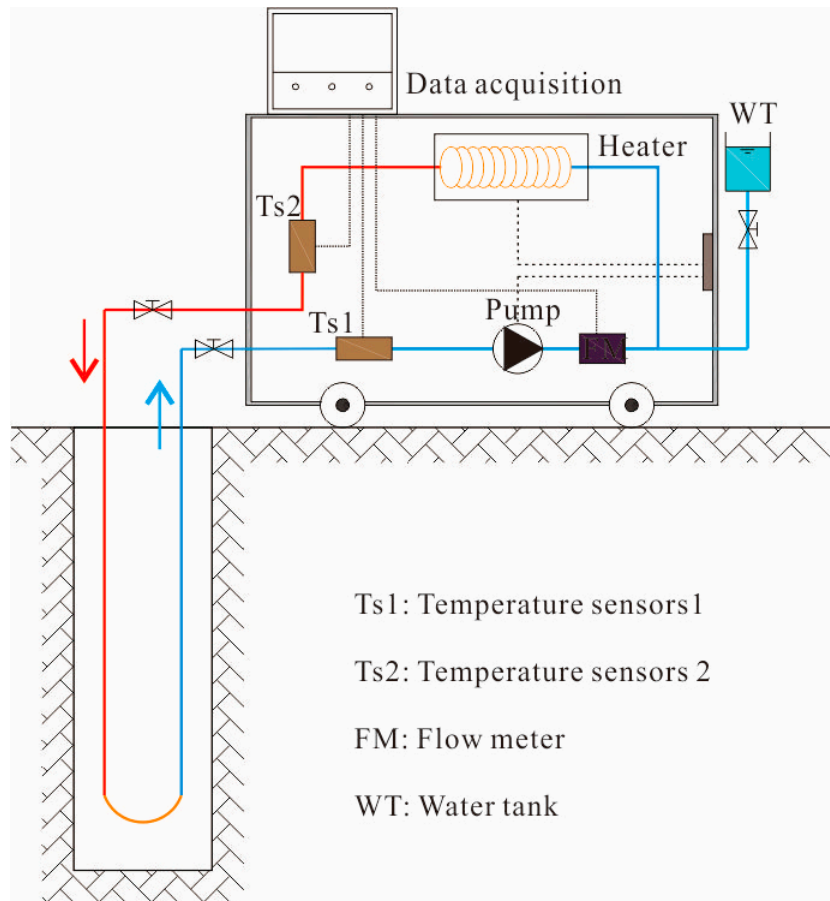
Several approaches have been proposed to minimize the impacts of unstable heat rates on the determination of borehole thermal parameters to treat an unstable heat injection rate [14–16]. Beier and Smith developed a deconvolution algorithm to remove unstable heat rate effects from the TRT. That algorithm is based on the LSM using the Laplace domain, where the inputs are the transient heat rate and the ground-loop temperature curves. Zhou et al. suggested a computational method by considering a linear source superposition theory to calculate ground thermal conductivity for two consecutive TRTs. Compared with the conventional LSM, the linear superposition model can achieve a more precise result for the subsequent TRT [17]. Zhang et al. [18] used the Nelder–Mead Simplex search algorithm (NMSA) estimating the parameters for calculating the ground thermal properties in in-situ TRT with an unstable heat rate. A duct storage system (DST) model for a borehole heat exchanger (BHE) was utilized to deal with variable heat rate and the vertical ground temperature distribution in the undisturbed ground. Choi et al. [19] developed a stochastic method based on Bayesian inference to estimate the two parameters (thermal conductivity and borehole thermal resistance). Austin et al. [20] utilized a numerical parameter evaluation method to remove variable-rate effects on a TRT. Liu et al. [21] proposed a new approach for determining the ground thermal conductivity. They were able to reduce the testing time to that of the current practice by 40–60% while maintaining roughly the same accuracy level of  $\pm 5\%$ . This proposed method can reasonably estimate ground thermal conductivity with varying and disrupted heat input, even with the potential to detect underground water movement or other variances in the ground formation near a BHE. Furthermore, recent studies by Nian et al. developed a method utilizing a heat transfer model, spearman correlation and Monte Carlo stochastic method to calculate the thermal properties of the borehole and the ground. [22,23]. Chen et al. in 2018 provided another approach in modeling and calculating thermal parameters, also usable for interrupted TRT [24].

The previous works proposed some approaches that can alleviate the impacts of TRT with unstable power input on the estimation of borehole thermal parameters. However, many of those methods show high complexities in treating TRT with interrupted power input. In this study, the aim was to develop a novel method to specifically treat TRT measuring datasets with interrupted power input, e.g., power shut down during the measuring process. For this, two simple algorithms are recommended, providing a significant improvement of data, without complicating the analysis too much. The remainder of this work is organized as follows: The implementation of TRT and the interpretation of effective thermal conductivity of the ground are summarized in Section 2. The impacts of unstable power input on measuring outputs of TRT are also introduced. Furthermore, an introduction to the strategy to modify the measuring datasets with interrupted power input is presented. The results are presented and discussed in Section 3. Finally, the conclusions of the present work are made in Section 4.

## 2. Materials and Methods

### 2.1. Thermal Response Test and Parameters Estimation

The implementation of a TRT was conducted by circulating the heat carrier fluid through a closed-loop in a vertical borehole in the ground, as shown in Figure 1. A constant heating power was applied to the heat carrier fluid, and the fluid temperature keeps increasing with time. The heat was then dissipated into the ground by the temperature difference between the fluid and the surrounding ground. The inlet-outlet temperature of the borehole, fluid flow rate and heating power were recorded during the testing process for later interpretation of the borehole thermal parameters.



**Figure 1.** A schematic diagram demonstrates the testing device of a thermal response test.

To determine the borehole thermal properties, a LSM was proposed by Hellström (1991) to interpret TRT results [25]. In this method, the heat source is presumed to be a one-dimensional infinite line. In practical use, the mean fluid temperature is assigned to be the linear heat source given by Equation (1):

$$T_f(t) = \frac{Q}{H} \left\{ \frac{1}{4\pi\lambda_{eff}} \left[ \ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma \right] + R_b \right\} + T_s \quad (1)$$

where  $T_f$  is the mean fluid temperature ( $^{\circ}\text{C}$ ),  $T_s$  is the undisturbed ground temperature ( $^{\circ}\text{C}$ ),  $Q$  is the input heat flux (W),  $H$  is the depth of the borehole (m),  $r_b$  is the borehole radius (m),  $\alpha$  is the thermal diffusivity ( $\text{m}^2/\text{s}$ ),  $t$  is the time (s),  $\gamma$  is the Euler constant (0.5772),  $R_b$  is the borehole thermal resistance ( $\text{m}\cdot^{\circ}\text{C}/\text{W}$ ) and  $\lambda_{eff}$  is the effective thermal conductivity of the ground ( $\text{W}/\text{m}\cdot\text{K}$ ). By linear

fitting, the development of the mean fluid temperature increases with logarithm time, Equation (1) can be simplified as a linear equation with one variable:

$$T_f = m * \ln(t) + n \quad (2)$$

$$m = \frac{q}{4\pi\lambda_{eff}}; n = \frac{q}{4\pi\lambda_{eff}} \left( \ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma \right) + q R_b + T_s \quad (3)$$

$$T_f = \frac{T_{0,in} + T_{0,out}}{2} \quad (4)$$

$$R_b = \frac{T_f - T_s}{q} + \frac{\ln\left(\frac{r_b^2}{4\alpha t}\right) + \gamma}{4\pi\lambda_{eff}} \quad (5)$$

where  $q$  is the heat flux per meter length of BHE (W/m),  $m$  is the slope for the linear fitting of the mean fluid temperature with logarithm time (-),  $T_{0,in}$  and  $T_{0,out}$  are the fluid temperatures measured at the inflow and the outflow of the borehole, respectively,  $R_b$  is the borehole thermal resistance (mK/W), and  $n$  is the intercept of the linear fitting at the vertical axial ( $^{\circ}$ C).

In the present work, two TRTs were implemented in Xi'an city of Shannxi Province, China. Both TRTs are geometrically configured in the same manner and both boreholes were grouted using a mixture of middle sand with clay. TRT No. 1 was started at 14:00 on 14 November 2016 and ended on 15 November 2016. TRT No. 2 was started at 14:00 on 15 November 2016, until 18:00 on 116 November 2016. A power off occurred at 15:30 on 16 November, and the power was recovered 50 min later. Figure 2 portrays the geological overview of the TRT site. The same geological conditions characterized both boreholes because they are closely located of 10 m distance.

Depth (m)	Geological profile	Thickness (m)	Lithology	Description
0		13	Loess and silt	Alluvium deposit, silt, silty clay, partially saturated. Groundwater table is 10 m below the ground surface.
20		5	Sand and Cobble	Brown in color, angular and poor sorted, the size of the cobble particle varies from few centimeters to tens of centimeters.
40		32	Silty clay	Silty clay and fine sand mixture, characterized by plasticity and low permeability.
60		70	Silty clay with some sandy gravel layers	This layer contains four sub-layers including the interbedded clay and sand/cobble layers. The structure can be horizontally treated as aquifer but vertically is impermeable.
80				
100				
120				

**Figure 2.** A geological profile displays the sedimentary sequence of rock formations on the testing site.

## 2.2. Analysis of the Uncertainty of Thermal Response Test

In general, no perfect fitting can be obtained for TRT's measuring datasets due to the possible unstable measuring process, e.g., unstable heating input or data noise. Therefore, it is desirable to evaluate the valid parameters by one optimal parameter combination. One parameter can be used to define the uncertainty of measuring the dataset. In this work, root mean square error (RMSE) is

used to quantify the uncertainty of the recorded set of data. The ASHRAE handbook [23] states that, when standard deviation of the input power ranges less than  $\pm 1.5\%$  and peaks less than  $\pm 10\%$  of average, the heat rate of a TRT input is recognized as stable power quality, if the resulting temperature variation is less than  $\pm 0.3\%$  [26]. The threshold is shown in Table 1.

$$RMSE(q) = \sqrt{\frac{1}{n} \sum_{i=1}^N (q_i - q_{av})^2} \tag{6}$$

$$Red(q) = \frac{RMSE(q)}{q_{av}} \times 100\% \tag{7}$$

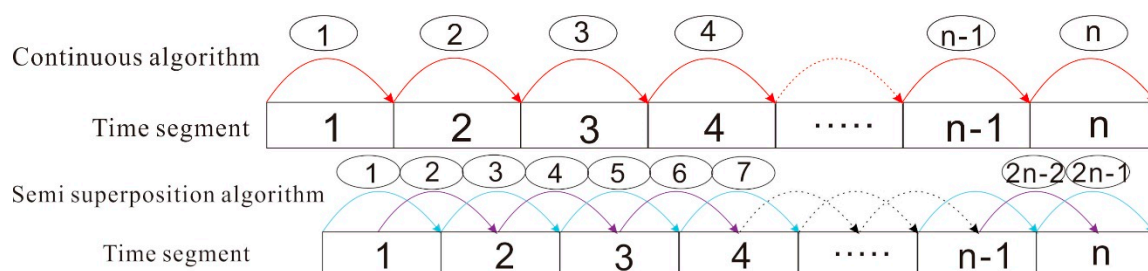
where  $q$  is the power input for a TRT (W),  $q_i$  is the power input at time  $i$  (kW),  $q_{av}$  is the average power input of a TRT (kW), which is an arithmetic mean value of all the measured power input during the testing process of a TRT,  $Red$  is the relative deviation (%).  $q_{peak^*}$  represents the maximum value of the recorded power input.

**Table 1.** A threshold to estimate a thermal response test (TRT) with an unstable power input [23].

Types	Red (q)	Red ( $q_{peak^*}$ )	Unstable Type
Stable heat rate	$Red(q) < 1.5\%$	$Red(q_{peak^*}) < 10\%$	Stable
Unstable heat rate	$Red(q) \geq 1.5\%$	$Red(q_{peak^*}) \geq 10\%$	Unstable

### 2.3. Treatment of the Interrupted Power Input

In this work, TRT’s measuring datasets were divided into several sections with a constant time interval. Each data-section was treated as an independent sub-TRT unit and the borehole thermal parameters were interpreted for each time segment. More specifically, two different approaches, one being the continuous method and the other being a semi-superposition algorithm were proposed. In the continuous method, each data segment was naturally placed in the time sequence. For example, a dataset with a testing period of 90 min can be segmented into three data sections, the first section takes data from 0 min until 30 min, the second one lasts from 30 min until 60 min and the last section covers the data from 60 min until 90 min, in a continuous method with a 30 min interval. The data segment was semi-overlapped, as shown in Figure 3. In a semi-superposition method, one data section half overlaps the following sequenced section, e.g., the first data segment covers data of 0–30 min, and the second is 15–45 min. More specifically, the data section was tested with different time intervals of 100 min, 60 min and 30 min. LSM method was deployed to interpret the effective thermal conductivity of the ground. The dataset of a TRT with an interrupted power input was treated using the proposed model and the effective thermal conductivity of the ground was then estimated by deploying LSM for each data section.

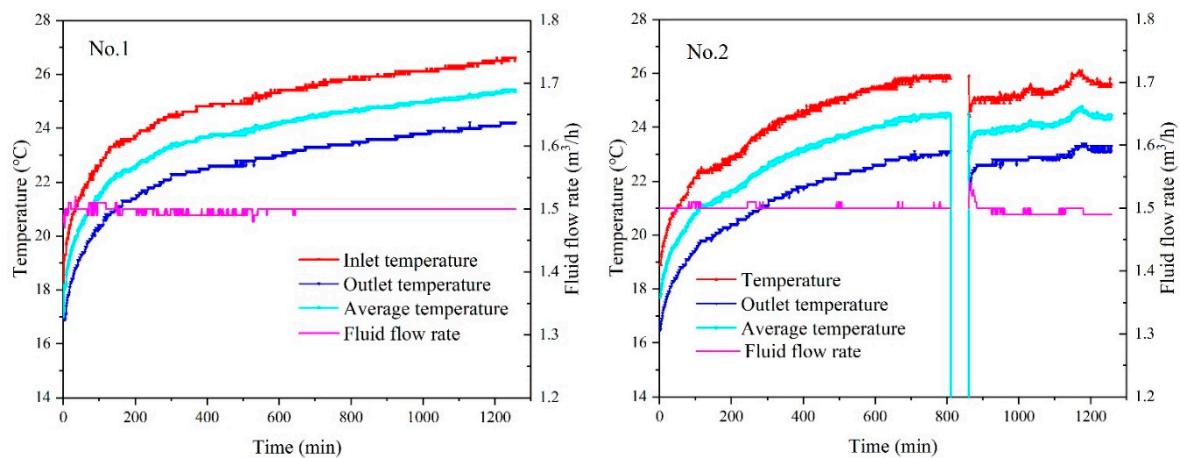


**Figure 3.** The two proposed algorithms for the treatment of the TRT.

### 3. Results and Discussion

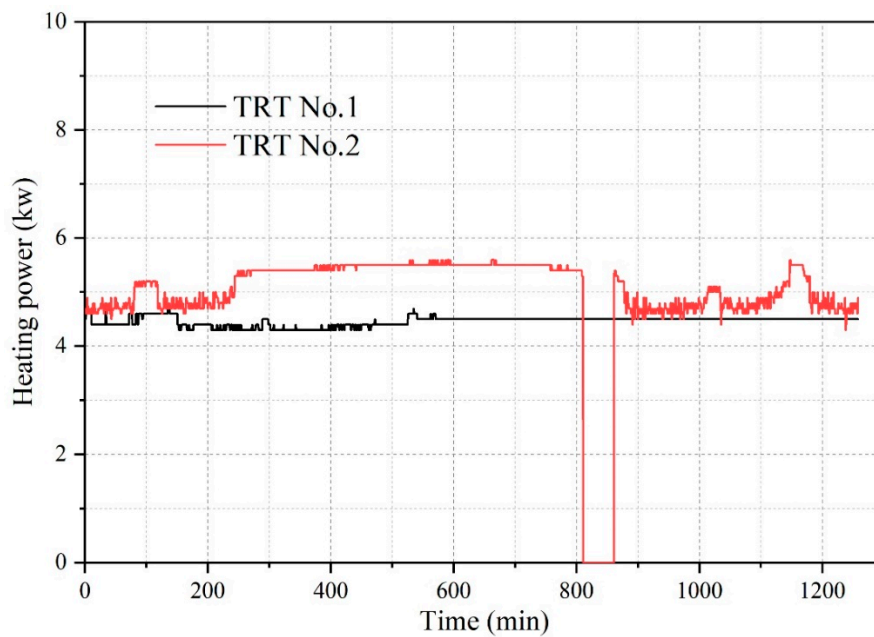
#### 3.1. TRT Measuring Records

Figure 4 plots the testing records of two TRTs that were implemented in the field. It shows that the TRT in the left sub-figure has relatively stable power input. The inlet-outlet fluid temperature keeps steadily increasing with time and the fluid flow rate remains nearly constant through the whole testing period, meaning a stable power input of TRT No. 1. In the right sub-figure, the fluid temperature increases at the beginning of the test and suddenly drops at 870 min. It implies an interrupted power supply, possibly through a power failure. This power off during the measuring process may induce unacceptable error in the later estimation of ground thermal property if the dataset of a whole testing period is used.



**Figure 4.** The records of thermal response test including inlet-outlet fluid temperature and fluid flow rate for two borehole exchangers. A significant drop at 800 min of the fluid flow and temperature indicates a power off event.

Figure 5 displays that the heating power of TRT No. 1 remains relatively stable throughout the whole testing period. The estimation of the RMSE shows that the red of the power input is 0.11% and 5.1% deviation for the peak to the average is observed. This indicates that the TRT No. 1 was tested with stable power input and the dataset of TRT can be used directly to interpret the borehole thermal parameters. Furthermore, TRT No. 1 is suitable to compare with the treated TRT No. 2.



**Figure 5.** The records of heating power for the thermal response test of two borehole heat exchangers. They show that power input of TRT No. 2 was interrupted at approximately 870 min.

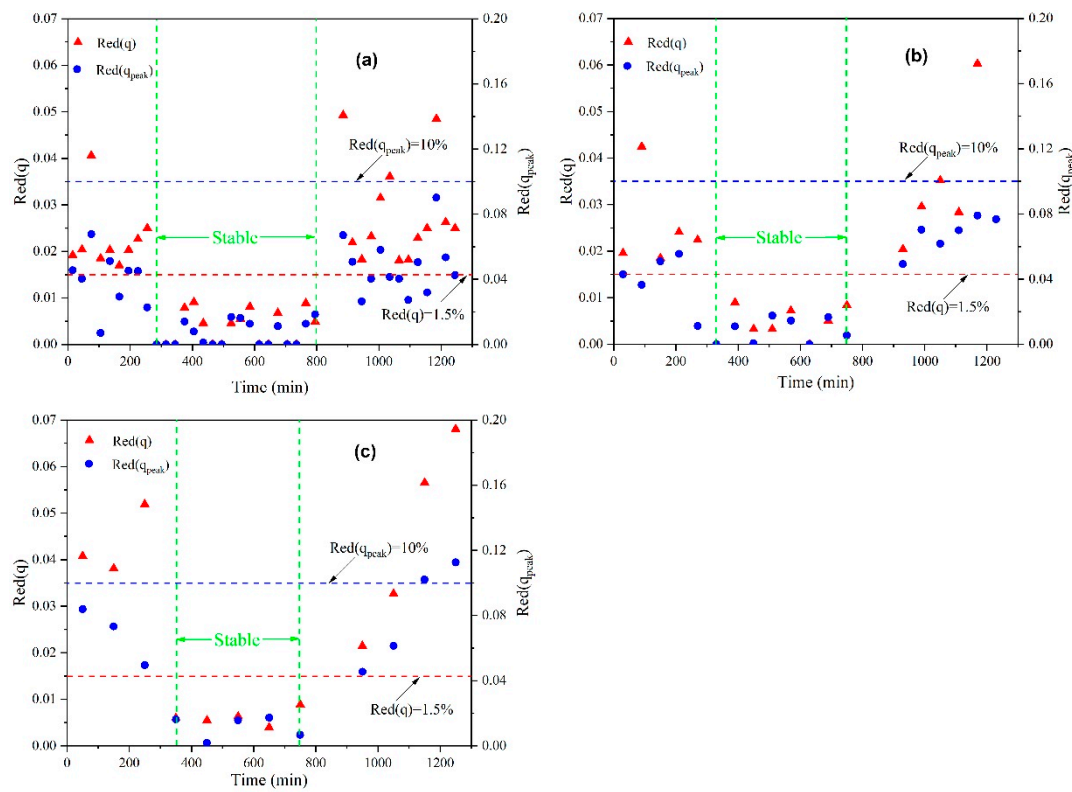
TRT No. 2 fluctuates at a time range of 0–250 min and 870–1350 min. The heating power suddenly dropped at 810 min and 870 min, inducing a drastically decreasing fluid temperature. As seen in Table 2, TRT no. 2 can no longer be stated as a case of stable power input, as  $R_d(q)$  is 21.54%, which exceeds 1.5% by a large margin, and the peak deviation was 13.6% which is also higher than 10%. This dataset could induce an unacceptable error in the later estimation of borehole thermal parameters. Thus, the results of TRT no. 2 are, therefore, treated by the method described in Section 2.3.

**Table 2.** The estimation of measuring uncertainty of two TRT datasets.

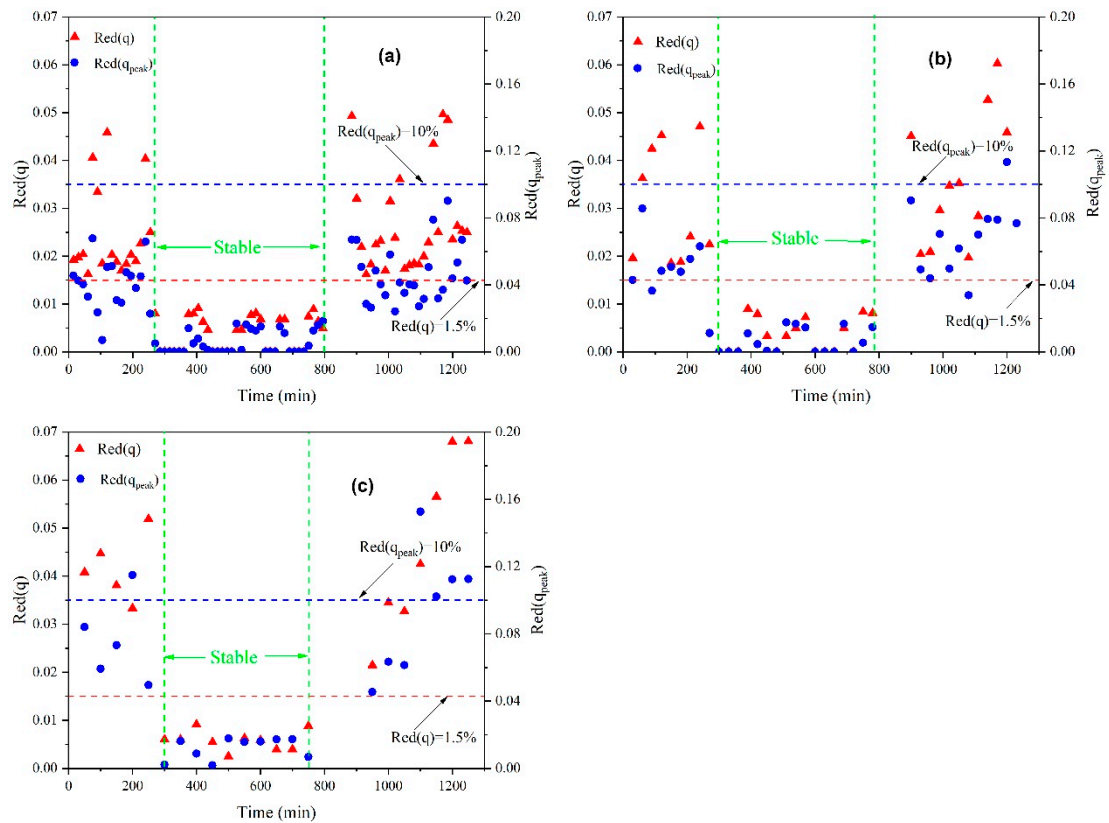
TRT	Red (q)	Red ( $q_{peak}$ )	Type
No. 1	0.11%	5.1%	Stable
No. 2	21.54%	13.6%	Unstable (Interrupted)

### 3.2. Treatment of the Datasets of TRT No. 2

As mentioned above, thermal parameters estimated by using dataset TRT No. 2 without further treatment may be invalid. The dataset of TRT No. 2 was then treated by the proposed method of Section 2.3. Figures 6 and 7 show TRT No. 2 treated with the algorithms mentioned in Section 3. The quality of each data segment with different time intervals was estimated. It shows that some data segments stay in stable power areas, which means these data segments match the criteria of stable power input very well. Those two figures show the impact of the data segmentation on the TRT No. 2. In general, these algorithms, both with no superposition and semi-superposition of time intervals, show stable conditions, at roughly the same time between around 270 min up to 810 min. This result correlates well with the period of stable conditions shown in Figure 5. These stable data will be used in Section 3.3 to estimate the effective thermal conductivity of the ground.



**Figure 6.** The determination of stable power input with different segmented time-sections of 30 min (a), 60 min (b), and 100 min (c).



**Figure 7.** The determination of stable power input with different semi-superposition segmented time-sections of 30 min (a), 60 min (b), and 100 min (c).

More specifically, Table 3 illustrates the estimation of the duration of data segmentation with a stable power input of the TRT No. 2. In the continuous method, the shortest time duration of the data segmentation is 500 min, which was treated as stable power duration at 100 min interval of the data segmentation. In the semi-superposition method, the shortest time duration of stable power input was 530 min, which was observed at the data-segments with 60 min interval.

**Table 3.** The estimation of data-segmentation with a stable power input of TRT No. 2.

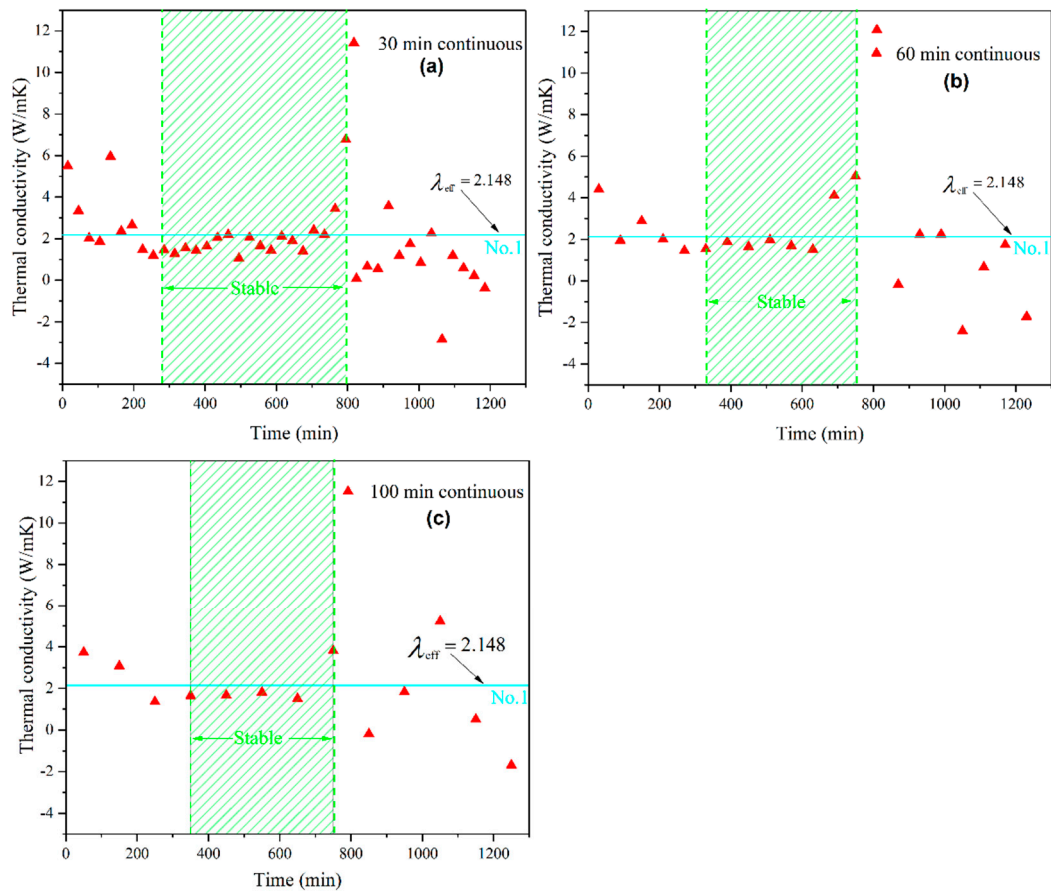
Algorithm	Interval (min)	Stable Period (min)	Duration (min)
Non-superposition	30	270–810	540
	60	240–780	540
	100	300–800	500
Semi-superposition	30	255–810	555
	60	270–780	530
	100	250–800	550

Overall, the duration of the individual stable periods is not subject to significant outliers. Thus, the difference with the non-superposition algorithm is 40 min, i.e., just under 7% of the maximum duration. With the semi-superposition algorithm, the difference is only 25 min, less than 5% of the maximum duration. Nevertheless, the short time intervals are preferable, since outliers can occur mainly at the borders of the stable period, which cannot be excluded from the long time intervals of, for example, 100 min. Thus, the shorter the time duration is, the higher the quality of the dataset was expected.

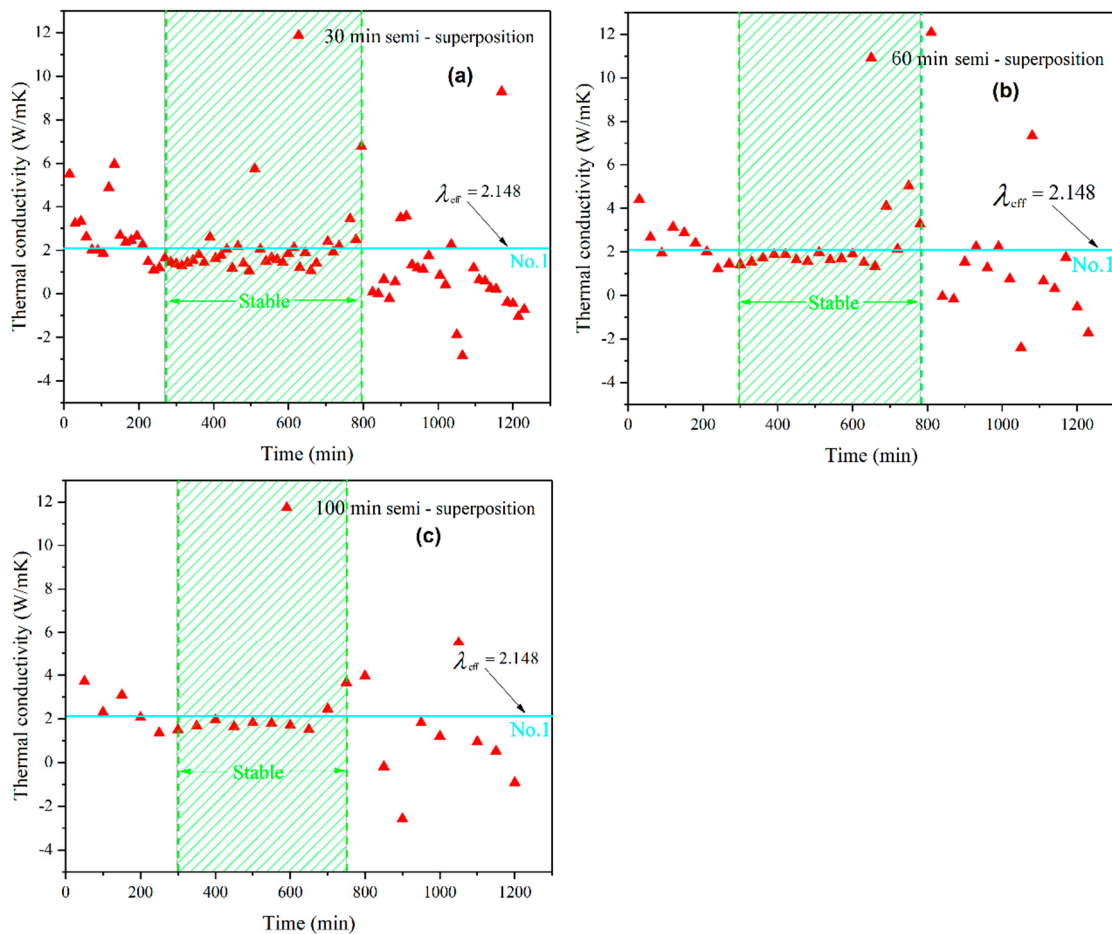
### 3.3. Interpretation of Borehole Thermal Parameters

The effective thermal conductivity of the ground was calculated by deploying the LSM. In Figures 8 and 9 the calculated ground thermal conductivities with the different methods and time intervals are depicted. The dotted symbols are the estimated effective thermal conductivity of the ground at each data segment of TRT No. 2. The line in blue color represents the results of the TRT No. 1 which is with a stable power input. It is observed that most of the dots in the stable area match very well with the blue line, except for few points at the end of the stable period. This could be attributed to the last few data segments contain the data at the interrupted period, which may induce an obvious deviation in the thermal parameters estimation as it is observed.

It can be seen that the thermal conductivity calculated from TRT No. 2 remains relatively constant during the “stable” period. The calculated thermal conductivity is now compared with that of TRT No. 1 and the relative differences are presented, as shown in Table 4. The differences between test No. 1 and No. 2 range between 0.9% and 9.8%. The highest accuracy of 0.9% was observed in the semi-superposition approach with a time interval of 60 min which has the shortest duration of 530 min. For the continuous method, the lowest deviation of 2.8% to TRT No. 1 was shown in the data segments with 100 min interval. Similarly, the data segments with 100 min interval has the shortest duration of 500 min as compared to that of the data segments of 30 min interval and 60 min interval both are 540 min duration of the stable power input, as show in Table 3. It shows a strong correlation between the accuracy and the estimated stable duration of the testing period, the shortest duration the highest accuracy of thermal parameter is estimated. Within the same method, the shorter the stable duration is detected, the higher stability of the data is due to the shorter duration may contain less unstable data points. Furthermore, with a time interval of 100 min in the non-superposition algorithm, for example, only five values for the thermal conductivity in the stable range are achieved. Since one of these values, at the right border to the unstable range, deviates strongly, the calculated mean value will deviate accordingly upwards, as can be seen in Table 4. At 60 min, this deviation is even more pronounced, since a quarter of the values recorded, a total of two out of eight, are far above the reference value of TRT No. 1. Only at a time interval of 30 min can these values be cushioned.



**Figure 8.** Calculated effective ground thermal conductivity estimated by deploying Non-superposition segmented data in time continuous method. (a) 30 min, (b) 60 min, (c) 100 min.



**Figure 9.** The effective thermal conductivity of the ground estimated by deploying the semi-superposition method. (a) 30 min, (b) 60 min, (c) 100 min.

**Table 4.** Comparing the effective thermal conductivity of the ground for a treated TRT with interrupted power input at a “stable” period with that of a TRT with stable power input.

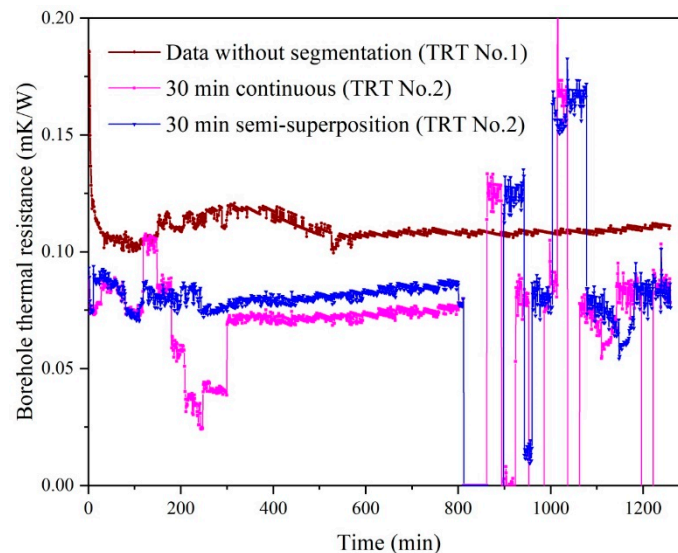
Algorithm	Interval (min)	Thermal Conductivity (W/mK)		Difference
		No. 1	No. 2	
Non-superposition	30	2.15	2.11	1.9%
	60		2.31	7.4%
	100		2.09	2.8%
Semi-superposition	30	2.36	9.8%	
	60	2.13	0.9%	
	100	1.97	8.4%	

With the semi-superposition method, the advantage is the more significant number of values contributing to the calculation. Nevertheless, the values are still calculated with a high deviation at a time interval of 100 min, which is why the shorter time interval of 60 min, with the lowest deviation of 0.9%, is preferred here. At 30 min, several very high values are recorded, which is why the deviation is also highest here. When looking at Figure 9, however, it is seen that a large part of the values can be classified in the range of the results of TRT No. 1.

The results of the thermal conductivity and the difference to that of TRT No. 1 show, that the estimated differences between the “stable” and “unstable” Test can be compared well to that of other proposed treatment methods [18,27] where the differences were calculated at around ±2.0%.

This deviation could be generally acceptable since the measuring uncertainty of the temperature and fluid flow rate sensors could also induce a deviation within such a range [28].

Figure 10 shows the calculated borehole thermal resistance,  $R_b$ , from TRT No. 1 and No. 2. The  $R_b$  values remain relative constant during the whole measurements due to a stable power input. A mean value of 0.11 mK/W was considered as borehole thermal resistance of TRT No. 1. For the TRT No. 2, during the stable period, between 300–800 min,  $R_b$  maintains relative stable. After the power off,  $R_b$  fluctuates drastically, indicating these values contain very high uncertainty. Thus, in the present work, an arithmetic value during the stable period was estimated for the TRT No. 2, as shown in Table 5. The  $R_b$  values of TRT No. 2 vary between 0.07 mK/W and 0.8 mK/W under the proposed continuous and semi-superposition methods with different time interval. Compare the TRT No. 1 with No. 2, an obvious deviation was observed even both boreholes with the same geometric configuration. This could be attributed to the quality of drilling and grouting of a borehole which is difficult to control in the field. In practice, thermal resistance of a borehole was suggested to be measured rather than by calculation in order to reduce the uncertainty of field work.



**Figure 10.** The borehole thermal resistance calculated at TRT No. 1 and No. 2 in which an example of data segmentation with 30 min interval was showed of TRT No. 2.

**Table 5.** Comparing the borehole thermal resistance for a treated TRT with interrupted power input at a “stable” period with that of a TRT with stable power input.

Algorithm	Interval (min)	Borehole Thermal Resistance (mK/W)	
		No. 1	No. 2
Non-superposition	30	0.11	0.07
	60		0.08
	100		0.07
Semi-superposition	30	0.11	0.08
	60		0.07
	100		0.07

#### 4. Conclusions

In this paper, a novel approach has been proposed to analyze TRT with interrupted power input. A synthetic TRT dataset with interrupted power input was divided into several sub-data sections. The borehole thermal parameters were interpreted by following the proposed approach to unstable datasets. The results were compared with the parameters of a TRT with stable power input. Significant findings obtained from this study were made as follows:

- Two TRTs have been implemented to determine the borehole thermal parameters. The measuring records show that the datasets of one of the TRT No. 2 does not fit the requirements of stable power input, which means the datasets contain high uncertainty for the interpretation of borehole thermal parameters. By dividing the whole datasets into different subsections, some data sections were found to have a stable power input. These data segments may be suitable to interpret the borehole thermal parameters.
- Two methods are proposed: one is a segmented data section in time sequence, and the other is semi-superposition approach data-section. The data-section with 100 min, 60 min, and 30 min intervals are considered and discussed. It has been shown that the shortest duration of the time-segment of 500 min was estimated in a continuous method with 100 min interval. On the other hand, the shortest time duration of stable power input was 530 min, which was observed at the data-segments with 60 min in the semi-superposition method.
- The estimation of the borehole thermal parameters was implemented by following LSM. The interpretation of effective ground thermal conductivity was estimated at the stable data-section by following LSM. The results indicate that the  $\lambda_{\text{eff}}$  matches very well with the stable dataset when using continuous data-segment with a time interval of 100 min, with a difference of  $\pm 2.8\%$  compared with the TRT parameters with stable power input. In the semi-superposition method, the  $\lambda_{\text{eff}}$  was estimated to 2.13 W/(m·K) in data-segmentation with a time interval of 60 min, meaning a difference of  $\pm 0.9\%$ . Similarly, the borehole thermal resistance remains relatively constant at a “stable” period and fluctuates drastically at “unstable” periods. The estimated arithmetic mean value during a “stable” period was suggested to be considered as a borehole thermal resistance in a practical application. Thus, both the proposed continuous and semi-superposition methods can effectively mitigate the effects of interrupted power input on the TRT measurements.

It is, therefore, with particular interest, considering the simplicity and effectiveness, to use these algorithms to analyze the borehole thermal parameters including the effective thermal conductivity of the ground and borehole thermal resistance with an interrupted power input, as long as there are time periods with an overall stable heat rate.

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