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An Experimental Investigation of the Accuracy of Thermal Response Tests Used to Measure Ground Thermal Properties

Saqib Javed, P.E.
Student Member ASHRAE

Jeffrey D. Spitler, Ph.D., P.E.
Fellow ASHRAE

Per Fahlén, Ph.D.
Member ASHRAE

ABSTRACT

This paper reports on the results of thermal response tests conducted with laboratory-grade instrumentation and equipment for a borehole system consisting of nine groundwater-filled boreholes, each about 80 m (262 ft) deep. The ground thermal properties, including the undisturbed ground temperature, the thermal conductivity and the borehole thermal resistance, are determined for each of the nine boreholes using standard evaluation methods. Comparison of the results of the ground thermal properties of the nine boreholes provides meaningful insight into the uncertainty issue of the thermal response tests. The ground thermal conductivity and the borehole thermal resistance estimations of nine boreholes are then used to investigate the sensitivity of the design of borehole systems to the random variations in the estimated thermal properties. The paper also presents the effects of the test duration and the heat injection rate on the estimated ground thermal properties when conducting thermal response tests.

INTRODUCTION

Accurate knowledge of ground thermal properties is important when designing borehole heat exchangers for ground source heat pump and thermal energy storage applications. These properties, including ground thermal conductivity, borehole thermal resistance and undisturbed ground temperature, directly influence the size and the configuration of the borehole field and the depth of individual boreholes. These properties are often determined using an in-situ thermal response test (TRT) of a pilot borehole.

The idea of using TRT to measure ground thermal properties was first presented by Mogensen (1983). Eklöf and Gehlin (1996) introduced a now commonly used testing procedure and estimated the ground thermal conductivity using the line source approximation method. Austin et al. (2000) and Shonder and Beck (1999) developed parameter estimation methods to evaluate TRTs. Martin and Kavanaugh (2002) investigated the effects of test duration, power quality, and borehole retesting for boreholes backfilled with different grouting materials. Gehlin (2002) studied groundwater-filled boreholes and, using laboratory and simulation studies, examined the influence of thermosiphon effects on the testing of groundwater-filled boreholes. More recently, Gustafsson and Westerlund (2010) studied the effects of heat injection rates on ground thermal conductivity and borehole thermal resistance estimations for groundwater-filled boreholes. Groundwater-filled boreholes are commonly used in Sweden. In much of the country, the underground structure is solid bedrock and boreholes do not usually require casing. Through small cracks the boreholes naturally fill with groundwater and local environmental regulations in general allow insertion of a U-tube directly into the borehole. The top, however, is always sealed against intrusion of surface water. Heat transfer between U-tube and rock is by buoyancy driven natural convection, sometimes assisted by advection (horizontal water currents in rock with large cracks).

Saqib Javed is a graduate student at Chalmers University of Technology, Sweden. **Jeffrey D. Spitler** is a professor at Oklahoma State University, Stillwater. **Per Fahlén** is a professor at Chalmers University of Technology, Sweden.

Although conducting a TRT for a single pilot borehole has become a standard practice, the issue of test accuracy has received little attention. Austin et al. (2002) conducted a sensitivity analysis to study the effects of various test and parameter uncertainties on the ground thermal conductivity estimation for tests evaluated by their numerical method. Javed (2010) performed a similar analysis for tests evaluated by the line source approximation method. These analyses were conducted for individual boreholes and were based mostly on propagation of uncertainties from primary sources. However, this work takes a different approach and uses nine nearby boreholes to check random errors between tests and borehole finishing effects, as well as possible inhomogeneities. It should be noted that the effects of possible inhomogeneities – local differences in the bedrock properties – are necessarily comingled with the effects of test uncertainties when using the approach described here. A comparison of ground thermal conductivity, borehole thermal resistance and undisturbed ground temperature values, estimated for nine nearby boreholes, provides meaningful insight into the issue of random uncertainties between different tests. The TRT results of nine boreholes are then used to perform a sensitivity analysis to study the influence of variations in ground thermal conductivity and borehole thermal resistance estimations on the design of borehole systems.

Other issues addressed in this paper include the effects of test duration and heat injection rates on the ground thermal conductivity and the borehole thermal resistance estimations. For economic and commercial reasons, tests shorter than 24 hours have been suggested (Smith, 1999; Smith and Perry, 1999). In contrast, ASHRAE (2007) recommends minimum test durations of 36-48 hours. Moreover, Spitler et al. (1999) and Gehlin (2002) emphasize minimum test durations of 50 and 60 hours, respectively. This paper uses a 270-hour test to analyze the effects of different test lengths on the ground thermal conductivity and the borehole thermal resistance estimations. The paper also addresses the issue of uncertainties caused by using different heat injection rates in groundwater-filled boreholes. Gehlin (2002) and Gustafsson and Westerlund (2010) have shown that, for groundwater-filled boreholes, the choice of heat injection rate can significantly influence the ground thermal conductivity and the borehole thermal resistance estimations. This paper investigates the effects of different heat injection rates on the ground thermal conductivity, and the borehole thermal resistance estimations, by retesting boreholes with injection rates between 25-150 W/m (8-46 W/ft).

EXPERIMENTAL FACILITY AND METHODOLOGY

A new ground source heat pump test facility (Javed and Fahlén, 2010) has been developed at Chalmers University of Technology, Sweden. This new test facility provides a unique opportunity to study thermal properties, including undisturbed ground temperature, ground thermal conductivity and borehole thermal resistance of nine boreholes in close proximity. The laboratory's borehole system consists of nine groundwater-filled boreholes, each about 80 m (262 ft) deep. The boreholes of the new test-site are drilled in a 3 x 3 rectangular configuration. The horizontal cross-section of an individual borehole and the layout of the whole borehole system are shown in Figure 1.

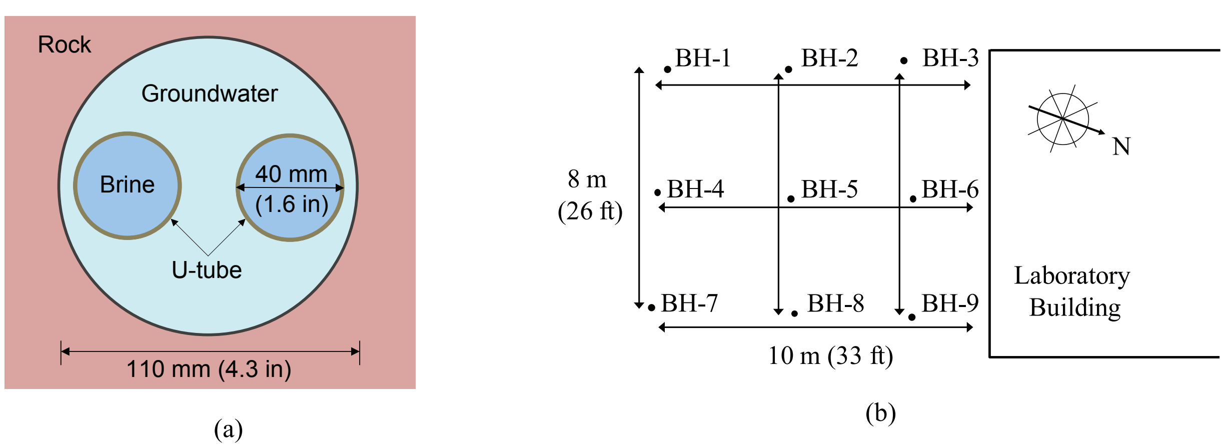


Figure 1 *Geometry and layout of the laboratory boreholes.*

The thermal response setup of the laboratory includes a variable capacity electric heater, variable speed circulation pumps and temperature and flow sensors. An electric resistance heater is used to conduct TRTs in heat injection mode. It is also possible to conduct tests in heat extraction mode using a heat pump. All the TRTs reported in this paper were conducted in the heat injection mode.

Before conducting TRTs of laboratory boreholes, undisturbed ground temperature measurements were taken for all nine boreholes. Following the undisturbed ground temperature measurements, TRTs were conducted for nine boreholes. Similar heat injection and flow rates were used for all tests. The input power was monitored and kept steady. The chosen heat injection rate matched the expected peak loads on the boreholes. The flow from the variable circulation pumps ensured turbulent regime in the ground loop. The tests were conducted for a minimum of 48 hours. The ground thermal conductivity values were estimated using the method proposed by Gehlin (2002). The method, which is based on the line source approximation, uses the slope of the borehole mean fluid temperature plotted against the logarithmic time to estimate the ground thermal conductivity value. The method suggested by Beier and Smith (2002) was used to determine the borehole thermal resistance values. This method utilizes the temperature difference between the experimentally measured mean fluid temperature and the borehole wall temperature calculated from the line source approximation. The borehole thermal resistance is then calculated as the ratio of this temperature difference to the heat transfer rate per unit length of the borehole.

UNDISTURBED GROUND TEMPERATURE MEASUREMENTS

The undisturbed ground temperature for each borehole was determined using two different approaches. In the first approach, the fluid was circulated through the undisturbed borehole for a minimum of 30 minutes. The inlet and outlet fluid temperatures were recorded at intervals of 10 seconds. The fluid temperature stabilized after approximately 30 minutes of circulation. The stabilized mean fluid temperature was taken as a measure of the undisturbed ground temperature. One of the problems with this approach is that, for longer times, the undisturbed ground temperature measurements are affected by the heat gains from the circulation pump. However, this problem was avoided by the use of highly efficient custom-made pumps for borehole applications. The measurements of the undisturbed ground temperature calculated by this approach vary between 8.1 and 9.2 °C (46.6 and 48.6 °F). One possible explanation of the variations in undisturbed ground temperature measurements is the ambient coupling of the circulating fluid temperatures. With the water table for the laboratory boreholes as high as the ground level, the top of the groundwater-filled boreholes is affected by the ambient temperature changes. The second approach used to measure the undisturbed ground temperature was to monitor the start-up exit fluid temperatures from the U-tube. If the fluid is kept long enough in the U-tube, it reaches equilibrium with the surrounding ground. The undisturbed ground temperature can then be determined by taking the average temperature of the fluid present in the U-tube. This approach gave a consistent estimation of 8.3 °C (46.9 °F) for all boreholes. The undisturbed ground temperatures, calculated using the start-up exit fluid temperature approach, have been used for results reported in this paper.

TRT RESULTS

The TRT of the nine laboratory boreholes were conducted over a period of four months. The duration of most of the TRTs was between 68 to 98 hours, but tests as short as 48 hours, and as long as 267 hours, were also conducted. The results of ground thermal conductivity and borehole thermal resistance estimations for the nine laboratory boreholes are summarized in Table 1. The ground thermal conductivity estimations for the nine boreholes vary between the extreme values of 2.81 and 3.2 W/m·K (1.62 and 1.85 Btu/h·ft·°F), whereas the estimated values of borehole thermal resistance vary between the extreme values of 0.049 and 0.074 m·K/W (0.085 and 0.128 h·ft·°F/Btu). The ground thermal conductivity and borehole thermal resistance estimations have noticeable random variations. The ground thermal conductivity estimations have a mean value of 3.01 W/m·K (1.74 Btu/h·ft·°F). The estimated values for all nine boreholes lie within ±7 % of the mean value. The estimated values are within commonly assumed uncertainties of 10 % in TRT measurements (Witte et al., 2002). On the other hand, the estimated borehole thermal resistance values exhibit larger variations. The borehole thermal resistance values of nine laboratory boreholes lay in a range of 0.062 ± 0.012 m·K/W (0.107 ± 0.021 h·ft·°F/Btu).

Table 1. Ground Thermal Conductivity and Borehole Thermal Resistance Estimations for Laboratory Boreholes.

Borehole	Duration, Hours	Ground Thermal Conductivity, W/m·K (Btu/h·ft·°F)	Borehole Thermal Resistance, m·K/W (h·ft·°F/Btu)
1	75	2.88 (1.66)	0.059 (0.102)
2	54	3.06 (1.77)	0.064 (0.111)
3	267	3.04 (1.76)	0.074 (0.128)
4	48	2.81 (1.62)	0.049 (0.085)
5	68	2.98 (1.72)	0.064 (0.111)
6	91	2.89 (1.67)	0.063 (0.109)
7	48	3.19 (1.84)	0.064 (0.111)
8	69	3.20 (1.85)	0.065 (0.112)
9	98	3.12 (1.80)	0.069 (0.119)

SENSITIVITY ANALYSES USING CASE STUDIES

As seen in the previous section, there exist random variations in the ground thermal conductivity and borehole thermal resistance estimations for nine laboratory boreholes. This section analyzes the effect of these variations on the design of the borehole systems using three case studies. The first case to be discussed involves the Astronomy-House building at Lund University, Sweden. The building has a gross floor area of approximately 5,300 m^2 (57,050 ft^2). It contains offices, a large lecture hall, a library and laboratories. The heating and cooling requirements of the building are met by a borehole system consisting of twenty, 200 m (656 ft) deep boreholes. The borehole system provides 475 MWh (1,620 x 10^6 Btu) of heating and 155 MWh (530 x 10^6 Btu) of free cooling, details of which are given in Table 2. The Astronomy-House building is essentially a heating-dominated building with some cooling requirements. The borehole system of the building uses a 4 x 5 rectangular configuration to store some thermal energy in the ground at a time of energy surplus (i.e. summer) and to extract it in winter. The ground thermal conductivity and the borehole thermal resistance values used to design the borehole system of Astronomy-House were 2.8 W/m·K (1.62 Btu/h·ft·°F) and 0.07 m·K/W (0.121 h·ft·°F/Btu), respectively.

Table 2. Monthly Heating and Cooling Demands of the Case Study Buildings.

Month	Lund		Tulsa		Burlington	
	Heating, MWh (10^6 Btu)	Cooling, MWh (10^6 Btu)	Heating, MWh (10^6 Btu)	Cooling, MWh (10^6 Btu)	Heating, MWh (10^6 Btu)	Cooling, MWh (10^6 Btu)
Jan	97.9 (334)	-	16.3 (56)	-	36.4 (124)	-
Feb	89.3 (305)	-	5.0 (17)	1.8 (6)	30.4 (104)	-
Mar	69.8 (238)	3.4 (12)	1.6 (5)	9.7 (33)	18.3 (62)	0.1 (1)
Apr	40.9 (140)	7.3 (25)	0.4 (1)	21.4 (73)	4.5 (16)	5.7 (19)
May	20.9 (71)	15.0 (51)	-	54.3 (185)	0.5 (2)	23.4 (80)
Jun	-	25.7 (88)	-	103.5 (353)	-	37.0 (126)
Jul	-	33.2 (113)	-	127.9 (436)	-	63.0 (215)
Aug	-	31.3 (107)	-	128.2 (437)	-	54.5 (186)
Sep	-	19.2 (66)	-	54.1 (185)	0.4 (1)	18.7 (64)
Oct	31.4 (107)	13.3 (45)	0.3 (1)	31.0 (106)	1.8 (6)	-
Nov	47.5 (162)	6.4 (22)	1.7 (6)	4.0 (14)	7.6 (26)	-
Dec	77 (263)	-	6.9 (24)	-	23.4 (80)	-
Year	475 (1620)	155 (530)	32 (110)	536 (1830)	123 (420)	202 (690)

For case studies 2 and 3, a hypothetical office building, based on three floors of an actual office building in Tulsa, Oklahoma, is used. The building has a footprint of approximately 49 m x 49 m (161 ft x 161 ft), and is 9 m (30 ft) high. The building façade is approximately 60% covered by double-pane glass windows. The building has high occupancy [1 person per 5 m^2 (54 ft^2)] and high lighting and equipment heat gains [combined 23.1 W/m^2 (2.1 W/ft^2)] with office-appropriate schedules. The building is described more fully by Gentry (2007). The hourly heating and cooling loads for this office building have been determined for very different climates conditions of Tulsa (warm-humid) and Burlington, Vermont (cold-humid) using building energy simulation software. As seen from Table 2, the heating and cooling requirements of the same building, located in Tulsa and in Burlington, are considerably different. For the case of Tulsa, the building has predominant cooling requirements of 536 MWh (1830 x 10^6 Btu) and heating requirements of just 32 MWh (110 x 10^6 Btu). To meet these requirements, a borehole system is designed using a commercially available software. Ideally, the borehole system of the Tulsa building should maximize the heat transfer between the borehole system and the surrounding ground and, hence, should have an open configuration. However, because the cooling requirements of the building are quite high, using an open configuration, like a Line or a U configuration, will result in a very large and impractical borehole field. Therefore, a rectangular configuration of 9 x 25 was chosen for the borehole field of Tulsa. For the Burlington building, the heating and cooling demands are 123 and 202 MWh (420 x 10^6 and 690 x 10^6 Btu), respectively. As this building has fairly balanced demands, a 7 x 10 rectangular configuration is chosen to exploit the seasonal heat storage ability of the ground.

The three cases presented above have been used to analyze the effects of random variations between test results of nine boreholes on the design of borehole fields of these cases. This is done by calculating the required length of the borehole field, for all three cases, using ground thermal conductivity and borehole thermal resistance values estimated for each of the nine laboratory boreholes. The calculations are made for minimum and maximum heat pump entering fluid temperatures of -5 and 35 °C (23 and 95°F) in heating and cooling modes, respectively. The results are summarized in Table 3.

In the case of the Lund building, the random uncertainties in ground thermal conductivity and borehole thermal resistance values for nine boreholes result in total borehole length varying between extremes of 3,770 m (12,370 ft) and 4,020 m (13,190 ft). The difference between these two lengths is 250 m (820 ft), approximately equivalent to one and a quarter boreholes out of 20. For the Tulsa building, 20,870 m (68,470 ft) and 22,615 m (74,195 ft) are respectively the smallest and largest required borehole lengths. The difference between these two lengths is 1,745 m (5725 ft), approximately equivalent to 17 boreholes out of 225. For the Burlington building, the 640 m (2,100 ft) difference between the extreme lengths of 6,860 m (22,505 ft) and 7,500 m (24,605 ft) correspond to approximately 6 out of 70 boreholes. For all three test cases, the random uncertainties between TRTs moderately affect the total length requirements of the borehole field. These uncertainties change the total borehole length requirements by 6-10 %. If these uncertainties are not accounted for in the design with a factor of safety, the resulting borehole systems can be moderately under-sized.

Table 3. Effect of Random Variations in Ground Thermal Conductivity and Borehole Thermal Resistance on the Size of Borehole Field.

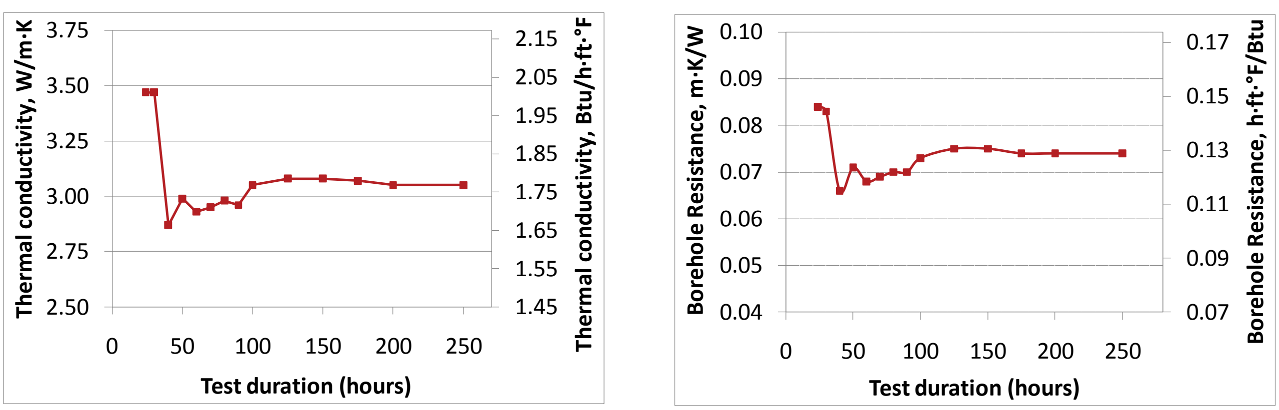
TRT	Lund		Tulsa		Burlington	
	Total Length, m (ft)	Individual Borehole Depth, m (ft)	Total Length, m (ft)	Individual Borehole Depth, m (ft)	Total Length, m (ft)	Individual Borehole Depth, m (ft)
1	4,005 (13,140)	200.2 (656.8)	22,410 (73,525)	99.6 (326.8)	7,120 (23,360)	101.7 (333.7)
2	3,900 (12,795)	195.0 (639.8)	21,600 (70,865)	96.0 (315.0)	7,120 (23,360)	101.7 (333.7)
3	3,990 (13,090)	199.4 (654.2)	22,500 (73,820)	100.0 (328.1)	7,500 (24,605)	107.1 (351.4)
4	3,990 (13,090)	199.5 (654.5)	22,165 (72,720)	98.5 (323.2)	6,860 (22,505)	98.0 (321.5)
5	3,970 (13,025)	198.5 (651.2)	22,140 (72,640)	98.4 (322.8)	7,195 (23,605)	102.8 (337.3)
6	4,020 (13,190)	200.9 (659.1)	22,615 (74,195)	100.5 (329.7)	7,260 (23,820)	103.7 (340.2)
7	3,775 (12,385)	188.8 (619.4)	20,870 (68,470)	92.7 (304.1)	6,955 (22,820)	99.3 (325.8)
8	3,770 (12,370)	188.6 (618.8)	20,890 (68,535)	92.8 (304.5)	6,980 (22,900)	99.7 (327.1)
9	3,880 (12,730)	193.9 (636.2)	21,595 (70,850)	96.0 (315.0)	7,235 (23,735)	103.4 (339.3)

TEST DURATION AND HEAT INJECTION RATE

Test duration has often been discussed as an uncertainty factor when conducting and evaluating TRTs. Beier and Smith (2003) reported a method to calculate the minimum test duration necessary to estimate ground thermal conductivity within 10 % of the converged value from a long TRT. Other researchers, including Smith (1999) and Gehlin (2002), have suggested minimum test durations ranging between 24 and 60 hours based on practical considerations and experiences from in-situ testing. One way to investigate the issue of minimum test duration is to conduct a long TRT and to observe the sensitivity of the TRT results to the length of the data used. However, very few tests with durations over 100 hours have been reported in literature. Austin et al. (2000) conducted a 180-hour test and investigated the effects of test durations on the thermal conductivity estimations evaluated using their parameter estimation method. They observed that, for test durations over 50 hours, the ground thermal conductivity estimations have a maximum absolute error of approximately 5 %. For test durations shorter than 30 hours, the absolute error was higher than 10 %.

To check the sensitivity of the TRT results to the length of the test duration, borehole 3 was tested for over 260 hours. The ground thermal conductivity of borehole 3 has been estimated for various test durations, between 24 and 250 hours, using the line source approximation. These results are shown in Figure 2a. The estimated ground thermal conductivity converges after approximately 100 hours and, subsequently, no significant changes are seen in the estimated values. For test durations, between 50 to 100 hours, a maximum absolute deviation of less than 4 % is observed. However, the deviation is significantly higher for test durations shorter than 50 hours. The absolute error increases up to 14 % for a 30-hour test. These results are similar to those reported by Austin et al. It may be noted that the trends of the estimates of conductivity and borehole resistance, shown in Figures 2a and 2b, are similar. For example, compared to the final converged values the estimates of both conductivity and borehole resistance at 30 hour are about 14 % high. The two parameters have counterbalancing effects on the design, and so use of both parameters estimated from a TRT may mitigate some of the error that would occur if only the conductivity was estimated from a TRT.

To investigate the uncertainties caused by shorter test durations, the required borehole lengths for the Lund, Tulsa, and Burlington cases are calculated based on ground thermal conductivity and borehole thermal resistance estimations for different test lengths of borehole 3. The results for test lengths of 30, 50 and 100 hours are given in Table 4. For all three cases, using ground thermal conductivity and borehole thermal resistance estimations, from 50 and 100 hour tests, give similar total borehole lengths. In contrast, using ground thermal conductivity and borehole thermal resistance estimations from a 30-hour test, results in borehole lengths undersized by approximately 9 % for the Lund and Tulsa cases.



(a) (b)

Figure 2 *Ground thermal conductivity and borehole thermal resistance estimations for different test lengths of borehole 3.*

Table 4. Effect of Test Length on the Size of Borehole Field.

Test Length, hours	Lund		Tulsa		Burlington	
	Total Length, m (ft)	Individual Borehole Depth, m (ft)	Total Length, m (ft)	Individual Borehole Depth, m (ft)	Total Length, m (ft)	Individual Borehole Depth, m (ft)
30	3,670 (12,040)	183.5 (602.0)	20,980 (68,830)	93.2 (305.8)	7,410 (24,310)	105.8 (347.1)
50	4,000 (13,125)	200.0 (656.2)	22,680 (74,410)	100.8 (330.7)	7,420 (24,345)	106.0 (347.8)
100	3,975 (13,040)	198.7 (651.9)	22,350 (73,325)	99.3 (325.8)	7,450 (24,440)	106.4 (349.1)

For groundwater-filled boreholes, the effect of the chosen heat injection rate on the TRT results has also been a topic of discussion. For boreholes located in solid, unfractured bedrock, the estimated values of borehole thermal resistance decrease with increasing heat injection rates, while the ground thermal conductivity estimates remain unchanged. In contrast, for boreholes located in fractured bedrock, a larger heat injection rate results in higher ground thermal conductivity estimation, whereas the borehole thermal resistance value remains unchanged. This is because a larger heat injection rate increases the convective heat transport in a solid bedrock borehole which, consequently, decreases the borehole thermal resistance. On the other hand, in the case of a borehole in fractured bedrock, a larger heat injection rate increases the convective heat flow through the surrounding rock which results in a higher estimate of the ground thermal conductivity.

Ideally, a TRT should be conducted with 50-80 W/m (15-25 W/ft) that are the expected peak loads on a borehole (ASHRAE, 2007). However, in practice it is common to conduct tests with heat injection rates outside this range. To investigate the uncertainties caused by using different heat injection rates, a series of retests were conducted on borehole 7 and 9. For the case of borehole 9, the tests are conducted for four different heat injection rates between 25 and 140 W/m (8 and 43 W/ft). For these tests, larger heat injection rates result in lower borehole thermal resistances, as shown in Figure 3b. The ground thermal conductivity estimations, however, remain nearly constant (Figure 3a). These results are in line with the observations of Gustafsson and Westerlund (2010) for boreholes with solid unfractured bedrock. In the case of borehole 7, only two levels have been tested, but the estimated borehole thermal resistance values are about the same for both cases, whereas the ground thermal conductivity value increases significantly at the high injection rate. The results of borehole 7 suggest that this borehole has fractured bedrock.

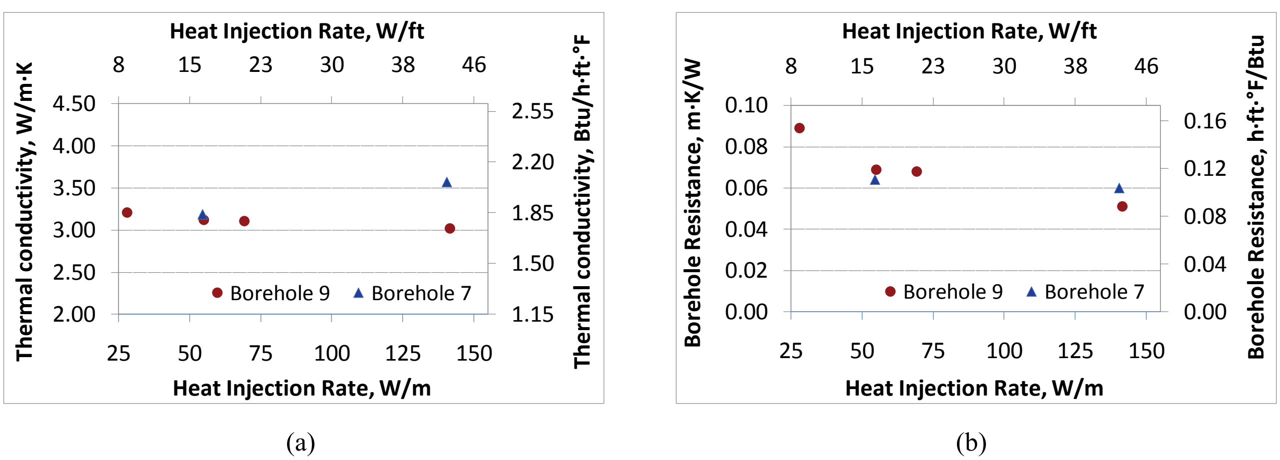


Figure 3 *a) Ground thermal conductivity and b) borehole thermal resistance estimations for different heat injection rates for boreholes 7 and 9.*

Table 5. Effect of Heat Injection Rate on the Size of Borehole Field based on Borehole 9 (Appears to be Solid, Unfractured Bedrock).

Heat Injection Rate, W/m (W/ft)	Ground Thermal Conductivity Estimation, W/m·K (Btu/h·ft·°F)	Borehole Thermal Resistance Estimation, m·K/W (h·ft·°F/Btu)	Total Length, m (ft)		
			Lund	Tulsa	Burlington
28 (9)	3.21 (1.86)	0.089 (0.154)	3,945 (12,945)	22,590 (74,115)	7,890 (25,885)
55 (17)	3.12 (1.80)	0.069 (0.119)	3,875 (12,715)	21,595 (70,850)	7,235 (23,735)
70 (21)	3.11 (1.80)	0.068 (0.118)	3,880 (12,730)	21,580 (70,800)	7,210 (23,655)
142 (43)	3.02 (1.75)	0.051 (0.088)	3,845 (12,615)	20,850 (68,405)	6,655 (21,835)

The uncertainties in ground thermal conductivity and borehole thermal resistance estimations, caused by using different heat injection rates, are investigated for the three case studies. Table 5 provides the details of required borehole lengths calculated for three buildings using ground thermal conductivity and borehole thermal resistance estimations for borehole 9. The heat injection rates of 55 and 70 W/m (17 and 21 W/ft), which lie in the range recommended by ASHRAE (2007), give similar results in all three cases. For the cases of the Lund and Tulsa buildings, the heat injection rates of 28 and 142 W/m (9 and 43 W/ft), respectively, result in slightly over-sized and under-sized systems in comparison to the 55 and 70 W/m (17 and 21 W/ft) tests. In the case of the Burlington building, the heat injection rates of 28 and 142 W/m (9 and 43 W/ft) result in boreholes oversized by 9 % and undersized by 8 %, respectively, compared to the 55 and 70 W/m (17 and 21 W/ft) tests.

Table 6. Effect of Heat Injection Rate on the Size of Borehole Field based on Borehole 7 (Appears to be Fractured Bedrock).

Heat Injection Rate, W/m (W/ft)	Ground Thermal Conductivity Estimation, W/m·K (Btu/h·ft·°F)	Borehole Thermal Resistance Estimation, m·K/W (h·ft·°F/Btu)	Total Length, m (ft)		
			Lund	Tulsa	Burlington
55 (17)	3.19 (1.84)	0.064 (0.111)	3,765 (12,350)	20,865 (68,455)	6,955 (22,820)
141 (43)	3.57 (2.06)	0.060 (0.104)	3,385 (11,105)	18,885 (61,960)	6,380 (20,930)

Table 6 presents the required borehole lengths when the borehole systems of the three case study buildings (Lund, Tulsa and Burlington) are designed, based on TRT results of borehole 7. When using the TRT results from the 141 W/m (43 W/ft) test, the borehole systems, for all three cases, are undersized by approximately 10 %.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, the random variations in undisturbed ground temperature, ground thermal conductivity and borehole thermal resistance were studied for a field of nine boreholes. The undisturbed ground temperature measurements were consistent when measured using the start-up, exit-fluid temperature approach. The ground thermal conductivity and the borehole thermal resistance estimations for nine boreholes have considerable variations despite conducting well-controlled tests of minimum 48 hour duration. The ground thermal conductivity estimations have a mean value of 3.01 W/m·K (1.74 Btu/h·ft·°F) and the estimations for all nine boreholes lie within ±7 % of this value. The estimated values of borehole thermal resistance were in the range of 0.062 ± 0.012 m·K/W (0.107 ± 0.021 h·ft·°F/Btu). The variations in the estimated ground thermal conductivity and borehole thermal resistance values were analyzed using three case studies. It was shown that the variations in ground thermal conductivity and borehole thermal resistance estimations can change the required length of borehole systems by 6-10 %.

The effect of uncertainties caused by test durations and heat injection rates were also investigated. Test durations of 30 hours resulted in wrongly-sized borehole systems. Hence, a TRT of a minimum 50 hours is recommended to eliminate uncertainties caused by shorter test durations. The heat injection rates also result in significant uncertainties for groundwater-filled boreholes. For a borehole with solid bedrock, a larger injection rate results in lower borehole thermal resistance estimations. For a borehole with fractured bedrock, a larger injection rate results in higher ground thermal conductivity estimations. The higher or lower values of ground thermal conductivity, and the borehole thermal resistance, can negatively influence the performance of a borehole system. Higher than expected values of ground thermal conductivity increases the thermal interaction between the boreholes of a field, which consequently affects the fluid temperatures. Similarly, lower than expected borehole thermal resistance values also affect the fluid temperatures. Therefore, it is important to perform a TRT at heat injection rates anticipated for the installation. Failing to do so can result in an under-sized or over-sized borehole system.

Finally, though more research is needed, the results reported here suggest that designs based on a single careful 50+ hours TRT, using the thermal conductivity, borehole resistance and undisturbed ground temperature estimated with the test, might be expected to have uncertainties on the order of 10 %, and hence a safety factor of 10 % may be recommended.

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