Horizontal Borehole Study

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Summary

Ten horizontal boreholes have been drilled to determine if thermal performance varies between boreholes with bentonite grout and those without grout. If grout is not used, drilling mud and cuttings remain in the borehole. All the boreholes pass through clay soil at a site in Stillwater, Oklahoma. The thermal performance has been quantified by performing an in-situ thermal response test on each borehole. The in-situ test provides estimates of borehole resistance and soil thermal conductivity. Boreholes with bentonite grout have a mean borehole resistance of 0.344 Btu/(hr-ft-°F), while boreholes without grout have a mean resistance of 0.366 Btu/(hr-ft-°F). The difference in these values is too small to be statistically significant. Thus, as a group the boreholes with grout perform about the same as the boreholes without grout. Also, the average borehole resistance in these horizontal boreholes is slightly smaller than the value found in a comparably completed nearby vertical borehole. We plan to retest the boreholes after one year has passed to check for any changes with time.

Introduction

Ground source heat pump systems often use closed-loops to exchange heat with the ground in cooling and heating buildings. Directional drilling of horizontal boreholes is a viable option that offers advantages especially for retrofit installations of GSHP systems. For example, the drilling of the borehole can be guided under an existing parking lot without disturbing the surface of the parking lot.

Horizontal boreholes are usually at shallow depths between 6 to 12 feet. Regulations regarding the use of grout to protect groundwater vary widely among states (Den Braven, 2000) for both horizontal and vertical boreholes. Independent of environmental issues, the choice of whether grout is used and the type of grout may impact on the thermal performance of the borehole. The present report addresses the issue of thermal performance of horizontal boreholes with and without grout. Drilling fluid and cuttings remain in the boreholes without grout.

Thermal performance has been evaluated on a set of ten boreholes drilled through clay soil in Stillwater, Oklahoma. All the boreholes are approximately 200 feet in length with a high density polyethylene U-tube (3/4 inch, SDR-11) placed in each borehole. A summary of the characteristics of each borehole is given in Table 1. A benotonite grout has been pumped in six of the boreholes, and no grout has been placed in the other four boreholes. Most of the boreholes have been drilled with a bentonite-based drilling fluid. In two boreholes a polymer based drilling fluid has been used. The drill diameter is either 4-1/2 inches or 5-1/2 inches. The boreholes are approximately parallel and about 7 feet apart.

Drilling Operations

The drilling of all the boreholes took place during the days of May 10 to May 14, 2010. The drilling was performed by Charles Machine Works, Inc. (Ditch Witch ®). Operators from Halliburton Baroid ® provided support for mixing the drilling fluid and grout. Figure 1 shows one of their drilling machines where the borehole starts at an embankment and follows a horizontal path of length 200 feet. Then the drilling bit is directed upward to eventually penetrate the surface. An illustration of the typical borehole path is shown in Figure 2.

The U-tube was placed in the borehole so that the straight ends of the loop would stick out of the embankment. To achieve this arrangement, the straight ends of a loop were pulled through borehole #1 starting at the south end and pulled northward. While pulling the loop, the operator pumped grout through the drill pipe, and the grout flowed though a hole near the drilling bit and into the borehole. The U-tube was placed in borehole #1 in this manner, but unexpected complications arose when the U-tube was pulled through the borehole. The loop arrived in a coil and the lengths of both pipes in the loop were not the same when the loop was straightened. Unequal lengths caused the U-bend at the end of the loop to turn as it was dragged into the hole. This turning created the possibility of collapsing one of the legs of the loop.

To avoid the possibility of collapsing one of the pipes, the drilling machines were placed on the south end of the site (Figure 2) away from the embankment while drilling the other nine boreholes. In these boreholes, the drill bit traveled through an angled section before following a horizontal path. After traveling at least 200 feet along the horizontal path, the drill bit broke through the embankment. Then the U-bend of the loop was pulled through the borehole. A rope was used between the U-bend and the drilling bit so that the final placement of the loop would be in the horizontal section. The rope was left in the angled section rising to the surface.

Enclosed in the drill pipe directly behind the drill bit was a beacon, which transmitted a radio signal with information about its location. An operator (Figure 3) with a locator stood above the drill bit to record its position and depth. In this way the depth and path of each borehole were recorded.

The exact placement of the U-tube within the borehole is unknown for a number of reasons. The coiled U-tube pipes remember their curved shapes and want to bend after they are straightened, which may cause each leg of the loop to change its position many times along the borehole path. Because the U-tube is filled with air when it is pulled, a buoyancy force would tend to push the U-tube toward the top of the borehole. In the boreholes with grout the space between the U-tube and the borehole wall is likely occupied by some mixture of grout, drilling mud, and cuttings (Figure 4). While placing the loop in the borehole the volume of grout pumped into the borehole exceeds the volume of the borehole. However, it is not known how much of the drilling fluid and cuttings are displaced. In the boreholes without grout, drilling mud is pumped into the borehole while pulling the U-tube to inhibit air pockets forming.

Thermal Conductivity of Borehole Fluids

The thermal performance of the borehole is affected by the thermal conductivity of the materials left in the borehole. Three samples were taken of the bentonite grout from the mixing tanks during drilling operations. The samples were stored in 5-gallon buckets. The thermal conductivity of the grout was determined with a thermal probe. For these three samples the grout thermal conductivity ranged between 0.43 and 0.47 Btu/(hr-ft-F). These values are slightly above the minimum thermal conductivity of 0.4 Btu/(hr-ft-F) specified by Halliburton Baroid®.

For the nine boreholes drilled from the south end of the site, a small pit was made to catch any fluid coming out of the borehole. After the loop was in place, 5-gallon samples of pit fluid were taken for boreholes #1, #2, #4, #7, #9 and #10. After the pit fluids set for over two months in closed containers, the containers were opened. The solids generally settled below a layer of water at the top of each container. In an attempt to remove the excess water, we poured each mixture through a screen and placed the solids back into the sealed container. After three days the containers were again opened, but a layer of excess water reappeared on top. Each mixture was then vigorously stirred before placing the thermal probe into the mixture for a thermal conductivity measurement. The temperatures of the mixtures were between 60 and 65 °F during the measurements.

The thermal conductivity of the pit fluids with grout ranged between 0.47 and 0.69 Btu/(hr-ft-°F) as shown in Figure 5. The two samples of the pit fluids without grout had thermal conductivity of 0.45 and 0.46 Btu/(hr-ft-°F). These results indicate the boreholes with grout may have fluids with higher thermal conductivity. Of course, we do not know for sure that the pit fluids are the same mixture as the actual fluids in the borehole. Note the thermal conductivity of water at 60 °F is 0.34 Btu/(hr-ft-°F).

In-Situ Thermal Response Tests

An in-situ thermal response test was performed on each borehole between June 17 and August 8, 2010. Two portable test units were built for this purpose. During the test a pump circulates heated water through a closed loop as illustrated in Figure 6. An electric heater supplies heat at nearly a constant rate. A portable generator supplies the electric power to the heater, pump and computer data acquisition system. Thermistors measure the temperatures of the fluid as it enters and leaves the ground loop. A flow meter records the flow rate through the loop. As shown in Figure 7, the system is placed in a portable box that is thermally insulated and sealed to minimize the influence of outside temperature changes and weather conditions. After the setup is complete, an outer insulation board (not shown in Figure 7) is also placed on top the box to minimize solar heat gain.

The in-situ test provides estimates for both soil thermal conductivity and borehole thermal resistance. The average of the entering and leaving fluid temperatures is taken as the average temperature for the circulating fluid. This average is plotted in a semilog graph as shown in Figure 8. The horizontal axis is the natural logarithm of time. Time equals zero when the heater is switched on. In an ideal test the heat input rate remains constant. A line-source model (Carslaw and Jaeger, 1959; Beier and Smith, 2003) indicates the late-time data should follow a linear trend in the graph. The soil thermal conductivity is calculated from the slope, m, as

$$k_s = \frac{q}{4\pi\, m\, L} \tag{1}$$

where

k_s = soil thermal conductivity (Btu/(hr-f-F)
q = heat input rate (Btu/hr)
m = late-time slope (F/cycle)
L = borehole length (ft)

The heat transfer through the borehole and soil may be represented by the resistance network shown in Figure 9. In this simplification the borehole wall is assumed to be at a uniform temperature, T_b. The soil thermal conductivity is captured in the soil thermal resistances (R_{s1} and R_{s2}) between the borehole wall and the undisturbed soil temperature. An overall borehole resistance takes into account all the thermal resistances between the circulating loop temperature and the borehole wall. Usually the borehole resistances for each leg of the loop are taken to be identical, because insufficient information is available to calculate individual resistances. Then for resistances in parallel $R_{b1} = R_{b2} = 0.5\ R_b$, where R_b is the overall borehole resistance.

The overall borehole resistance is simply the temperature difference between the circulating fluid and borehole wall divided by the heat transfer rate per unit length of the borehole, q/L, or

$$R_b = \frac{T \;\; - T_b}{q / L}$$

The borehole resistance (Beier and Smith, 2003) is estimated from the expression

$$R_b = \frac{1}{4\pi k_s}\left[\frac{T_{1hr} - T_s}{m} - \log\left(\frac{4\alpha_s t_{1hr}}{\gamma\, r_b^2}\right)\right] \tag{2}$$

In Equation 2 the symbol T_{1hr} represents the extrapolated loop temperature at one hour along the late-time linear trend. The value of t_{1hr} is equal to one hour and its logarithm is zero as illustrated in Figure 10. Thus, temperature at one hour, T_{1hr}, can be viewed as the intercept value. The undisturbed soil temperature is T_s, and α_s is the soil thermal diffusivity. The constant γ has a value of 1.78. The borehole radius is represented by the symbol r_b.

The results for the borehole resistances are summarized in Figures 11 and 12. Among the 4.5-inch diameter boreholes with grout, the borehole resistance ranges from 0.263 to 0.353 Btu/(hr-ft-°F) with an average value of 0.322 Btu/(hr-ft-°F). For the three 4.5-inch boreholes without grout the borehole resistance ranges from 0.364 to 0.394 Btu/(hr-ft-°F) with an average value of 0.368 Btu/(hr-ft-°F).

There are many reasons for the borehole resistance to vary among the different boreholes even if the borehole size and grout are the same. The composition of the material in the different boreholes may vary, because the mixture contains drilling fluid, cuttings, and grout. Also the placement of the legs of the U-tubes is not controlled, but their locations affect the borehole resistance.

One would expect the borehole resistance to increase as the borehole diameter increases. In the two 5.5-inch diameter boreholes with grout (Figure 12) the borehole resistances are 0.385 and 0.392 Btu/(hr-ft-°F), which are larger than the values in the smaller diameter boreholes. In the 5.5-inch diameter borehole without grout the borehole resistance is 0.359 Btu/(hr-ft-F).

If all the boreholes are placed together, the mean resistance (0.344 Btu/(hr-ft-°F)) for the boreholes with grout is smaller than the mean resistance (0.366 Btu/(hr-ft-°F)) of the boreholes without grout. Statistical tests (Beckwith et al., 2007) are available to determine if the larger average borehole resistance in the wells without grout is statistically significant, or if the apparent difference between boreholes with and without grout is simply due to the random scatter in the data. A t-test comparison of the two average borehole resistances indicates that there is greater than a 20% chance the difference is due to random scatter in the data. Thus, the apparent difference in the mean thermal resistances is not statistically significant.

Although the thermal conductivity of the soil is not the main interest of this study, an interesting pattern emerged among the boreholes. The average depth of boreholes #1 and #2 are 11.2 ft and 9.6 ft, respectively. The other eight boreholes have average depths of less than 7.6 ft. As shown in Figure 13, the soil thermal conductivity around the two deeper boreholes is between 1.5 and 1.6 Btu/(hr-ft-°F), while the soil thermal conductivity around the shallower boreholes is below 1.2 Btu/(hr-ft-°F). Borehole # 6 has the shallowest average depth (6.3 ft) and the lowest soil thermal conductivity of 0.77 Btu/(hr-ft-°F). Thus, a clear trend of increasing soil thermal conductivity with increasing depth appears in Figure 13.

We plan to retest the boreholes after one year has elapsed to see if the borehole resistance changes over a one year period.

Acknowledgements

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Table 1. Horizontal boreholes.

Borehole Number	Drilling Bit Size (in)	Drilling Mud	Grout
1	4.5	Baroid Bore-Gel® (bentonite-based)	Baroid Bore-Grout (bentonite)
2	4.5	Baroid Bore-Gel® (bentonite-based)	Baroid Bore-Grout (bentonite)
3	5.5	Polymer Based Drilling Fluid	None
4	5.5	Baroid Bore-Gel® (bentonite-based)	Baroid Bore-Grout (bentonite)
5	5.5	Baroid Bore-Gel® (bentonite-based)	Baroid Bore-Grout (bentonite)
6	4.5	Polymer Based Drilling Fluid	None
7	4.5	Baroid Bore-Gel® (bentonite-based)	None
8	4.5	Baroid Bore-Gel® (bentonite-based)	Baroid Bore-Grout (bentonite)
9	4.5	Baroid Bore-Gel® (bentonite-based)	None
10	4.5	Baroid Bore-Gel® (bentonite-based)	Baroid Bore-Grout (bentonite)

Figure 1. Drilling horizontal borehole into embankment as done for borehole #1. (Operator Blaine Easter, Charles Machine Works, Inc.)

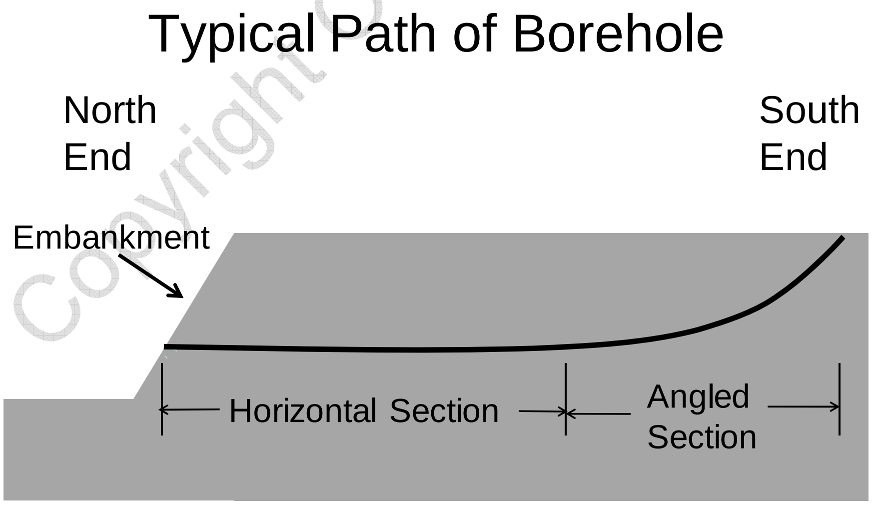

Figure 2. Typical path for a borehole.

Figure 3. Operators recording location of beacon on drill pipe. (Gary Lawson, left, and John Lamerton, right, Charles Machine Works, Inc.)

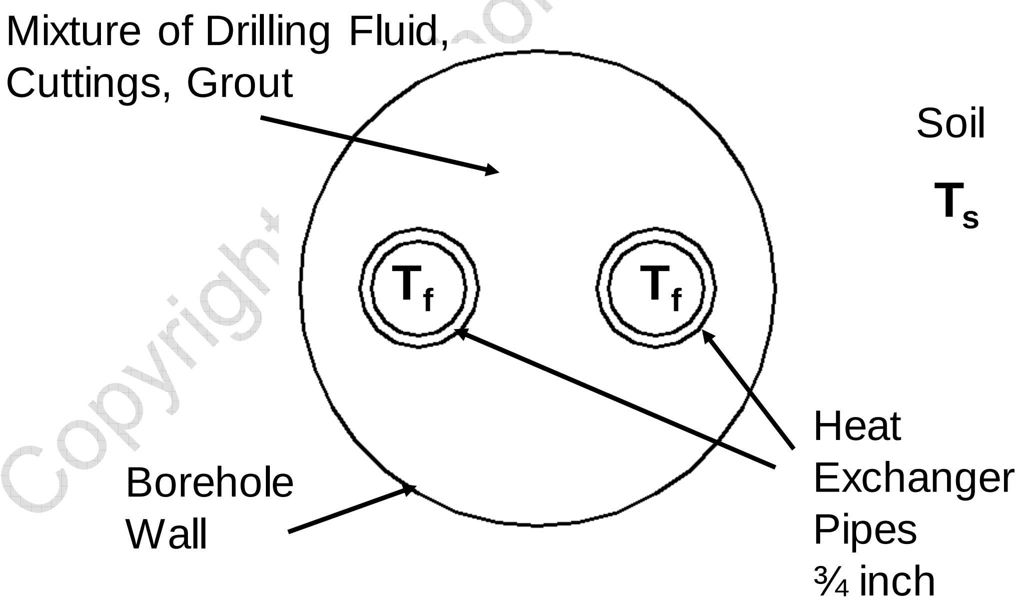

Figure 4. Cross section of ground loop heat exchanger.

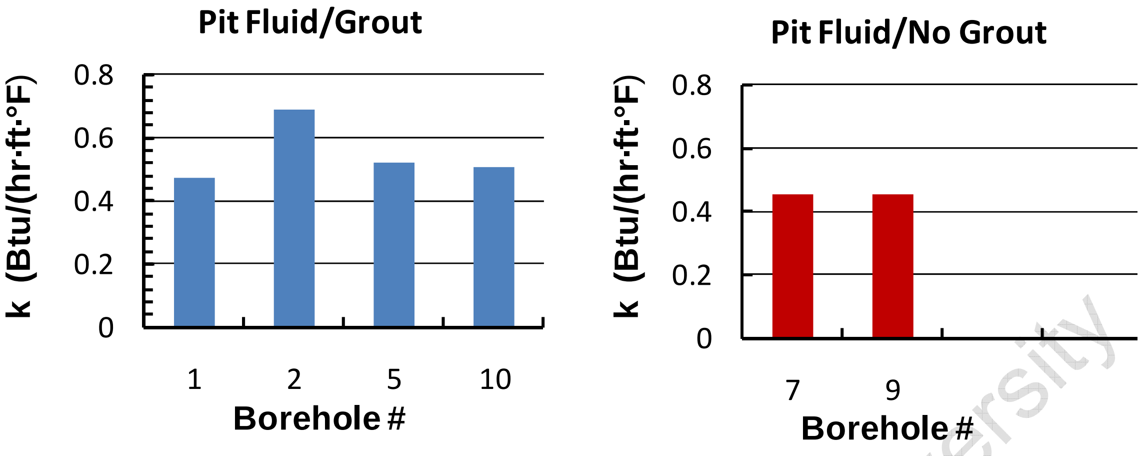

Figure 5. Thermal conductivity of fluid from drilling pit.

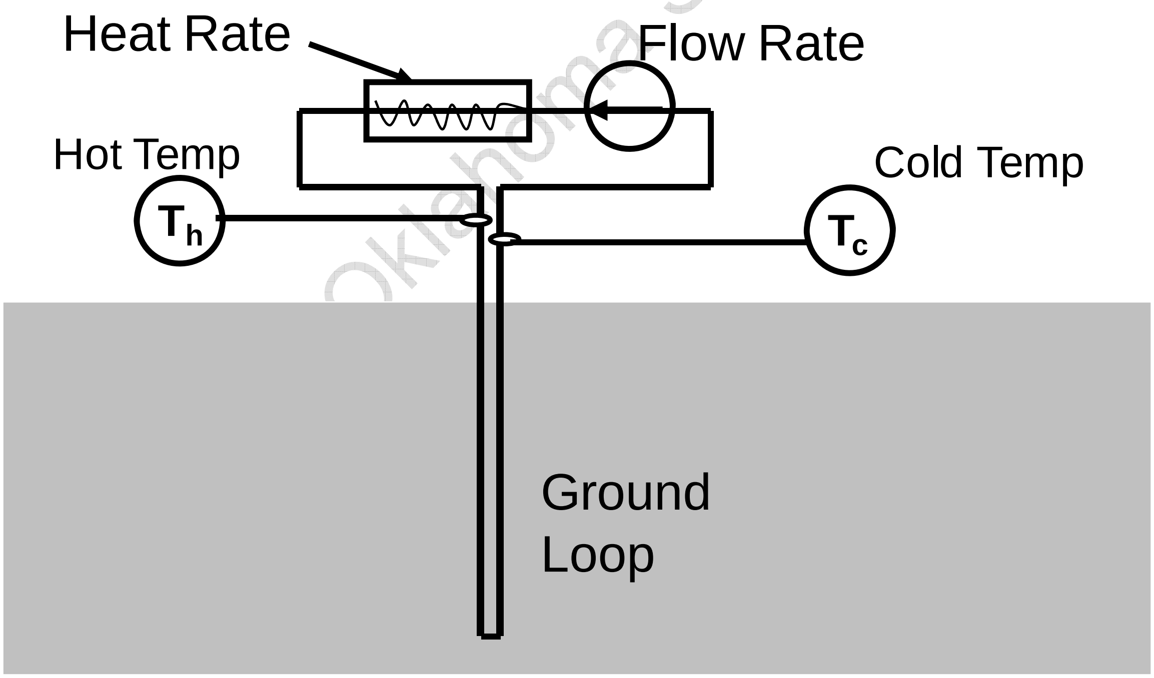

Figure 6. Measurements for in-situ thermal response test.

Figure 7. Equipment boxes for in-situ thermal response tests.

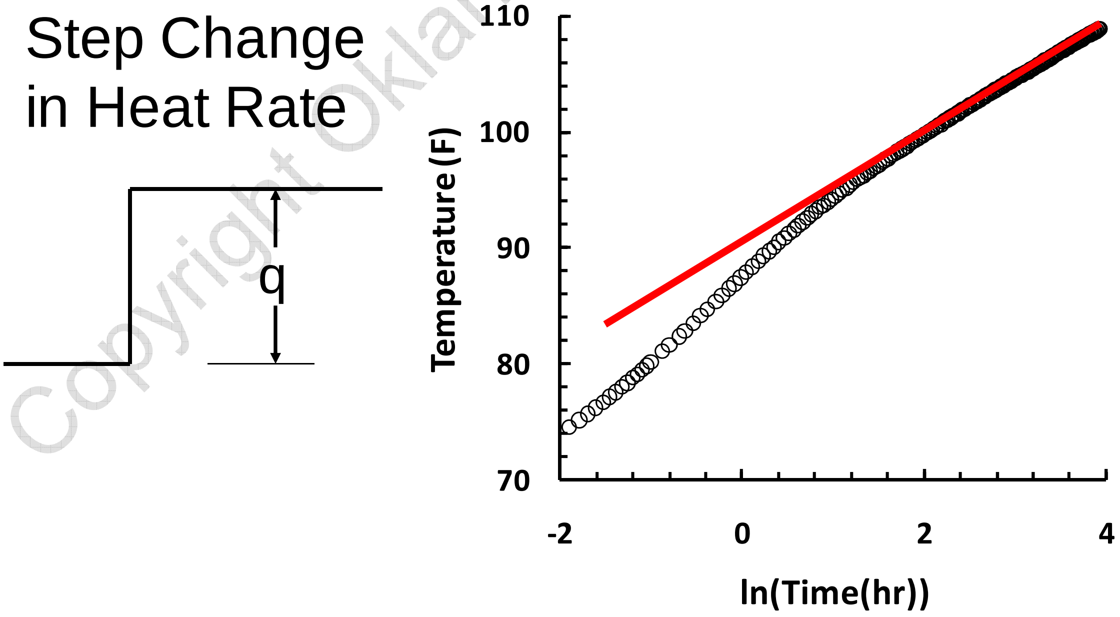

Figure 8. Temperature of circulating water during in-situ test on borehole # .

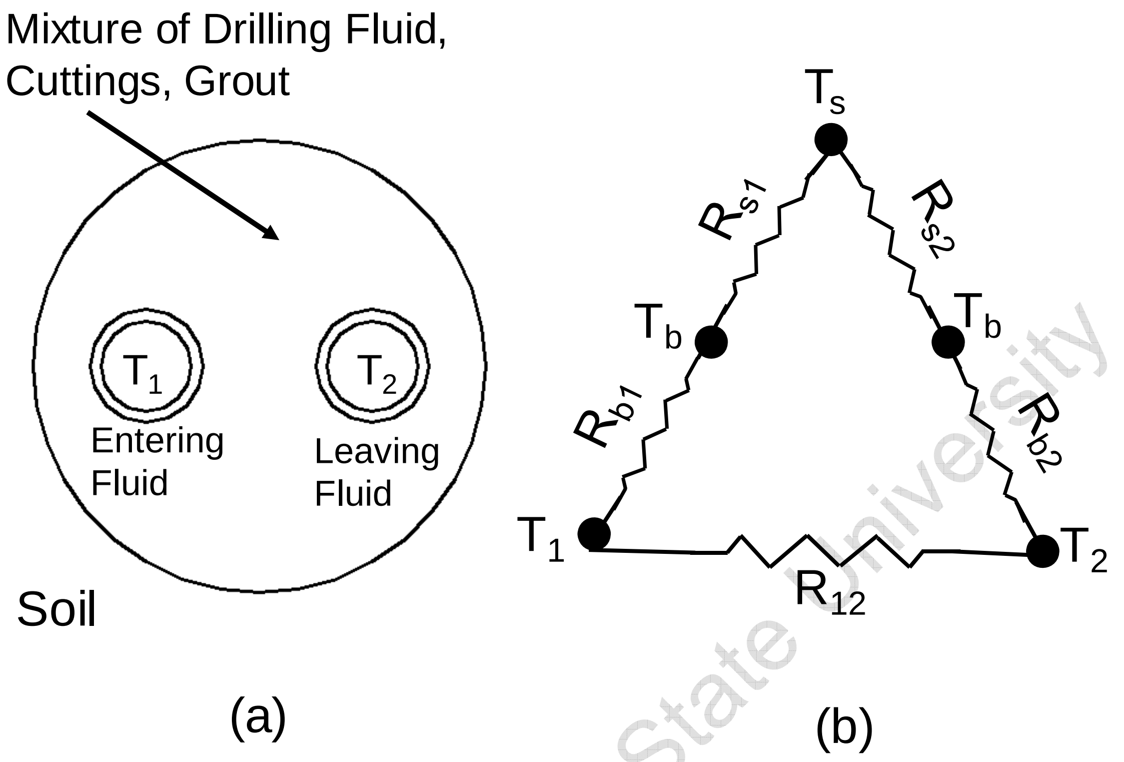

Figure 9. (a) Borehole cross section and (b) thermal resistive network.

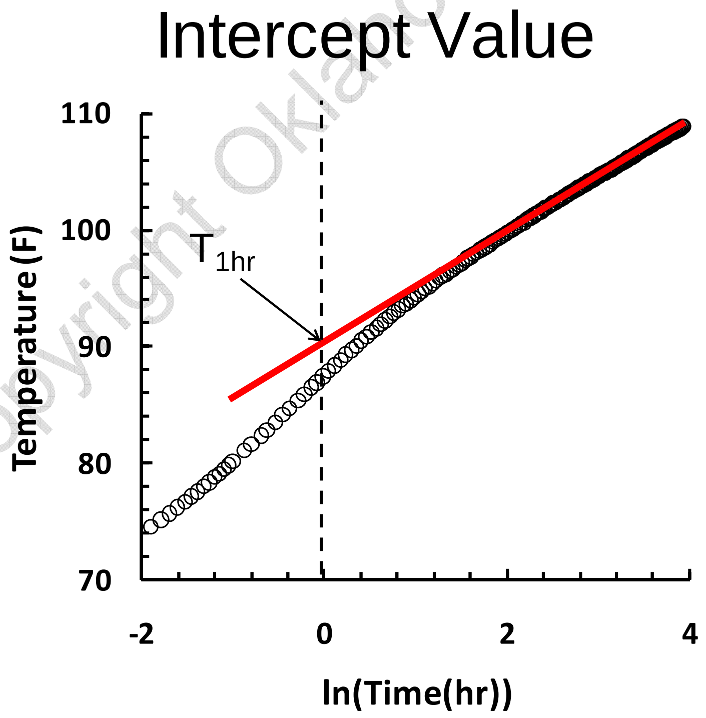

Figure 10. Intercept value used for borehole thermal resistance estimate.

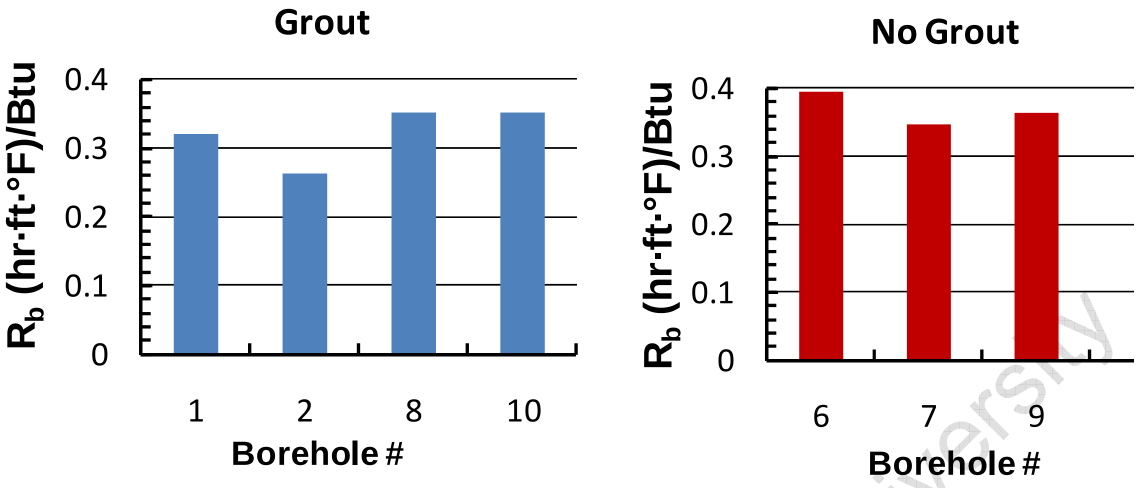

Figure 11. Borehole thermal resistance for 4.5-inch boreholes.

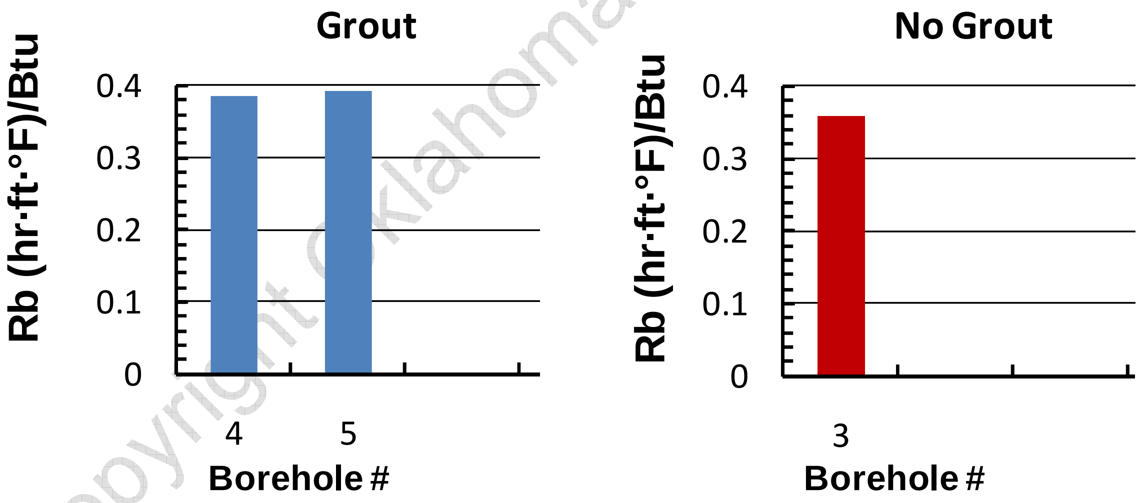

Figure 12. Borehole thermal resistance for 5.5-inch boreholes.

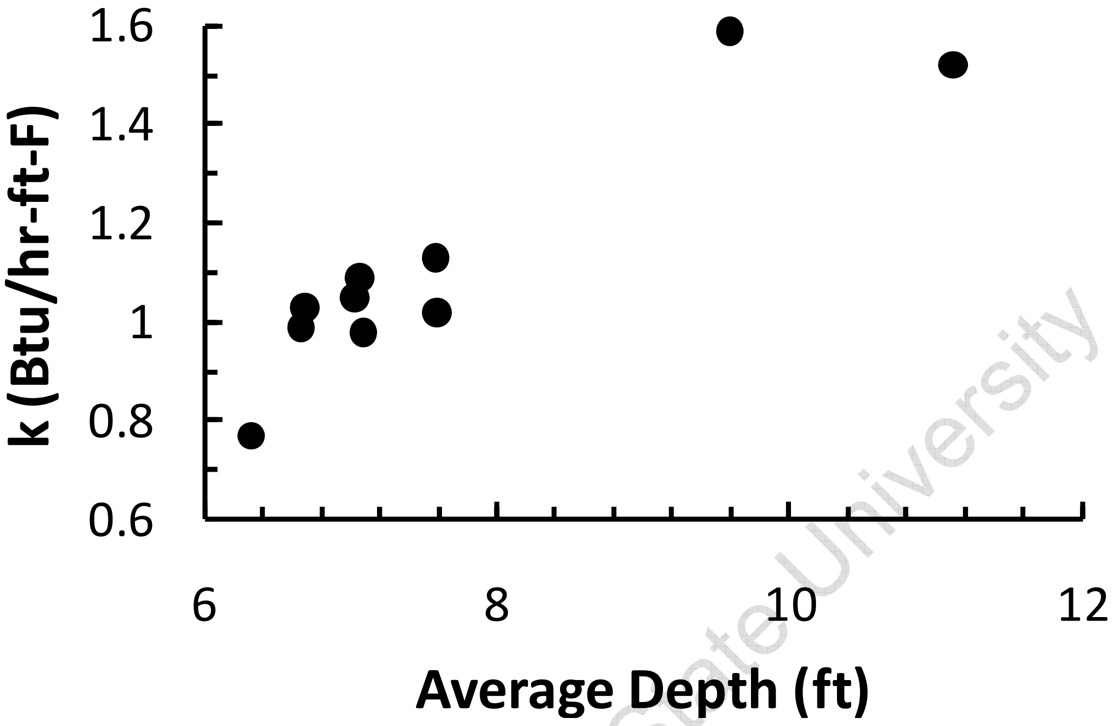

Figure 13. Soil thermal conductivity with average depth.