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Research paper

Changes in the thermal performance of horizontal boreholes with time

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HIGHLIGHTS

- Thermal response tests are analyzed on ten horizontal boreholes.
- Quasi-3D model fits measured temperatures during thermal response tests.
- Ground thermal conductivity decreased as much as a factor of 2 after two years of drought.
- Borehole thermal resistance increased as much as a factor of 2 after two years of drought.
- Changes under drought conditions would adversely affect a ground source heat pump performance.

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ABSTRACT

Ground source heat pump systems use boreholes to exchange heat with the ground. The thermal performances of ten horizontal boreholes have been evaluated by performing in-situ thermal response tests (TRT) on each borehole. The tests determine both ground thermal conductivity and borehole resistance. Ground thermal conductivity depends on moisture content, which may change with weather conditions for shallow horizontal boreholes. All the boreholes pass through clay soil at a site in Stillwater, Oklahoma (USA). A drought occurred during the two years separating two sets of TRTs. The ground thermal conductivity decreased as much as a factor of 2 in shallower boreholes where depths ranged from 1.9 to 2.3 m. On the other hand, the ground thermal conductivity remained nearly unchanged for two deeper boreholes with depths of 2.9 and 3.4 m. The borehole resistance increased by a factor of 2 for the shallower boreholes, but remained nearly unchanged for the two deeper boreholes. The changes observed in the shallower boreholes would adversely affect a ground source heat pump system.

1. Introduction

Ground source heat pump (GSHP) systems are used to efficiently heat and cool buildings. Within these systems the heat pump is often coupled to the ground through vertical or horizontal boreholes. In the United States the most common piping configuration within the borehole is a single U-tube of high density polyethylene (HDPE) pipe. The space between the U-tube and the borehole wall is usually filled with grout (Fig. 1a). The grout not only affects the heat transfer rate between the pipes and borehole wall but also serves as a barrier to the movement of water and contaminants along the borehole. Together the piping, grout and borehole are commonly referred to as a borehole heat exchanger (BHE). Water or an anti-freeze mixture circulates through a closed loop between the heat pump and the BHE. Vertical boreholes are the better choice for installations with limited land area. With sufficient land area 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 road without disturbing most of the ground surface.

Regulations regarding the use of grout to protect groundwater vary widely within the United States, because the regulations are made by each individual state [1]. Different regulations may apply to horizontal and vertical boreholes. Lackey et al. [2] evaluated a variety of grouts in vertical boreholes with clear pipes through visual assessments. The boreholes include configurations for water wells and a single U-tube BHE. Early results indicated the grout sections developed cracks and sometimes voids above the

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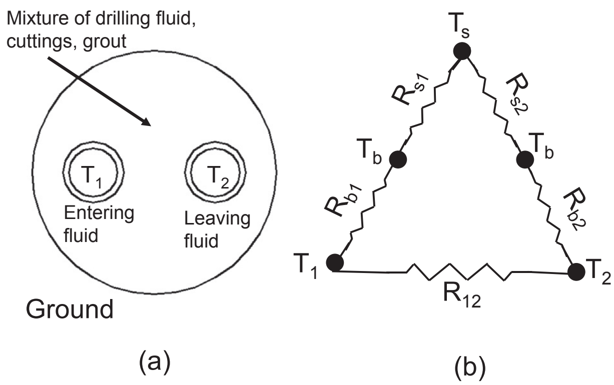

Fig. 1. (a) Borehole cross section and (b) thermal resistance network.

groundwater level but did not visually degrade below the groundwater level. These visual observations were later confirmed by dye tests in grout sections above the groundwater level.

In addition to the environmental issues, the long-term condition of the grout impacts the thermal performance of BHEs. Voids or cracks in the grout tend to increase the borehole thermal resistance, which is the thermal resistance between the circulating fluid and the borehole wall.

Because the entire length of a horizontal borehole may be above the groundwater level, the grout in a horizontal borehole may be more susceptible to change with time. Typical depths for horizontal boreholes fall between 2 and 4 m. At these depths horizontal boreholes are expected to be affected more by the time-varying moisture content of the shallow ground than vertical boreholes. Because vertical boreholes often reach depths of 100 m or more, near-surface changes in ground moisture due to annual weather cycles or prolong droughts do not directly affect the vertical borehole over most of its length.

In addition to the effects on grout, changes in the ground moisture content have a strong effect on the ground thermal conductivity. Farouki [3] and Bose [4] report significant variations in the thermal conductivity of soils and rocks as moisture content varies. Mostafa et al. [5] have measured the effects of ground moisture on heat recovery from shallow ground layers.

The design models for BHEs require values of the ground thermal conductivity and borehole thermal resistance. These input parameters are usually treated as constants with time. If these parameters vary with time, the changes affect the thermal performance of the BHE. An in-situ thermal response test (TRT) on a borehole provides a method to estimate both the ground thermal conductivity and borehole resistance. Analytical models such as the line-source model, which is explained by Carslaw and Jaeger [6] and Ingersoll and Plass [7], were the first analysis methods applied to TRT data sets. Gehlin and Spitler [8] and Sanner et al. [9] review the history of TRTs.

The equipment to perform a TRT is placed on the ground surface where the pipes emerge from the ground. The typical equipment setup includes a pump, electric heater as the heat source, flow meter, temperature sensors and computer data acquisition system. The pump circulates a fluid through the heater and U-tube, which are connected in a closed loop. The electric power to the heater is controlled to be nearly constant with time in order to provide a constant heating rate. The fluid temperatures are measured where the fluid enters and leaves the U-tube.

The present report addresses the issue of thermal performance of horizontal boreholes over time with and without grout. Drilling fluid and cuttings remain in the boreholes without grout. The study was carried out over a time period that included two years of drought at the test site in Stillwater, Oklahoma (USA). Changes in ground thermal conductivity and borehole thermal resistance have been determined on eight horizontal boreholes. A TRT was carried out on each borehole within a few months of drilling ten boreholes. Approximately two years later, a second TRT was carried out again on eight of the boreholes. Due to the regional drought between tests, the two TRT data sets show significant changes with time in the ground thermal conductivity and borehole thermal resistance. These changes greatly affect the thermal performance of the boreholes and would adversely affect a ground source heat pump system.

2. Horizontal boreholes

The horizontal boreholes penetrate clay soil in Stillwater, Oklahoma (USA). Placed in each borehole is a high density polyethylene U-tube (nominal pipe diameter of 3/4 in, SDR-11) with a length of approximately 60 m. A summary of the characteristics of each borehole is given in Table 1. Other parameters common to all boreholes are listed in Table 2. A benotonite grout (23% solids) has been pumped in six of the boreholes, and no grout has been placed in the other four boreholes. The boreholes have been drilled with a bentonite-based drilling fluid except two boreholes where a polymer based drilling fluid has been used. The drilling bit diameter is either 11.4 cm or 14 cm. The boreholes are approximately parallel and about 7 feet apart.

The drilling of all the boreholes took place during the days of May 10 to May 14, 2010. The drilling was performed with directional drilling equipment including electronic guidance. Borehole #1 penetrates an embankment and follows a horizontal path for at least 61 m to accommodate the U-tube, as illustrated in Fig. 2. Then the drilling bit was directed upward to eventually penetrate the surface.

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 through a hole near the drilling bit and into the borehole. The U-tube was placed in borehole #1 in this manner, but this procedure was unexpectedly cumbersome. The U-tube arrived in a coil and the lengths of both pipes were not exactly the same when the pipes were straightened. Unequal lengths caused the U-bend at the end of the loop to turn as it was dragged into the hole. Although the installation in borehole #1 was successful, a different procedure was implemented for the other boreholes.

During the second procedure, the drilling machines were placed on the south end of the site (Fig. 2) while drilling toward the embankment. The drill bit traveled through an angled section

Table 1
Information for horizontal boreholes.

Borehole number	Drilling bit size (cm)	Drilling fluid	Grout	Average depth (m)	Depth range (m)
1	11.4	Bentonite-based	Bentonite	3.4	3.2–3.6
2	11.4	Bentonite-based	Bentonite	2.9	1.8–3.4
3	14.0	Polymer based	None	2.3	2.0–2.5
4	14.0	Bentonite-based	Bentonite	2.3	2.0–4.3
5	14.0	Bentonite-based	Bentonite	2.2	2.0–2.3
6	11.4	Polymer-based	None	1.9	1.8–2.1
7	11.4	Bentonite-based	None	2.0	1.9–2.2
8	11.4	Bentonite-based	Bentonite	2.0	1.8–2.4
9	11.4	Bentonite-based	None	2.1	2.0–2.4
10	11.4	Bentonite-based	Bentonite	2.2	2.3–2.4