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Influence of regional groundwater flow on ground temperature around heat extraction boreholes

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ABSTRACT

The increasing popularity of ground-coupled heat pumps has resulted in almost 20% of all Swedish family houses being heated this way. To avoid undesirable interactions between neighboring boreholes and disturbance of the ground temperature, the general rule and recommendation of Swedish authorities is that the distance between two neighboring boreholes must be ≥20 m. However, according to previous studies, relatively low groundwater flow rates may significantly reduce the borehole excess temperature compared to the case of pure heat conduction.

In this work the Influence Length is defined and its relations with flow rate, *real* thermal conductivity of the ground and *effective* thermal conductivity obtained by thermal response analysis are investigated. The aim of this study was to find a way to use the thermal response test as a means to determine the groundwater flow influence in order to reduce the borehole spacing perpendicular to groundwater flow direction.

The results confirm that very low groundwater flow rates are enough to significantly reduce the Influence Length, hence this is a crucial parameter which should be considered. Moreover, a first estimation, even before the thermal response test analysis, of the Influence Length is possible if the knowledge of hydrogeological conditions of the site allows good predictions about *real* thermal conductivity of the ground and flow rate.

1. Introduction

Increased energy cost and environmental concerns have made ground-coupled heat pumps (GCHP) increasingly popular in Europe and North America. Almost 20% of all Swedish single family houses are heated this way i.e. by extracting heat from boreholes in the ground. Such heat extraction systems mean that the surrounding ground is slowly cooled until a steady-state is reached after some years. Borehole systems that are placed too close together will therefore influence each other, by further lowering the ground temperature.

To avoid conflicts between neighbors that also might want to use the ground in a similar way, the Swedish authorities have set up some rules to consider before the required drilling permit is granted. The general rule or recommendation (for single family houses) is that the distance between two neighboring boreholes must be ≥20 m to avoid significant thermal interaction. For a typical heat extraction borehole system (see Table 1) the steady-state ground temperature is ≈1.4 °C lower than the undisturbed temperature at a distance of 10 m from the borehole, assuming that the heat is transported away from the borehole by conduction only, see Fig. 1.

Unlike the case of a heat source of finite length, pure conduction will never result in steady-state for a heat source of infinite length. In current work, a two-dimensional numerical model is used (see

Table 1
Typical Swedish heat borehole system average values; (*) according to Statens Energimyndighet (2006); (**) according to Swedish Energy Agency (2008).

Total borehole depth: 132 m(*)
Active borehole depth: 117 m(*)
Annual heat extraction: 22,000 kW h(**)
Bedrock mean thermal conductivity: 3.5 W (m K)$^{-1}$
Bedrock mean undisturbed temperature: 5 °C

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Nomenclature

α	thermal diffusivity, Eq. (7) ($m^2\,s^{-1}$)
ϵ_p	porosity (–)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ_{eff}	effective thermal conductivity calculated by the TRT data analysis ($W\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\,m^{-3}$)
τ	time (s)
τ_{end}	duration of the simulation (s)
$\mathbf{n}$	outer unit normal from the borehole surface to the ground
$\mathbf{U}$	volumetric flow rate per unit of cross-sectional area, Eq. (1) ($m\,s^{-1}$)
c	specific heat ($J\,kg^{-1}\,K^{-1}$)
h	hydraulic head (m)
i	hydraulic gradient, Eq. (2) (–)
k	hydraulic permeability (m^2)
K	hydraulic conductivity ($m\,s^{-1}$)
p	static pressure (Pa)
q'	heat transfer rate ($Wy\,m^{-1}$)
q''	uniform heat flux released from the borehole surface ($W\,m^{-2}$)
r	radial distance from the borehole axis (m)
T	temperature (K)
T_f	heat carrier mean fluid temperature (°C)
T_0	unperturbed ground temperature (=278.15 K)
x	Cartesian coordinate
Pe	Peclét number, Eq. (12)
L_{inf05}, L_{inf1}	Influence Lengths as defined in Section 3.2, considering the temperatures $T_0 \pm 0.5$°C and $T_0 \pm 1$°C, respectively
$\forall$	for all

Subscripts

b	denotes quantities, defined on the borehole surface
r	denotes thermophysical properties of soils and rocks
w	denotes thermophysical properties of water
gr	denotes thermophysical properties of the porous media (soil/rocks + water), Eq. (6a)
TRT	denotes value related to Thermal Response Test (TRT) analysis
SS	denotes steady state conditions

Section 2.2) and the state after 40 years of heat injection/extraction is assumed as steady-state condition.

However, groundwater flow through the ground will change the ground temperature disturbance so that the temperature plume around the borehole will be distorted, as shown in Fig. 2. The radial distance from the borehole, perpendicular to the flow direction of the groundwater, shows that any given temperature disturbance is closer to the borehole than in the case of no groundwater flow (Figs. 1 and 2).

The distance to the same steady-state temperature disturbance as that at 10 m distance for conductive flow perpendicular to the groundwater flow direction (Figs. 1 and 2) is called Influence Length, L_{inf}. This length decreases with increasing groundwater flow rate.

Since the steady-state temperature change of the ground is the basis for the recommended minimum borehole spacing it would be possible to reduce the borehole spacing perpendicular to the groundwater flow, provided that this temperature influence could be determined in advance. Here the idea is to use a thermal response test as a means of determining the Influence Length.

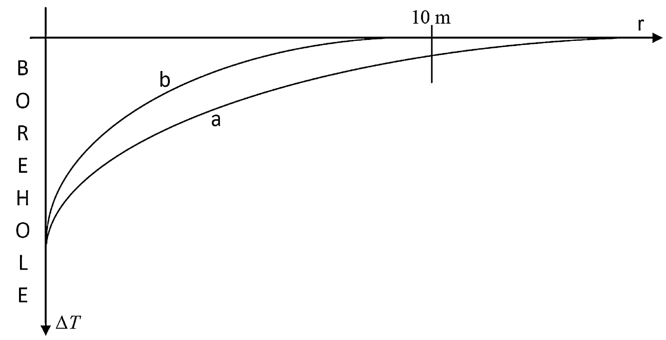

Fig. 1. Section through the ground. Radial steady-state ground temperature difference ($\Delta T = |T - T_0|$) in the ground outside a typical Swedish heat extraction borehole. (a) The ΔT at 10 m distance from the borehole is 1.4 °C without any groundwater movements. (b) The ΔT at 10 m distance from the borehole, perpendicular to the groundwater flow, is considerably lower with increasing groundwater flow.

1.1. Thermal response test and groundwater flow

Mobile thermal response test (TRT) is an in situ measurement method developed by Eklöf and Gehlin (1996) and Austin (1998). It is used to determine the effective thermal conductivity of the ground and the thermal resistance within the borehole. These data are necessary to design and to predict the thermal performance of a borehole heat exchanger (BHE) system (Nordell, 2011). Most commonly these tests are performed with heat injection. The evaluated effective thermal conductivity of the bedrock must be greater or equal than the thermal conductivity that would be obtained by laboratory testing of rock cores. The reason is that the heat transfer from the borehole is not only by heat conduction but also carried by occurring groundwater movements and in fact, according to Sanner et al. (2000), groundwater movements influence the test results.

Chiasson et al. (2000) developed a finite-element groundwater flow and heat transfer model to simulate forced convection of heat in various geologic materials and concluded that regional groundwater flow only influenced the heat transfer in BHEs for certain geohydrological conditions. Results suggest that in these cases, the advection of heat by groundwater flow significantly enhances heat transfer due to the high hydraulic conductivity of the geologic materials, such as sands, gravels, and formations showing secondary porosity (fractures and solution channels).

The phenomena was further studied by Witte (2001) who performed experimental analysis combined with a numerical study of a clayey cover layer and a water bearing formation consisting mainly of sand. His results show that even small groundwater flows cause higher estimated value of the effective thermal conductivity.

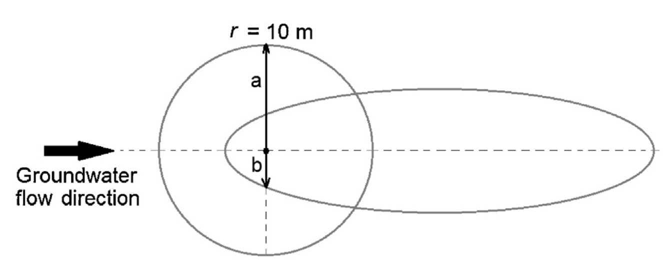

Fig. 2. Plan. Radial steady-state ground ΔT in the ground outside a typical Swedish heat extraction borehole. (a) The ΔT at 10 m distance from the borehole is 1.4 °C without any groundwater movements. (b) The ΔT at 10 m distance from the borehole, perpendicular to the groundwater flow, is considerably lower with increasing groundwater flow.