Fast Calculation Method for Borehole Heat Exchanger Fields in Groundwater Flow

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ABSTRACT

One class of methods for the design of borehole heat exchanger fields is the use of analytical, non-dimensional thermal step responses, such as g-functions. A main simplification and restriction of most such analytical approaches for BHE design is the neglection of groundwater advection.

The theory and concept of moving line sources can, in principle, be used to calculate the thermal behaviour of BHEs in groundwater flow. However, application of the moving line source to grouted boreholes needs a correction for the disturbance of the groundwater flow field and the lower heat transfer rates in the borehole region.

Based on such a correction developed earlier, the applicability of the infinite moving line source model on borehole fields is shown by comparison with numerical simulation. Together witch spatial superposition of the long-term temperature responses and influences, fields of arbitrarily placed borehole heat exchangers can be calculated. This yields an analytical, simple and fast calculation method for borehole heat exchanger fields with the boreholes being completely (or at least mainly) immersed in flowing groundwater.

A design example is presented, in which one of three borehole heat exchangers can be saved when a significant groundwater flow is present and taken into account.

Keywords: borehole heat exchangers, analytical line source models, thermal interference, groundwater advection.

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1. INTRODUCTION

The design of vertical borehole heat exchangers (BHEs) for ground source heat pumps (GSHP) and direct geothermal cooling requires calculation of the thermal response of the BHEs to the thermal loads imposed. Since the system of BHEs and surrounding ground coupled to them exhibits a transient thermal behaviour and is subject to time-dependent loads, appropriate dynamic calculation methods are necessary for dimensioning.

The calculation methods used are either numerical simulations, or (semi-)analytical mathematical models [1]. Accurate numerical simulations for BHE fields, especially when a large number of are BHEs has to be considered, are highly flexible but expensive in terms of computer power and calculation time. Established analytical calculation for BHE fields are simple and fast, but they include conceptual simplifications und thus are only valid for particular conditions [1]. One main simplification and restriction of most existing tools for BHE design, such as EED [2], is the neglection of groundwater advection.

The theory and concept of infinite and finite moving line sources can be used to calculate the thermal behaviour of BHEs in groundwater flow. But in the case of grouted boreholes, which are mandatory in many countries and regions, the original moving line source theory may fail in many cases, since it assumes a homogenous ground with constant permeability [1].

This article describes the application of a simple and fast calculation method for BHE fields consisting of grouted boreholes which are completely embedded in a homogenous groundwater flow.

2. ANALYTICAL MODEL

The base of the analytical model used here is the infinite moving line source (IMLS) [3]. Since the influence of a groundwater flow on the thermal response of a BHE under thermal loads is most pronounced in the long-term, groundwater flow is considered for the steady-state solution. The steady-state g-function, i.e. the stationary non-dimensionless temperature response, resulting from the IMLS is given by:

$$g_{GW,End,IMLS}(Pe) = I_0\left(\frac{Pe}{2}\right)\ K_0\left(\frac{Pe}{2}\right) \tag{1}$$

To take the grouting, i.e. the very much lower permeability within the borehole, into account, a correction function for the borehole wall temperature calculated from the IMLS was developed in a former work [1]:

$$f_{cor}(Pe) = -6.11 \cdot 10^{-3} \cdot Pe^2 + 3.68 \cdot 10^{-1} \cdot Pe + 1 \tag{2}$$

Figure 1 shows a comparison of the original steady-state groundwater g-function and the corrected function in dependence of the Péclet number *Pe*.

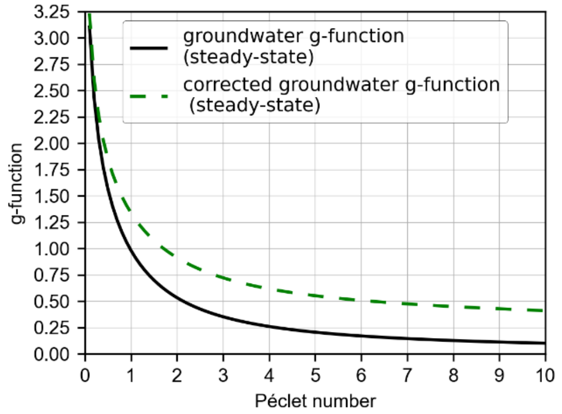

Fig. 1: Steady-state groundwater g-function with and without correction for the grouted borehole (taken from [1])

With equations (1) and (2) the steady-state temperature response at the borehole wall (averaged over the borehole wall) of a single BHE to a constant thermal load can be calculated:

$$\Delta T = \frac{\dot{q}}{2 \cdot \pi \cdot \lambda} \cdot \left(f_{cor}(Pe) \cdot g_{GW,End,IMLS}(Pe) \right) \quad (3)$$

For design and dimensioning purposes, only maximum resulting temperature responses of the fluid temperature within the BHE are needed. Therefore, a calculation or simulation of the whole time-dependent temperature response may be replaced by a transient calculation which aims directly on the design point (maximum and minimum fluid temperatures) [4-7].

The calculation of the response of a whole BHE field completely embedded in groundwater flow to a transient thermal load profile is then based on three assumptions:

1. Established calculation methods for the borehole resistance R_b of the grouted boreholes or values obtained from a short-term thermal response test are still applicable under groundwater advection.
2. A correction of the temperature field calculated with the IMLS is necessary at the borehole wall because of the backfilling of the borehole, but can be omitted at a greater distance from the borehole.
3. For a fast, simple and approximate, but sufficiently accurate calculation method for practical engineering purposes, consideration of groundwater advection can be limited to the steady-state part.

While the validity of the first assumption has already been shown in [1], assumptions 2 and 3 are discussed in the following sections.

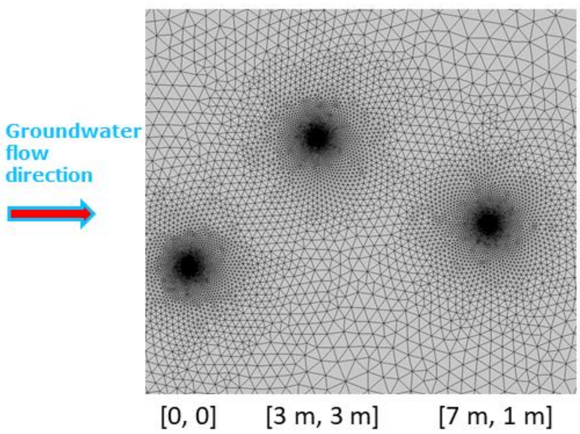

Fig. 2: Finite element grid of the numerical simulation model

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3. NUMERICAL SIMULATION

A test case of a BHE field with three boreholes was simulated with COMSOL Multiphysics® software V6.1. The model and the simulations were 2D and steady-state. Fig. 2 shows the positions of the boreholes and the finite-element grid used with a very fine grid near the boreholes, and a coarser grid in between. Each test case was simulated twice, first with a permeable borehole (borehole region identical to surrounding, permeable ground) and second with a grouted borehole (borehole region impermeable). Results of both, permeable and grouted borehole, for Pe = 0.55 are depicted in Fig. 3 and Fig. 4. Fig. 5 shows the relative deviation of both calculations.

It can be seen, that in the case shown here, the resulting temperature field around the boreholes is only influenced by the grouting in the near-field around the boreholes, i.e. within a radius in the order of 1 m. Only there the rel. deviation is larger ±1% and for that reason displayed in white without coloured marking.

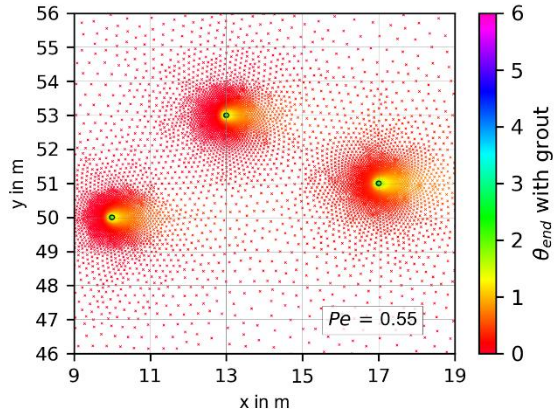

Fig. 3: Dimensionless temperature response for grouted boreholes

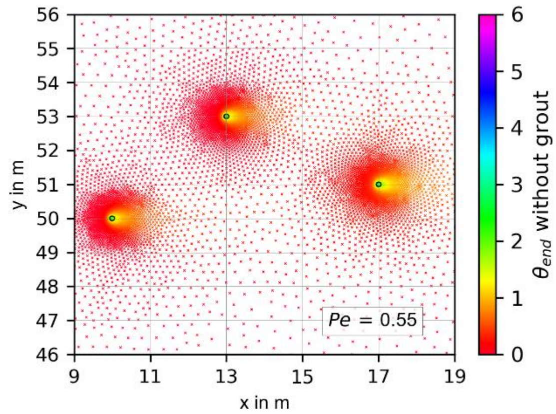

Fig. 4: Dimensionless temperature response for ungrouted boreholes

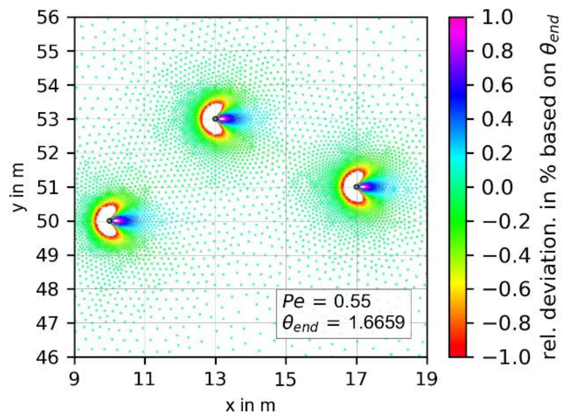

Fig. 5: Relative deviation of the dimensionless temperature response with and without grouted boreholes

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4. BHE FIELD STEADY-STATE G-FUNCTIONS

From the results of the numerical calculations it can be concluded that, while the correction according to equation (2) has to be applied at the borehole wall, no such correction is necessary in the far-field. This means that the analytical IMLS solution can be applied to calculate the thermal influence of one borehole on another within a BHE with groundwater flow field, even for grouted boreholes. For steady-state, this can be done with the angle and radius dependent IMLS solution:

$$\Delta\vartheta = \frac{\dot{q}}{2\ \pi\ \lambda_{eff}} \left\{ e^{\frac{Pe}{2}\ cos(\varphi)}\ K_0\left(\frac{Pe}{2}\right) \right\} \quad (4)$$

with: $Pe = \frac{U_{eff}\ r_b}{\alpha_{eff}}$ (5)

The average steady-state g-function of the complete BHE field is then obtained by spatial superposition of the thermal influences between all BHEs and averaging the resulting values of all BHEs. The according angels and radii of the pairs of boreholes can easily be calculated from the horizontal coordinates of the boreholes (as given in Fig. 2 for the example investigated here). The procedure of superposing temperature responses and influences of arbitrarily located vertical BHEs is outlined in [8] where it is applied to BHE fields without groundwater influence.

5. TRANSIENT BEHAVIOUR APPROXIMATION

So far, stead-state conditions have been considered. However, in case of time-dependent thermal loads on the BHE field, a transient calculation of the thermal response of the underground an the BHEs has to be conducted. This is done by load decomposition according to the calculation method and software GEO-HAND^{light} which is originally based on analytical solutions given by Eskilson [4] and was further developed over the years [5].

The decomposition of a thermal load profile according to this method results in three components (and three thermal responses, accordingly):

a) steady-state, i.e. average load over the year (corresponding to the annual amount of thermal load),

b) periodic, i.e. seasonal component by using the maximum monthly average load, and

c) short-time constant load representing maximum heat load and duration (e.g. of a single GSHP operating phase).

Yet, GEO-HAND^{light} can only treat purely conductive heat transfer in the ground. The extension introduced here is the use of an average steady-state g-function with groundwater advection for component a), as described in the previous section. Periodic and short-time constant components, b) and c), are still calculated without groundwater advection as an approximation.

To obtain some picture of the accuracy of the latter approximation for components b) and c), g-functions calculated with the infinite line source ILS (pure conduction like in standard evaluation of a thermal response test) the transient IMLS, and the steady-state value of the IMLS are plotted in Fig. 6. In this example, steady-state under groundwater flow with *Pe* = 0.55 is reached already within 5 days. The maximum deviation between a response function composed of ILS and steady-state IMLS (red dashed lines in Fig. 7) and the more accurate transient IMLS is approximately 16%. Therefore, the treatment of components b) and c) is maintained without groundwater advection as a first approximation. However, when the g-functions without groundwater advection yield larger values than the steady-state IMLS, the latter is used for the respective component.

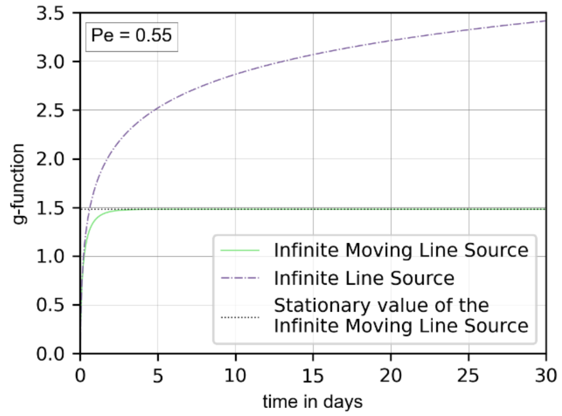

Fig. 6: Comparison of infinite line source and infinite moving line source for Pe = 0.55, linearly plotted over time in days

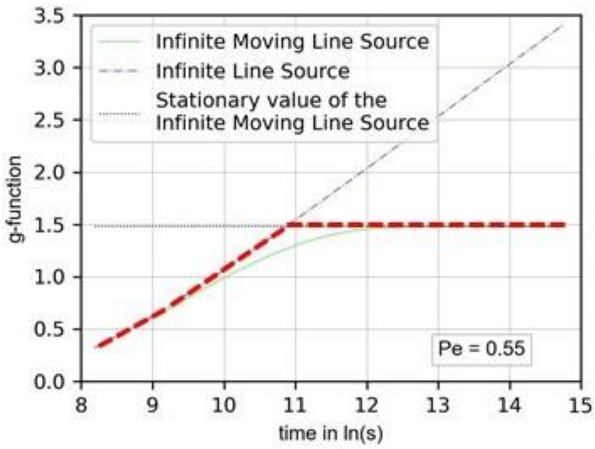

Fig. 7: Comparison infinite line source and infinite moving line source for Pe = 0.55, plotted over logarithmic time scale

6. DESIGN EXAMPLE

The design example listed in table 1 demonstrates the capability of the fast calculation method presented here. Two cases are compared: case I without groundwater flow and case II with a homogenous groundwater advection over the complete BHE field.

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Table 1: Parameters for the design example

heat pump properties:		
heat capacity	6	kW
COP	4.5	
SCOP	4.5	
Annual full load hours	1800	h/a
max. monthly full load hours	300	h/mon
max. uninterrupted operation hours	10	h
geology:		
thermal conductivity of the solid	2.0	W/(m·K)
thermal conductivity of the groundwater	0.6	W/(m·K)
porosity	0.3	
effective thermal conductivity	1.6	W/(m·K)
annual mean surface temperature	10	°C
Darcy velocity (case II only)	0.275	m/d
Péclet number (case II only)	0.55	
BHE properties:		
number of BHEs	3	
borehole depth	50	m
borehole radius	0.065	m
borehole resistance	0.08	m·K/W
temperature spread over the BHE	3	K

The resulting maximum heat extraction rate is 31.1 W/m borehole length. The long-term minimum inlet temperature to the borehole field is -3.1 °C in case I (no groundwater flow) and +2.4 °C in case II (with advection). Theses values correspond to a temperature decrease versus the undisturbed ground temperature of -14 K and -8.5 K, respectively. Given -3 °C as a limit, like it is the case in the German federal state of Baden-Württemberg [9], for example, the three BHEs are just sufficient when there is no groundwater flow, but only two BHEs would be sufficient if the groundwater flow is present over the hole depth of the BHE field.

7. SUMMARY AND CONCLUSIONS

The presented analytical fast calculation method extends the already established (semi-) analytical models for the design of BHE fields to the case with significant groundwater when it is present over the entire height of the BHE field. Through the comparison with numerical simulations, it is shown that the correction function for grouted boreholes published in [1] is only necessary in the near-field of the considered BHE, i.e. within a radius of 1 m around the BHE. Thus, the interference of BHEs can be calculated with the infinite moving line source solution without any correction. Since the presented method uses the load decomposition, which besides the long-term thermal interference and temperature decrease also considers the time-dependent, periodical and peak loads, in the latter cases the ILS solutions are used as long as these values are lower as the steady-state solution of the IMLS. This simplification leads to inaccuracies compared to the transient IMLS solution, while always being conservative concerning the temperature forecast. Despite of being somehow conservative in the present state on development, a design example shows the advantage, i.e. a reduction of 30% of the needed drilling meters, if the influence of a groundwater flow can be considered with this design method.

Since analytical simulation and design methods like the one presented here need only little computing time, they are well-suited for potential analysis over large regions, design of energy systems for whole building districts, and for integration into complex plant and building simulations.

Further development of the approach presented here is prepared, such as extension on stratified ground with different layers, e.g. with and without groundwater flow. Also, coupling with other shallow geothermal systems shall be developed.

8. REFERENCES

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