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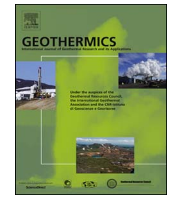

Experimental and numerical investigation of a long-duration Thermal Response Test: Borehole Heat Exchanger behaviour and thermal plume in the heterogeneous rock mass

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ABSTRACT

This paper presents in-situ measurements of a long-duration Thermal Response Test (TRT) (heating phase of 7 months), conducted in a heterogeneous bedrock of conduction dominated heat transfer. The in-situ test was simulated by 3D numerical modelling, by assuming homogeneous and isotropic ground conditions considering the TRT data of the first few days. Based on the analysis of the experimental and numerical results, the behaviour of the Borehole Heat Exchanger for longer heating and recovery periods can be predicted based on the typical-duration TRT results. However, this behaviour is sensitive to the heat input variations, indicating the need for an accurate estimation of the energy needs of the building and the variable thermal loading during the operation of the system. Critical factors for the prediction of the temperature field evolution in the surrounding ground were detected based on the analysis of high-resolution temperature profiles. They include the distance to the heating source, borehole bottom end effects, bedrock heterogeneity and air temperature variations. Anisotropic effects are not detected, despite the expected anisotropic behaviour of the bedrock.

1. Introduction

Vertical closed-loop geothermal systems, also known as Borehole Heat Exchangers (BHEs), can provide economical and environmental benefits compared to other heating systems (Self et al., 2013), since they have low operating costs, high heat pump coefficient of performance and low CO_2 emissions related to their operation. Subsurface characteristics are among the critical parameters for the design and the long-term behaviour of BHEs (MIS 3005; Luo et al., 2016). Though, in practice, they are often not adequately considered (Blum et al., 2011). This can result in increased capital costs, in the case of oversizing, and to malfunctions or short life spans, in the case of undersizing, overwhelming the potential and the applicability of these systems.

Thermal Response Tests (TRTs) allow to estimate the effective ground thermal conductivity including the influence of the in-situ conditions (Spitler and Gehlin, 2015). Determining the optimum duration of the test is critical, since it allows to minimize the cost by assuring the accuracy of the thermal conductivity estimation. Singorelli et al. (2007) conducted numerically TRTs and analysed the results by using the widely applied Infinite Line Source (ILS) model. They proposed that a test duration of 50 h can provide a satisfactory estimation of the ground thermal conductivity, in the case that groundwater effects are not dominant. Choi and Ooka (2016) analysed statistically 36 numerical TRTs influenced by various weather conditions, interpreted by the ILS model. They recommended a minimum test duration of 60 h, to retain the ILS results error lower than 5%.

The TRT results are used as input parameters for the modelling of the long-term behaviour of the system. Analytical models are widely used to simulate BHE behaviours and thermal plume in the surrounding ground (Philippe et al., 2009; Li and Lai, 2015). Each model is based on simplifying assumptions of BHE geometry, of boundary conditions, ground homogeneity or ground flow. Subsequently these models are often specialised to take into account short-term effects (Yavuzturk and Spitler, 1999) or long-term effects (Eskilson, 1987; Hellström 1991), heat advection in the ground (Diao et al., 2004; Erol et al., 2015), thermal effects associated with the finite length of the BHE (Philippe et al., 2009) or interactions between pipes of the BHE (Marcotte and Pasquier, 2008; Beier et al., 2013). However these methods suffer from several limitations regarding complex geometries, ground heterogeneity, grouting modelling or variable thermal loading. Finite element simulations allow to overcome these difficulties but the computational costs increases. The pioneering work of Al-Khoury (Al-Khoury et al., 2005; Al-Khoury and Bonnier, 2006) proposes to model the BHE as a 1D element and assumes a priori a thermal resistance within the grouting,

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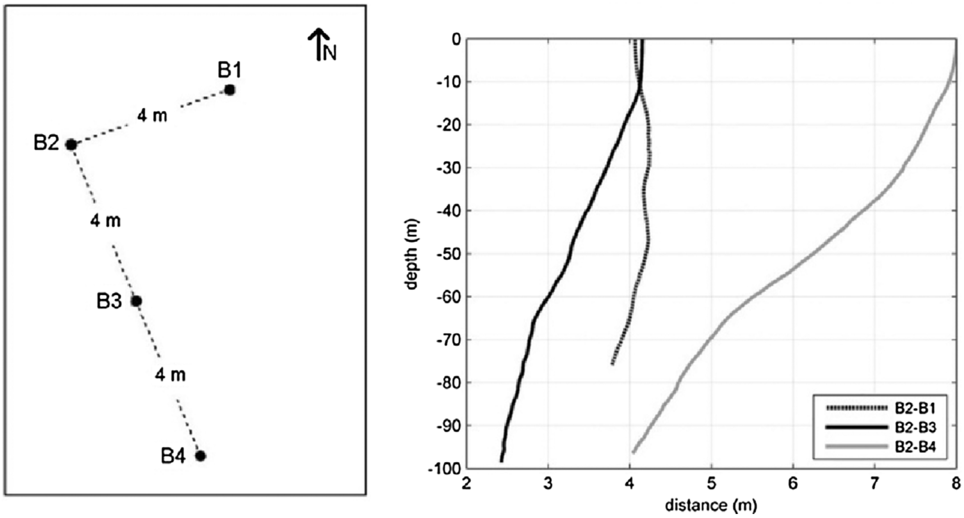

Fig. 1. Relative position of the four BHEs at the ground surface (left) and horizontal distance between B2 and the other three BHEs through depth (right).

providing a tool to study long-term behaviour of BHE. Some other studies consider explicitly the behaviour of the grouting, allowing the study of transient short-term behaviour and temperature evolution close to the borehole (Ozudogru et al., 2015; Cerfontaine et al., 2016).

However, applying the TRT results to predict the behaviour of the system and the temperature field evolution in the surrounding ground remains challenging. The limited duration of the TRT presupposes that the results are representative of the ground thermal properties for longer heating periods and different applied modes. Moreover TRTs provide a depth-average value of the ground properties, which indicates that ground heterogeneity and anisotropy can be ignored. There is therefore the need for an experimental validation at real scale of these assumptions and of the evaluation of the modelling results.

This paper focuses on the extrapolation of the TRT results for longer heating and recovery periods and on the detection of the critical parameters for the simulation of the BHE behaviour and of the temperature field evolution in the surrounding ground. It presents a case study of a long-duration TRT (heating phase of 7 months), conducted in a conduction dominated, heterogeneous bedrock at the campus of the University of Liege (Liege, Belgium). During the test, temperature was measured at the pipe-inlet and outlet, as well as in the surrounding bedrock (by fiber optics in three observation BHEs). The in-situ test was simulated by 3D numerical modelling, by assuming homogeneous and isotropic ground conditions. The ground thermal conductivity was estimated by applying the ILS model of the first a few days (typical TRT procedure). We compare the numerical and the experimental results to evaluate the typical TRT duration and the validate the homogeneity assumption in a real case-study. Moreover, we study the effect of various factors on the temperature field evolution at the heterogeneous bedrock at the in-situ scale, based on this unique data set.

The remainder of the paper is organised as follows. First the site characteristics are presented together with the materials and methods used in this study. Then, the BHE behaviour is studied based on the comparison between the numerical and experimental results, focusing on the homogeneity assumption and the effect of the varying applied thermal load. Numerical and experimental data follow, concerning the thermal plume in the surrounding bedrock. Critical factors are detected and discussed. Finally conclusions are provided as well as a discussion on the applicability of the results in the case of dominant groundwater flow.

2. Site set-up

2.1. Site description and geological settings

The site consists of four double-U BHEs (namely B1-B4), of about 100 m long, installed in 2013 on the campus of the University of Liege (Liege, Belgium). The relative position of the boreholes (B1-B4) was chosen as presented in Fig. 1 (left), in order to investigate any possible anisotropic thermal behaviour of the bedrock along two perpendicular planes: the first along the axis crossing B1 and B2 and the second along the axis crossing B2, B3 and B4. Azimuth and deviation were measured by magnetometers and inclinometers in the four boreholes with an orientation precision of ± 1.0° and ± 0.5° respectively. The horizontal distance between B2 and the other three boreholes was calculated based on theese data (Fig. 1, right). The distance between B2 and B1 oscillates around 4.1 m. The distance between B2 and B3 decreases through depth, becoming almost the half at the bottom of the boreholes. This is also the case for the distance between B2 and B4. The bedrock consists mainly of siltstone and shale interbedded with sandstone layers and the average layer dip angle is approximately 45° SE. A detailed bedrock characterisation based on borehole televiewer measurements, laboratory measurements and temperature profiles analysis is presented in Radioti et al. (2016).

The geothermal pipes were equipped with fiber optic cables in order to obtain continuous, high-resolution temperature profiles along the pipe loops (Radioti et al., 2013, 2015). Three different grouting materials were used in-situ: two commercial (B1, B2 and B3) and one homemade admixture with graphite (Erol and François, 2014).

2.2. Materials and methods

2.2.1. TRT phases and measurements equipment

Table 1 summarizes the different phases applied during the long-duration TRT in B2. The heating phase had a total duration of 7 months, including two short interruption phases. The nominal heat input for the double-U configuration (42 W/m length) was chosen according to the VDI 4640 propositions (for 2400 run hours and normal rocky

Table 1
Applied phases during the long-duration TRT in B2 (June 2015–June 2016).

time (d)	water circulation	heat injection	configuration
0 – 1.63	√	–	double-U
1.63–95.18	√	√	double-U
95.18–95.61	–	–	–
95.61–96.67	√	–	double-U
96.67–191.7	√	√	double-U
191.7–192.6	–	–	–
192.6–214.7	√	√	single-U
214.7–367	–	–	–