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Monitoring and Forecasting the Thermal Response of an Existing Borehole Field

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ABSTRACT

Ground coupled heating and cooling systems have become very popular during the last decades in Sweden, with about 425000 small Ground Source Heat Pumps (GSHP) and 400 large Borehole Thermal Energy Storage (BTES) systems. The large installations have a total installed capacity of about 140 MW and deliver around 800 GWh of energy, out of which circa 80% are used for heating and about 20% for cooling. Normally, all installations are monitored to some extent. At most of them, temperatures and energy flows on the building side are followed up and even logged. Electricity consumption is also known, as well as energy used by secondary back-up systems. On the ground side only temperatures going in and out from manifolds are followed up in the best case. However, no information is recorded about how the thermal loads are distributed across the borehole field or along the depth. This paper is the very beginning of monitoring activities where several new and existing GSHP installations are going to be studied and forecasted during the next coming years in terms of their thermal response, the object being in this case an existing borehole field consisting of 26 boreholes located in Sweden that has been operating during 15 years. The boreholes are connected to 3 heat pumps that provide space heating to 150 apartments. The field is divided in two sub-groups: one consisting of 14 boreholes drilled in 1998 and connected to two of the heat pumps and a second group drilled in 2009 which is connected to the third heat pump. The layout of both fields is uneven (e.g. not following linear or rectangular pattern) and comprise vertical and inclined boreholes, which is normal in Sweden. The predicted lack of thermal interaction between the borehole groups allowed the independent study of each sub-borehole field. A method based on the finite line source theory was used to calculate the g-function of both borehole fields and measured thermal loads were subsequently used as inputs to predict secondary fluid temperatures.

1. INTRODUCTION

Ground Source Heat Pump (GSHP) systems have become popular during the last decades. These systems are installed in both family house and large residential and/or commercial buildings. Sweden has been a one of the leading markets with a large number of installations every year during the last two decades. The most common type of system consists of one or several single Borehole Heat Exchangers (BHEs) through which a secondary fluid circulates and heat from or to the ground is transferred. The heat is subsequently delivered to a heat pump through the evaporator heat exchanger.

A design of a GSHP system often requires an analysis of the thermal behavior of the ground. Nowadays, there are commercial software programs that can tackle hundreds of borehole field configurations. However, commercial tools are often limited to a pre-calculated library of linear or quadratic straight borehole field configurations which are in many cases far away from reality. This can sometimes be a problem since the available drilling space is often non-uniform and split in separate areas, and the boreholes often deviate from the planned direction.

This paper evaluates the thermal response of a particular large borehole field, which consist of an uneven pattern with vertical and inclined boreholes. The installation is part of a relatively large condominium (150 apartments) located in Saltsjöbaden, at the outskirts of Stockholm. The system consisting of two oil burners used to cover the heat and tap warm water demand. It was in 1998 when the first part of the GSHP system was put in operation. This technology was chosen to reduce the consumption of the oil-burners. The total annual energy demand was estimated at 1700 MWh in 2013. Two heat pumps, VP1 and VP2, of 65 kW nominal capacity each, were installed to cover part of the demand and one of the oil-burners was kept as a back-up system and to cover the peak loads. VP1 and VP2 were connected to a field of 14 BHEs. A second upgrade was carried out in 2009, including a third heat pump (VP3) of 145 kW nominal capacity connected to a new field of 12 BHEs. Despite these changes, the oil consumption in the burners is still an issue to some extent, being 60 cubic meters per year (about two times larger than the residents' expectations). Technical help is being given to the condominium in order to optimize the system and reduce the oil consumption of the backup heater system. Part of the help is reflected in this study.

The borehole field presents a particular pattern and history which is not easy to handle with available commercial design tools, requiring an analysis that considers all the geometrical differences among the boreholes, i.e. irregular distance between them, different inclinations and depths, groundwater level, etc. The fact that two borehole fields were constructed at two different stages implies also some extra considerations. The prediction of the secondary fluid temperatures is carried out by temporal superposition of measured heat loads over the time dependent ground thermal resistance, an approach described in Ingersoll et al. (1954), Eskilson (1986), Eskilson (1987), Yavuzturk and Spitler (1999), and Bernier et al. (2004). The ground thermal resistance includes the ground thermal conductivity λ and the temperature response factor, g-function, as expressed in eq. (1).

$$R_g = \frac{1}{2\pi\lambda} \cdot g\left({}^{t}/_{t^*}, {}^{r_b}/_{H}, {}^{B}/_{H}, {}^{D}/_{H}\right) \tag{1}$$

The g-functions are obtained using the known finite line source analytical approach of Lamarche and Beauchamp (2007) and Lamarche (2011), including an estimation of the active borehole depth (excluding a few upper meters close to the ground surface) for each borehole.

As inferred from eq. (1), the g-function depends on a non-dimensional time t/t^* , being t^* a characteristic time defined as the Fourier number where H is the characteristic active length and α the thermal diffusivity of the ground, that is $Fo_H = \alpha t/H^2$). Moreover, the g-function also depends on the borehole field geometry: the borehole radius r_b, the borehole spacing (B) and the upper inactive part of the borehole (D) are expressed as a ratio over the active borehole length H. In Eskilson (1987), for a fixed length of 110 m, the influence of D was not clearly described but it was found negligible for values of D between 2 and 8 m. A value of 4 or 5 m was then chosen to formulate the g-functions. Recent studies have shown that the influence of D may have a significant influence, especially when the borehole is short as shown in Cimmino and Bernier (2013) and Monzó et al. (2014b).

Eskilson proposed both a numerical and an analytical method, and the former approach was preferred for generating the g-functions with the so called Superposition Borehole Model (SBM), Eskilson (1986). This was the base of a g-function database implemented in some commercial software today. The proposed analytical solution was based on the Finite Line Source (FLS) which assumes constant and equal heat flux at the borehole wall of all boreholes. It has been mathematically modified by Zeng et al. (2002) Lamarche and Beauchamp (2007). On the other hand, the numerical solution based on the finite different method allows imposing either constant heat flux or uniform temperature as a boundary condition. In BHEs hydraulically connected in parallel, the boreholes share the same inlet fluid temperature, i.e. they are also thermally connected.

The g-function resulting from this analytical approach has been found to overestimate those generated with SBM with an acceptable error, Fossa (2011a) and (2011b), Monzó et al. (2013a), the differences being more significant for large borehole fields and large times. Although the limitations, the traditional FLS approach (assuming constant heat flux along the whole depth) was chosen as the method of attack in the study presented in the present paper. The authors are conscious of the fact that assuming uniform temperature is a more realistic approach and that there are methods to account for variable heat flux along the depth and across the borehole field, e.g. Cimmino and Bernier (2013) and Lazarotto (2014), respectively. Monzó et al. (2014a) propose a finite element method based concept using a fictitious Highly Conductive Material (HCM) to impose a uniform temperature condition at the borehole wall. This approach may lead to better results in this particular study. The g-function generated by Cimmino and Bernier (2014) and Monzó et al. (2014a) present good agreement with the solutions from SBM-Uniform temperature. These methods may give better results if used in this study.

The choice of method is irrelevant if the thermal loads are balanced, as described in Monzó et al. (2013b) and Monzó et al. (2014b). Although balanced load is not the case in this study, we consider our method for obtaining the g-function to be valid given the short time scales considered here. With this motivation and background, the calculated borehole wall temperatures T_b are calculated using eq. (2), superposing the thermal loads (q) according to eq. (3).

$$T_b(t) - T_g = \frac{q}{2\pi\lambda} * g\left(\frac{t}{t^*}, \frac{r_b}{H}, \frac{B}{H}, \frac{D}{H}\right) \tag{2}$$

$$T_b(t) - T_g = \frac{1}{2\pi\lambda} * \left(q_1 * g\left(\frac{t}{t^*},,\right) - q_n * g\left(\frac{(t - t_n)}{t^*},,\right) + \sum_{i=1}^{n-1} (q_{i+1} - q_i) * g\left(\frac{(t - t_i)}{t^*},,\right) \right) \tag{3}$$

Our calculated borehole wall temperatures are offset with a constant borehole resistance and compared with measured data for the last 6 operation months of the site, registered with an existing logging system installed at the site during the upgrade in 2009.

2. DESCRIPTION OF THE BOREHOLE FIELD, THERMAL LOADS, AND STUDY APPROACH

The total borehole field consists of 26 boreholes split into two smaller sub-borehole fields of 14 and 12 boreholes. These two sub-fields correspond to the two drilling phases, 1998 and 2009. In this paper, the older field is referred as sub-borehole field VP1-VP2, whereas the sub-borehole field VP3 makes reference to the field drilled in 2009. Their location has been registered by the condominium and Figure 1 shows a satellite image of the site (a) together with a sketch of the borehole field (b). The black lines drawn from each borehole in **Error! Reference source not found.** intend to illustrate the borehole orientation considering the registered inclination.

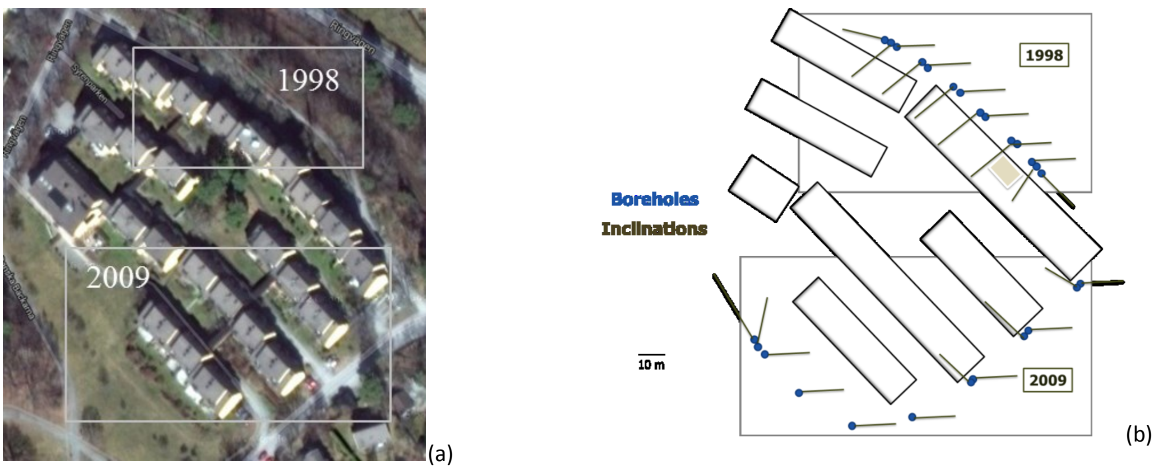

Figure 1. Satellite picture of the condominium (a) and sketch of the borehole field: sub-borehole field VP1-VP2 (drilled in 1998) and sub-borehole field VP3 (drilled in 2009)

The two closest boreholes from each sub borehole field are at a distance of about 50 meters. Thermal interaction between these has been estimated and it is not expected to occur until 40-years of operation of the system. Thus, the two sub-fields have been studied separately. Table 1 and

Table 2 show the coordinates, drilled depth (H_D) and the inclination angle of the boreholes (alpha). The groundwater level, D, is estimated at 5 meters in depth.

Table 1 Local coordinates and geometrical characteristics of the borehole field drilled in 1998

Borehole	x	y	H_D	alpha
1	0.00	0.00	210	17
2	1.76	0.00	210	17
3	2.21	2.21	210	0
4	9.26	10.59	210	0
5	10.59	11.91	210	17
6	21.18	21.18	210	0
7	22.50	22.50	210	17
8	30	30.88	210	0
9	31.76	32.65	210	17
10	41.47	41.03	210	0
11	43.24	41.91	210	17
12	52.94	48.53	210	0
13	54.71	49.41	210	17
14	56.91	51.18	210	17

Table 2 Local coordinates and geometrical characteristics of the borehole field drilled in 2009

Borehole	x	y	H_D	alpha
1	-18.00	-48.50	260	0
2	-16.00	-49.50	250	5
3	2.87	-68.80	240	0
4	4.03	-69.90	256	5
5	17.94	-81.54	250	0
6	19.10	-82.41	250	5
7	44.03	-91.40	250	0
8	61.71	-97.78	250	0
9	79.39	-83.28	250	0
10	94.46	-71.11	250	0
11	95.62	-69.95	250	5
12	96.78	-68.79	250	15

Error! Not a valid bookmark self-reference. shows the ranges within which the non-dimensional parameters vary in the borehole fields. Based on the existing documentation, each borehole has been modeled according its own geometry for the g-functions generation. It should be mentioned here that the inclinations correspond to those provided by the drilling company according to their drilling plans. The inclination/deviation has not been measured.

Table 3 Range of the geometrical characteristics of the borehole fields

Geometrical Characteristic Ratio	Range
r_b/H	Between $2.192 \cdot 10^{-4}$ and $2.714 \cdot 10^{-4}$
D/H	Between 0.019 and 0.024
Inclination alpha	Between 0° and 17°

The thermal properties of the site have been assumed to be those presented in Table 4. Some of these will be updated after a thermal response test measurement planned at the site. The values are, though, consistent with commercial tests done at locations close to this site. Table 4 includes the value of the thermal resistance that has been used to calculate the fluid temperature based on the calculated borehole wall temperature.

Table 4 Thermal parameters at the borehole fields

Diffusivity α [$m^2 \cdot s^{-1}$]	$1.62 \cdot 10^{-6}$
Thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$]	3.5
Undisturbed ground temperature T_g [°C]	8.0
Pipe thermal resistance R_b [$m \cdot K \cdot W^{-1}$]	0.08

The site has been equipped with a logging system in 2009 where several measurements are continuously taken. The measurements include inlet and outlet temperatures from both borehole fields, electricity consumption in the heat pumps, power on the condenser side, information about the amount of compressors operating at specific times, and a large amount of sensors on the building's distribution side (ventilation, tap warm water, heating in radiators, among others). The heat loads on the borehole site have been calculated using performance data from the heat pump and the measured condensing and electric power at all given time steps. Figure 2 shows the heat load profile of the installation VP1-VP2 (drilled in 1998) and VP3 (drilled in 2009), varying from 0 to about 150 kW. The total annual energy demand of the building is about 1700 MWh.

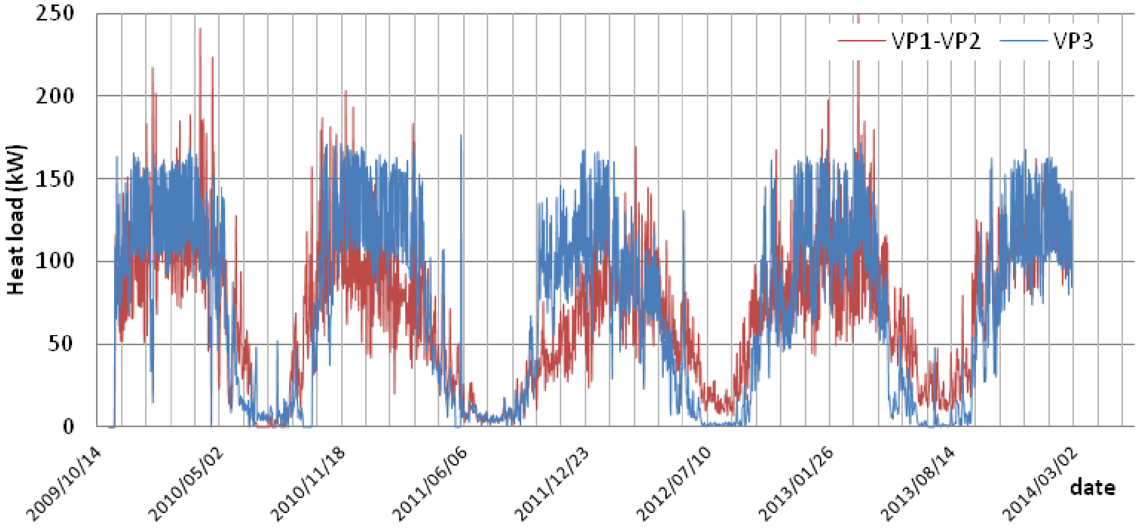

Figure 2 Heat loads profile on heat pumps VP1-VP2 and VP3

As described above, once the geometry, boundaries, and inlet parameters were identified, the thermal response of the borehole field is simulated using the FLS analytical approach for vertical and inclined BHE. The g-functions are calculated separately for each of the sub-borehole fields given the estimated lack of thermal interaction between them during until today. Once the g-function is known, temporal superposition of the measured daily loads (presented in Figure 2) is used to calculate the average fluid temperature, which later is compared to the measured values.

3. RESULTS

Figure 3 shows the g-function calculated for the sub-borehole fields VP1-VP2 and VP3 (drilled in 1998 and 2009, respectively). In addition, the figure includes the case for the total borehole field with all boreholes. The time is expressed at some points along the horizontal axis. The g-function from borehole field drilled in 1998, sub-borehole field VP1-VP2, indicates a more compact configuration which will, in the long term, show a tendency to get colder than the field from 2009, sub-borehole field VP3. This added to the fact that it has been operating about 11 years more than the sub-borehole field VP3.

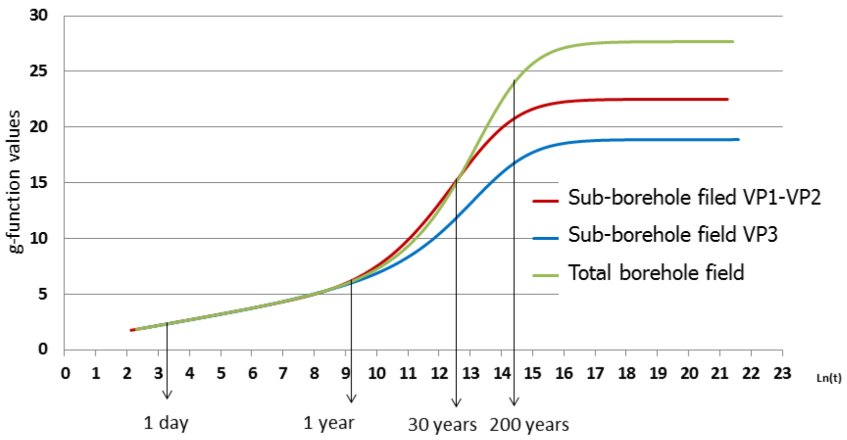

Figure 3 g-function calculated for the two sub- borehole fields VP1-VP2 and VP3, as well as the total borehole field which is calculated using all boreholes

The secondary fluid temperature to VP1-VP2 and VP3 has been registered during the last 6 months. Although the precision of the measured data is at this moment somewhat unknown, a comparison between the measured secondary fluid temperatures Tf_m and the calculated temperatures Tf_e is carried out. Thanks Figure 4 and Figure 5 shows both of these for VP1-VP2 and VP3, respectively.

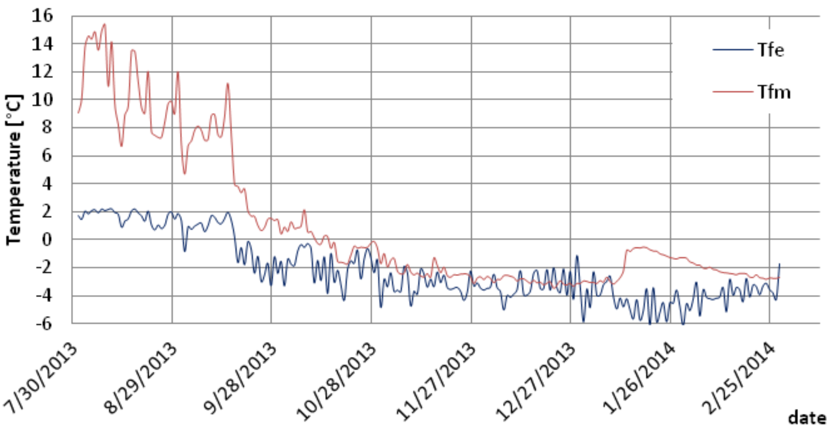

Figure 4 Measured and predicted temperatures of the secondary fluid at the sub-borehole field VP1-VP2

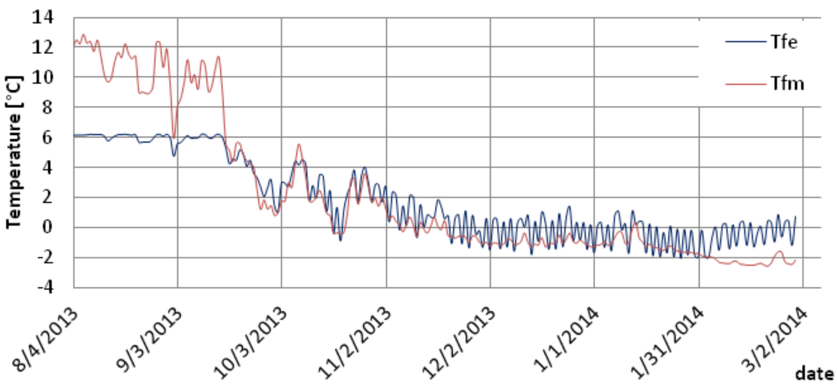

Figure 5 Measured and predicted temperatures of the secondary fluid at the sub-borehole field VP3

During the summer months (August and September), the differences between the predicted and the measured temperatures are high in both cases. During this period, the heat pumps operate between 2 and 4 hours per day and, since the values are daily averages, the measured curve (red) is misleading, i.e. not representative of the reality. The differences are otherwise within a range of about 0 to 2 K. The agreement between the two curves is, in general, considered acceptable. In January-February, however, the measured temperatures in the borehole field connected to VP1-VP2 had a sudden and unexpectedly increase at the same time as they decreased in the group connected to VP3. The secondary fluid temperature should have remained following the same tendency at a level of around -4°C for VP1-VP2 and -1°C for VP3. Some experiments carried out with the oil burner used as a back-up of the system can be a part of the cause for the temperature jump. A couple of hypotheses regarding this are being investigated at the moment.

The comparison presented in Figure 4 and 5 gave confidence to carry on and do a forecast on how the borehole field will behave in the next years. Assuming the heat loads to be equal to those in Figure 2, the result is shown in Figure 6. For both VP1-VP2 and VP3, a decreasing of temperature is observed. For VP1-VP2, the temperature will decrease by 2°C compared to today's values. VP3 will be less affected with a temperature decrease by 1.5°C. Each 1°C temperature change will affect the condominium as a lost about 3% efficiency reduction for the system. During the next 20 years, the temperature levels in the borehole field will most likely lessen the systems SPF by around 6.0% efficiency for VP1-VP2 and around 4.5 % for VP3. The borehole fields are judged to operate fine and no major changes seem to be needed on this side of the system. Future adjustments in these calculations will be done once the ground properties from in-situ tests and the groundwater level from all boreholes are available.

4. CONCLUSION

The high and somewhat unexpected consumption of oil in the back-up heating system of an existing building in Sweden has raised some hypotheses about the design of a ground source heat pump system which was built in two steps. One aspect of the necessary studies to test the hypotheses has been to verify the performance of the borehole heat exchangers. The borehole field, consisting of an uneven (non-symmetric and with different inclinations) borehole arrangement pattern of 26 boreholes, has been studied using finite line source based g-function calculations for two sections of the borehole field which are connected to two different heat pump groups. One of the two borehole groups has been operating for 15 years and the second for about 4 years. No thermal interaction was estimated to occur between these. Once the g-functions were calculated for each field, temporal superposition of measured thermal loads were used as inputs for predicting the fluid temperature. The calculated values are compared to measured temperature data over the last winter season. The results show a rather good agreement in both installations, with lower differences in newest borehole field. A forecast was carry out repeating the same measured loads for the next 20 years resulted in a further decrease of ground temperatures of about 2K, i.e. a reduction on SPF of about 5%. The borehole field was, however, judged to operate properly and other parts of the system are being study at the moment.

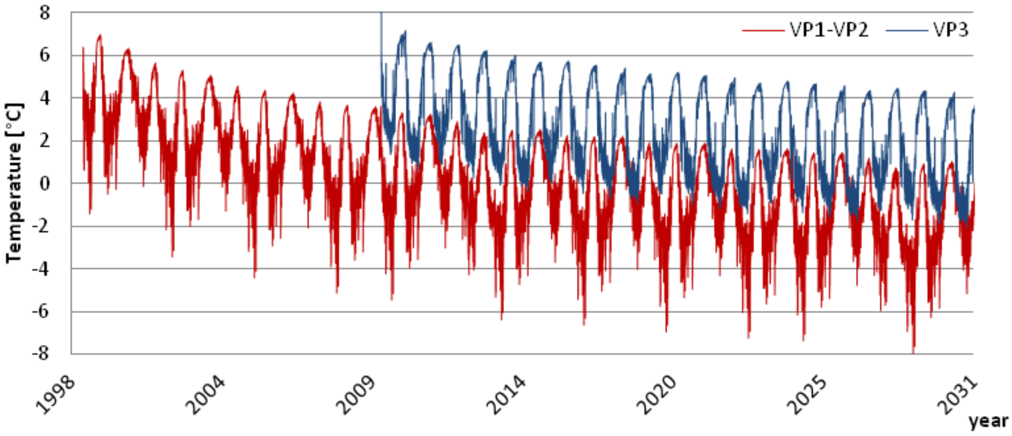

Figure 7 Borehole wall temperature forecast for sub-borehole field connected to VP1-VP2 (1998) and VP3 (2009)

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