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Modelling the Change of Heat Exchange Rate of Borehole Heat Exchangers in Large GSHP Systems

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ABSTRACT

As a low-carbon technology for providing heating and cooling to buildings, utilizing shallow geothermal energy through Ground Source Heat Pump (GSHP) systems is increasingly applied all over the world. A recent trend in the industry is to build large GSHP systems targeting commercial buildings and small neighborhoods. Such systems are typically constructed by linking hundreds of Borehole Heat Exchangers (BHEs) through a pipe network. In such applications, the heat exchange rate of individual BHE is strongly dependent on the hydraulic and thermal processes in the pipe network. In this study, a numerical model has been developed to simulate this coupling effect. Two existing open-source software, namely the finite element simulator OpenGeoSys and the Thermal Engineering Systems in Python (TESPy), are linked together in this work to simulate large GSHP systems equipped with hundreds of BHEs. The coupled model allows the inflow temperature of each BHE to be dynamically calculated based on the hydrothermal flow processes within the pipeline network. Compared to the superposition-based analytical approach, in which the heat extraction rate of each BHE is imposed as a fixed boundary condition, the newly developed model is more realistic and capable of predicting the dynamic behavior of system efficiency. Modelling results demonstrate that the heat extraction rate in the center of the BHE array will lower itself after a couple of years' operation, and the thermal load is shifted to the outskirt of the borehole field. The heat exchange rates are considerably different as soon as the cold/heat starts to accumulate in the system. The newly developed model provides a more accurate approach to predicting the subsurface temperature evolution, as well as the dynamics of large GSHP system's performance.

1. INTRODUCTION

In recent years, Ground Source Heat Pump (GSHP) systems are increasingly being installed all over the world to provide heating and cooling to both residential and commercial buildings. A recent trend in the GSHP industry is to build systems with larger size, which is capable of meeting the need of an entire neighborhood or block. Such projects are increasingly being built in urban areas, where the land space is often limited. In order to extract the shallow geothermal energy as much as possible, large GSHP projects often include a BHE array, in which hundreds of Borehole Heat Exchangers are connected through a pipe network and the distance between BHEs is kept at a minimum. As large BHE arrays new to the market, current industrial standards and guidelines have not yet fully recognized the load shifting effect from the coupled pipe network. Most guidelines only specify a minimal distance between neighboring BHEs to mitigate thermal interference. For example, Switzerland requires a minimum distance of 5 m between BHEs (cf. Miglani et al. (2017)). In United Kingdom, the value is 7 m (EST, 2007) whereas in China, this distance is kept between 3 to 5 m (GB50366, 2009). The German guideline increased this value from 5 to 6 m in its latest version (VDI4640, 2015). In the German guideline (VDI4640, 2015), a penalty factor was introduced on the value of specific heat extraction rate for systems containing less than five BHEs. For larger systems or ones with a capacity greater than 30 kW, modelling studies become a mandatory requirement.

In most of the real-world projects, analytical or semi-analytical models are often utilized due to its simple implementation and fast calculation time. For example, Eskilson (1987) presented the superposition borehole model to estimate the soil temperature distribution induced by infinite line source. This method was further improved by Bernier et al. (2004) by considering the thermal response effect of past steps to the current temperature distribution. Using this superposition principle, several analytical solutions are further developed. Lamarche and Beauchamp (2007) demonstrated a mathematical algorithm which is independent on the thermal response of the previous step. Koohi-Fayegh and Rosen (2014) analyzed two neighboring boreholes and further developed a more accurate analytical approach considering the thermal interference among BHEs that are connected in an array. Qian et al. (2014) presented a model to investigate the relationship between the soil temperature distribution and the GSHP performance. Based on the finite line source model, Rivera et al. (2016) presented a semi-analytical approach, which estimates the transient temperature distribution in a three-dimensional domain.

Despite the convenience provided by the above-mentioned analytical approaches, they are not able to capture one of the most important features of the large BHE array. In a real GSHP system, the inflow and outflow temperatures of each individual BHE are time-dependent and closely coupled to the pipeline network. On the one hand, the heat flux on each BHE is determined by the temperature difference between the surrounding soil and the circulating fluid. On the other hand, the pipe network distributes and recollects the fluid towards and from each BHE. The network itself has an intrinsic feature of balancing thermal extraction rates among different BHEs. Without the explicit consideration of hydraulic and thermal balance in the pipe network, the above-mentioned coupling effect cannot be accurately quantified. The intention of this work is to extend the existing numerical model to include the interaction between BHEs and the pipe network. Based on realistic modelling scenarios, the change of heat exchange rate due to this coupling effect will be quantitatively analyzed.

2. MODEL CONFIGURATIONS

2.1 Coupling of OpenGeoSys and TESPy

The numerical model employed in this work is based on the finite element simulator OpenGeoSys (OGS, Kolditz et al., 2012). In OGS, the modelling of BHE is achieved by following the dual continuum approach (Diersch et al., 2011). The transient heat transport process within and surrounding the BHE can be accurately simulated and it has already been verified against both analytical solution and lab experiment (Hein et al., 2016). In this work, the OGS code has been coupled with Thermal Engineering Systems in Python (TESPy, Witte,2019)) to explicitly simulate both the BHE and pipe network. The coupling was achieved through a Python interface. Within every time step and each iteration, the outflow temperature T_{out} from each BHE is simulated by OGS and transferred to TESPy via the interface. The T_{out} and the current hydraulic state are then used as boundary conditions for the pipeline network simulation in TESPy. TESPy will calculate the current inflow temperature T_{in} of each BHE and their flow rates. These computed data are then transferred back to OGS for the next iteration. Convergence is achieved when the difference between the last two iteration results is smaller than a preset tolerance.

2.2 Configuration of Model Scenarios

In order to investigate the change of heat extraction rate, three different scenarios were set up and simulated. They share the same basic geometry but increase in the number of BHEs, starting from one single BHE up to 9 and 25 BHEs connected in a square array form. For the subsurface domain, a 300 x 300 x 160 m mesh was constructed with prism and line elements (Figure 1). The total number of nodes and elements in the 1x1 scenario was 3144 and 5530, respectively. For the 3x3 and 5x5 scenarios, the number of nodes has been increased to 37248 and 68432, along with 70884 and 126197 elements respectively. The BHE arrays were always installed in the center of the domain and composed of line elements in all scenarios. All BHEs have an identical length of 50 m, with the top located at a depth of 2 m. To satisfy the design requirements by the Germany VDI guideline (VDI4640, 2015), the distance between the adjacent BHEs is kept at a minimum of 6 m.

A closed-loop pipeline network system was constructed in TESPy to couple the different BHE array models. Figure 2(a) illustrates the basic configuration of the entire network for the single BHE case. After lifted by the pump, the circulating fluid is divided into different branches by the splitter and then flow into each BHE sub-arrays according to the pre-defined arrangement (see Figure 2). In the 3x3 scenario, the array is divided into three sub-arrays, in which three BHEs are connected with each other in a parallel way. In the 5x5 case, the number of sub-arrays and the connected BHEs are increased accordingly. The fluid leaving the BHEs are first mixed at the merge point and then extracted for heat through the heat pump. We have simplified all numerical scenarios so that all the connecting pipes are assumed to have no hydraulic or heat loss. It means that the thermal and hydraulic states of the system are not affected.

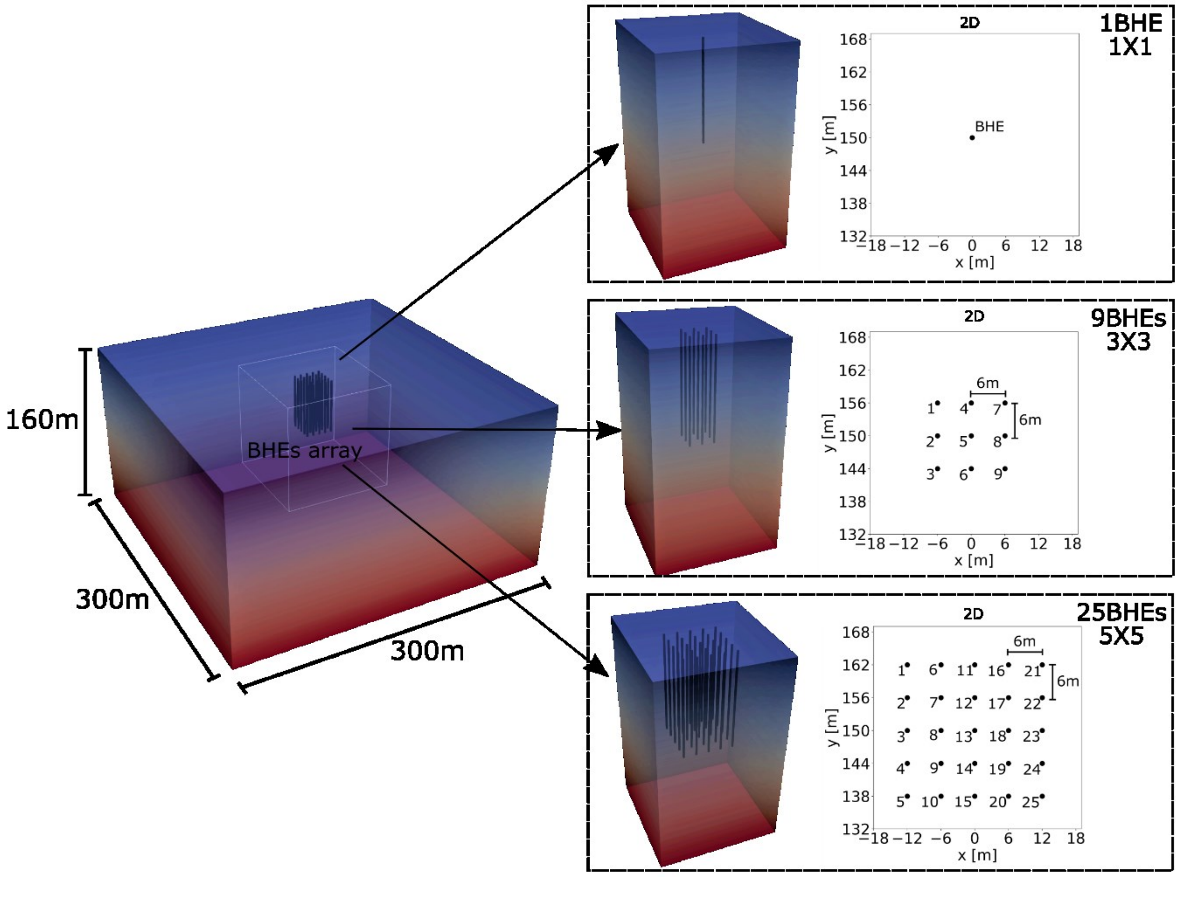

Figure 1: Configuration of the modelling scenarios

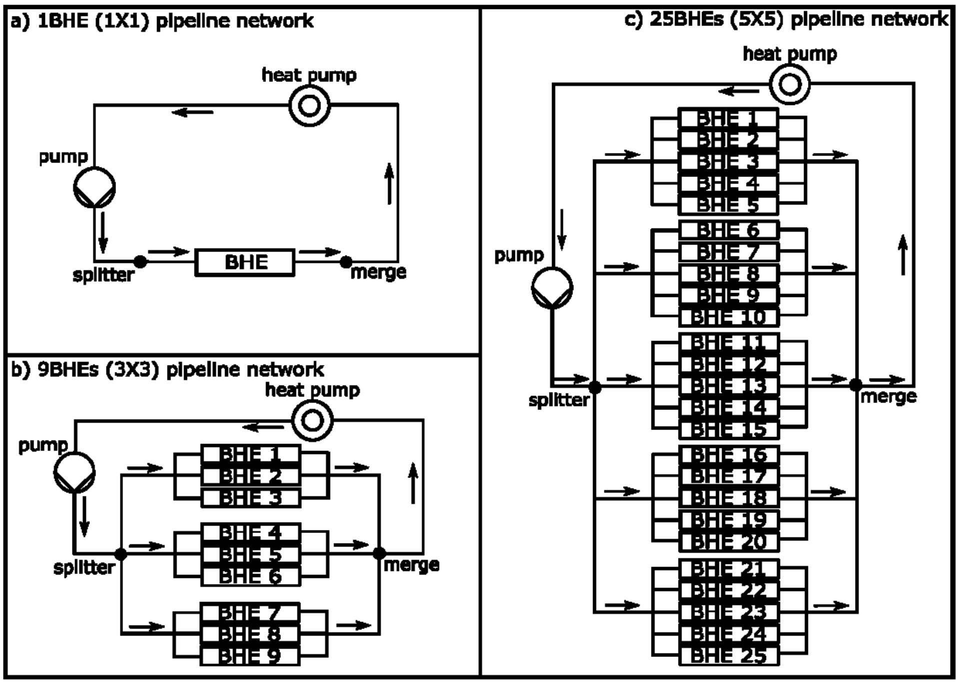

Figure 2: Topology of the pipe network forming the BHE array

3. RESULTS AND DISCUSSIONS

3.1 Temperature

Figure 3 depicts the simulated evolution of soil temperature at 1 m distance from the selected BHEs at a depth of 27 m (middle of the BHE length) in the end of January, when the system is imposed with the peak heating load of each year. For comparison, the result of 1x1 BHE is also illustrated in both figures as the reference case (black line). It can be observed that the soil temperature decreases gradually over time. For the single BHE, the temperature reduction is the minimum, only about 0.6 ºC after 10 years. After around 3 years, the soil temperature is already approaching a quasi-steady state. Compared to the single BHE case, the temperature decrease in the 3x3 setup is much stronger due to the thermal interference from neighboring BHEs. The temperatures at three different locations dropped by at least 2.6 ºC after 10 years. The most intensive temperature decrease is found in the 5x5 case, where a reduction of at least 4 ºC can be observed. Since the average heat extraction rate (625 W) of individual BHEs are identical, the 5x5 case has the maximum total system power (15625 W). In both the 3x3 and 5x5 cases, the soil temperature at the edge (i.e. BHE #1) is generally higher than that in the central part of the array. When moving from the edge towards the center, the temperature decrease also becomes larger. Since the soil near the center suffers the most intensive accumulative effects from all sides, the temperature drop there is the most significant.

Similar trends can be observed for the evolution of BHE inflow and outflow temperature, as illustrated in Figure 4. The inflow and outflow refrigerant temperature in the single BHE case decreases slightly during the beginning 2 years and then stabilizes at 4.4 and 4.9 ºC respectively. Compared to that, the temperature drop in the multi-BHE array cases is considerably larger. In the 3x3 case, the inflow temperature is about 1.9 ºC and the outflow remains at about 2.4 ºC after 10 years for the central BHE. In the 5x5 case in which more BHEs are coupled, a much lower inflow and outflow temperature are observed, with a minimum temperature of 0.2 ºC and 0.7 ºC, respectively. Similar to the change of soil temperature presented above, the inflow refrigerant temperature was forced to decrease to a lower value when a larger BHE array is present. This is because the increase in the number of BHEs connected in the system also implies that the total amount of imposed thermal load has increased. The insufficient recharge of heat in the shallow subsurface can only result in a decreasing temperature in the circulating refrigerant. As demonstrated in Figures 3 and 4, the circulating temperatures in the 3x3 and 5x5 cases are also changing over time. It suggests that the ability of each BHE to extract heat from the subsurface is deteriorating once the extracted thermal energy is beyond the recharging capacity of the subsurface.

It needs to be noticed that although the soil, BHE inflow and outflow temperatures are dropping over time, the inflow and outflow temperatures of different BHEs in the same array are not deviating much from each other at the same moment. For example, In the 3x3 scenario, the maximal outflow temperature difference is observed between BHE #1 and BHE #5 with 0.06 ºC after 10 years. Compared with that, the difference increases slightly up to 0.14 ºC between BHE #1 and BHE #13 in the 5x5 case. The reason for the different evolution of the outflow temperature of each BHE within a multi-BHE array is due to the different soil temperature distribution near each BHE in the array over the time, which is shown in Figure 3. Since the inflow temperatures of all BHEs in an array arrangement are kept identical due to the parallel-connected network, it indicates that the heat extraction ability of each BHE is different during the system operation.

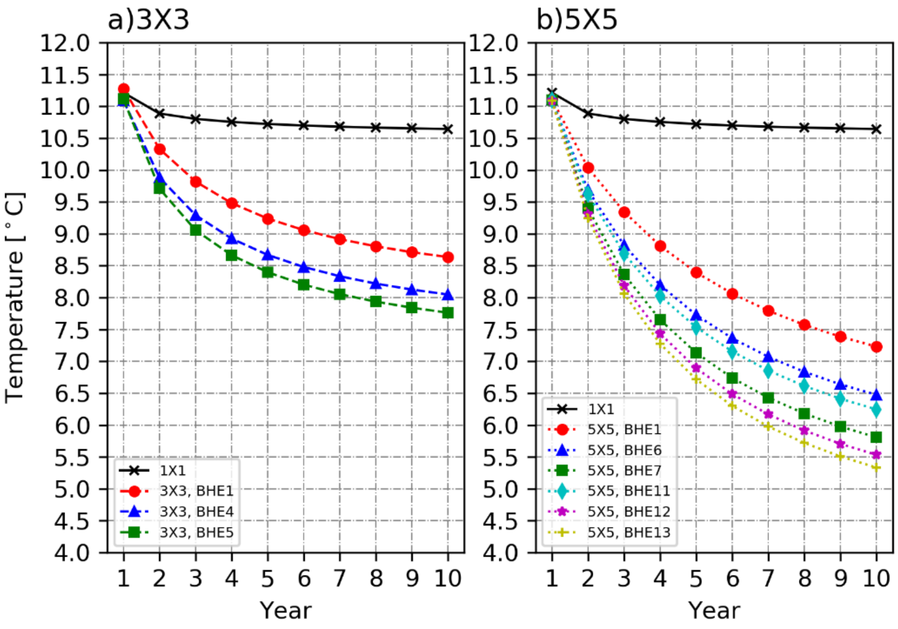

Figure 3: Simulated evolution of soil temperature in the 3x3 and 5x5 scenarios

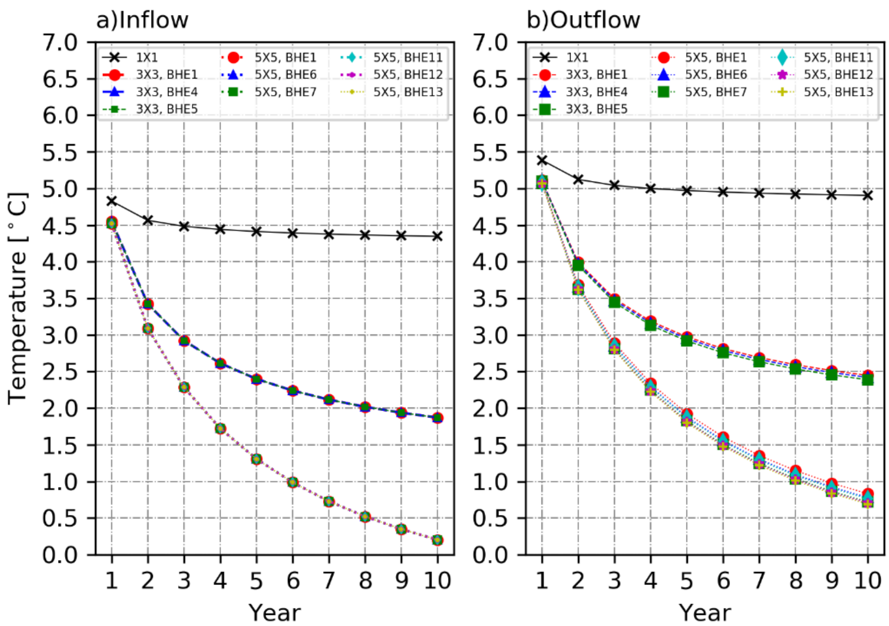

Figure 4: Simulated evolution of inflow and outflow temperature at specific BHE

3.2 Change of Heat Extraction Rate

With the data in Figure 4 available, the actual average thermal extraction rate Q of each individual BHE can be calculated based on the difference between inflow and outflow temperatures. For each individual BHE, results over the 10-year-long simulation period was analyzed for the individual heat extraction rate. First, the amount of shifted thermal load ΔQ was calculated for each BHE by subtracting the actual heat extraction rate by the system average value. Then the shifted load is further normalized by the average value to show its percentage. The evolution of the shifted load and its proportion is illustrated in Figures 5 and 6. A few interesting phenomena can be observed:

In both array setups, the shift of the heat extraction rate of BHEs can be classified into two categories: BHEs located at the outer part of the array (BHE #1 in the 3x3 scenario; BHE #1, #6, and #11 in the 5x5 scenario) are experiencing an increase in heat extraction rate. Meanwhile, the BHEs located at the inner part of the array (BHE #4, #5 in the 3x3; BHE #7, #12, and #13 in the 5x5 scenarios) are experiencing a reduction in its load. The maximal increase and reduction are observed either at the edge or at the center of the array. It indicates that the thermal load is systematically shifted away from the center towards the outer part of the array through the operation of the pipe network. In the 3x3 array case, the maximum change of heat extraction rate (-49 W) was observed for BHE #5 located at the center. Compared to it, the maximal value of -87 W was observed for BHE #1 at the edge of the 5x5 scenario, which means that the shifting effect is enhanced in the larger array setup. In the 3x3 scenario, the shifted heat extraction rate changes intensively for all BHEs in the first 2 years, before a quasi-steady-state is reached. Whilst in the 5x5 scenario, reaching the quasi-steady-state takes more than 5 years. It indicates the system with a larger array setup needs more time to reach the balance. In the 3x3 case, the absolute values of the shifted heat extraction rates of all BHEs become smaller after the recovery period in each year. For instance the shifted rate of BHE #5 located at center changes its value from -50 to -33 W after the recovery period in the 10th year. In the 5x5 case, the change of shifted heat extraction due to recovery becomes smaller. The maximum difference of shifted heat extraction due to recovery was observed for BHE #1 at the edge with only 6.5 W. The shifted rates of BHE #6 and BHE #13 becomes even larger after recovery. This indicates that the recovery period mitigates the heat extraction rate shifting phenomena, but its effect decreases with the increase in the number of the installed BHEs.

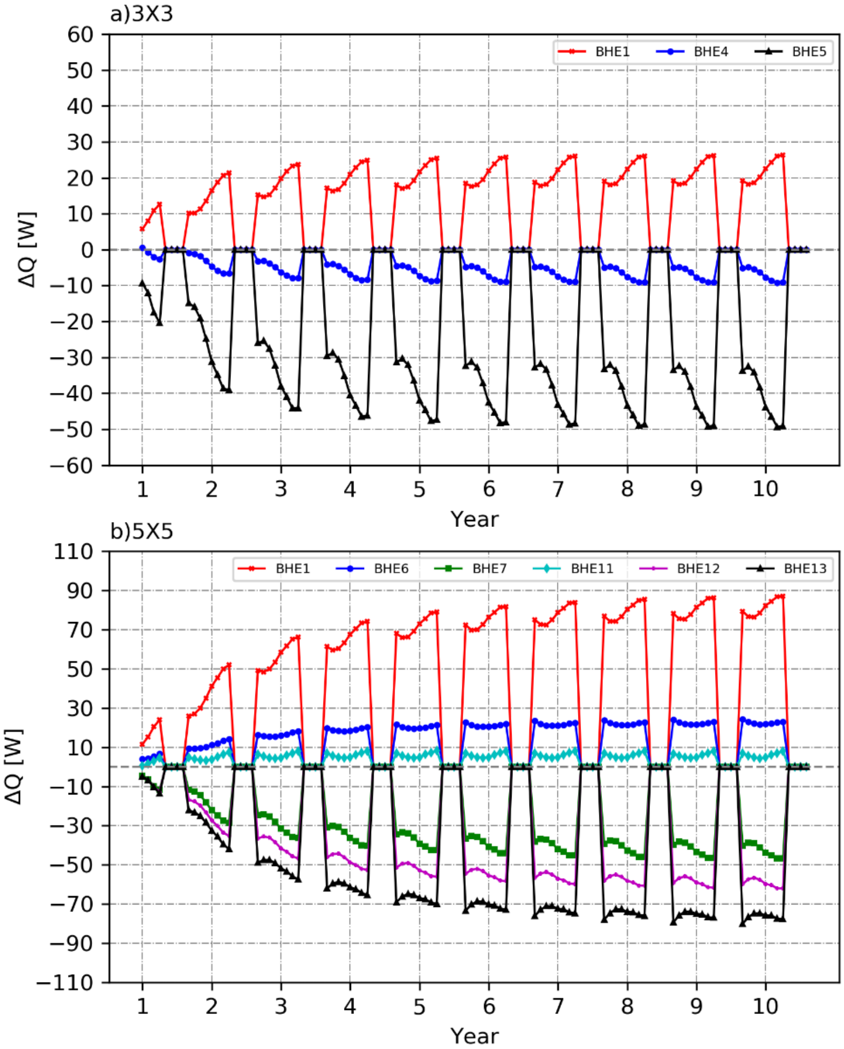

Figure 5: Simulated change of heat extraction rates on multiple BHEs.

As illustrated in Figure 6, the shifting situation could be presented with respect to its proportion to the original designed value. Over the 10 years, the evolution of the shifted proportion follows the similar overall trend as ΔQ in Figure 5. Apart from the similarities, two phenomena should be noticed. Compared to the behavior of ΔQ, the shifted proportion varies much more intensively within every year. Besides, in the 5x5 scenario, the maximum shifted proportion was observed with a value of more than 100% after 8 years, which means the BHE located at the center was already experiencing a negative thermal load during the relevant heating seasons. It can also be interpreted that during the operation of large BHE arrays, shutting down part of the BHEs located in the center during specific periods is valuable for the performance of the entire system.

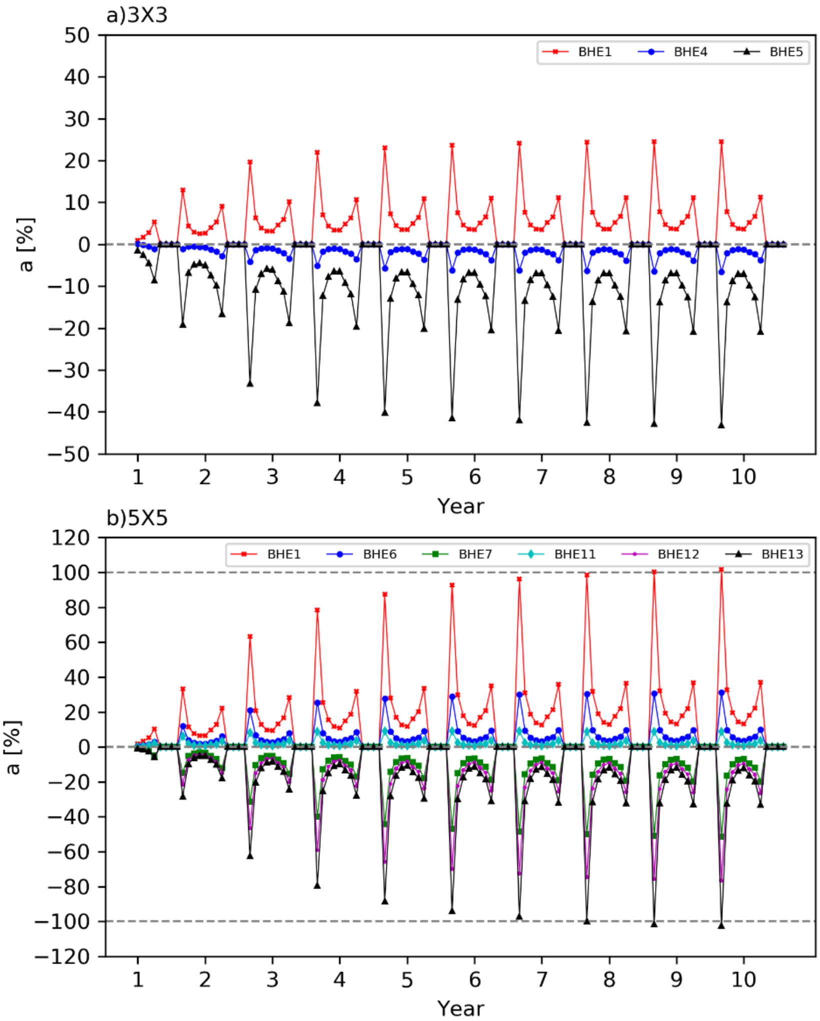

Figure 6: Percentage of changed heat extraction rates on multiple BHEs.

3.2 Discussions

As has been discussed in the introduction of this work, most superposition-based analytical approaches assume a constant heat extraction rate of each BHE and also do not consider the thermal interference as shown in this work. The soil temperature distribution computed by such approaches may lead to considerable deviations in comparison to the reality. It is thus meaningful to quantify such deviation by comparing results from the traditional analytical approach and the newly extended numerical model. For this purpose, three configurations were designed based on the 25 BHEs scenario. The analysis was based on 10 years operation. In the first case, the superposition method (Rivera et al., 2016) is applied to predict the soil temperature distribution. Then, the OpenGeoSys numerical model was applied to simulate both without (Case 2) and with the pipe network (Case 3) cases. In Case 2, each BHE was imposed with the same annual thermal extraction rate curve over the heating season. In case 3, a total thermal load was calculated by summing up the heat extraction rate curves of each BHE and was imposed on the pipe network. In this case, redistribution of the total load is activated among different BHEs. The soil temperature distributions along the observation profile (along the diagonal from lower-left to upper-right corner) are depicted at a depth of 27 m and compared in Figure 7.

As shown in Figure 7a, a clear deviation can be observed with respect to the soil temperature distribution predicted by the analytical and two numerical approaches. A maximum 2.5 ºC difference (Figure 7b) was obtained between the analytical and numerical results. The result from analytical approach consistently predicts lower soil temperatures. It confirms the hypothesis that the seasonal ground surface temperature and bottom geothermal flux contribute to the subsurface recharge (see also the results by Hein et al., 2016). It needs to be noticed that the mean specific heat extraction rate of each BHE is assumed to be 12.5 W/m under the peak load, which is considerably lower than the usually applied load in field applications (around 20 to 35 W/m). It suggests that a larger deviation in soil temperature will be produced by the analytical approach if the heat extraction rate is higher. Compared to this effect, the soil temperature deviation caused by the shifted thermal load among BHEs is around 0.3 ºC as demonstrated by the blue curve in Figure 7b. This suggests that thermal interference and load shift lead to a different soil temperature distribution. Yet, such deviation is rather negligible compared to that caused by the recharging effect.

The above comparison leads to several implications for the applicability of the analytical and numerical approaches. For long-term and high thermal load (e.g. thermal storage) applications, ignorance of the subsurface recharge process will over-estimate the drawdown in soil temperature. In such applications, analytical results based on super-imposed solutions may lead to deviations in the soil temperature distribution. Hence, the application of such analytical approach should be limited.

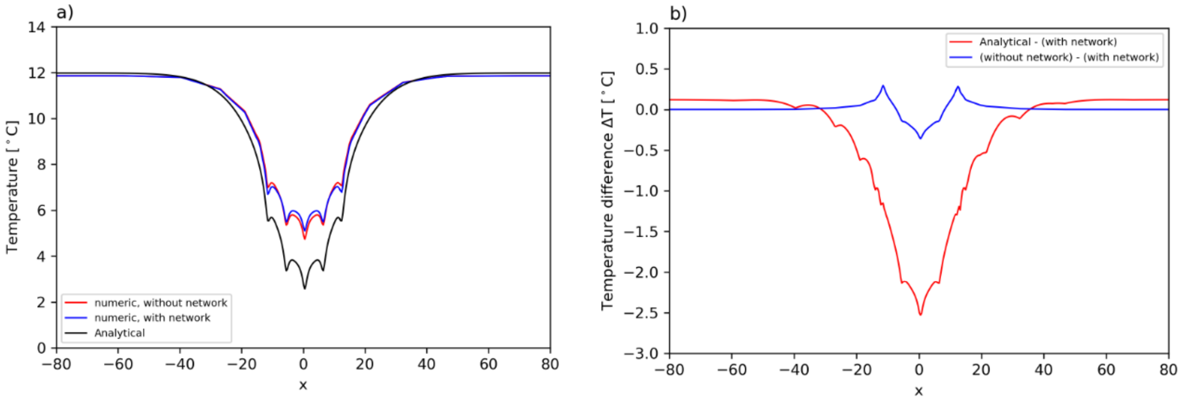

Figure 7: (a) Soil temperature distribution over the profile (A-A') at a depth of 27 m after 10 years of BHE operation, predicted by analytical and two numerical approaches with or without the pipe network (b) Differences in the predicted temperature distribution

4. CONCLUSIONS AND OUTLOOK

In this work, a comprehensive numerical model was developed, with the shallow subsurface, multiple BHEs, and pipe network explicitly considered in a single modelling framework. Compared to other existing models, the thermal and hydraulic processes in the pipeline network was explicitly quantified to reproduce the shifting heat extraction rate caused by the thermal interference among multiple BHEs. It has been found that over the long-term operation of a large BHE array, the heat extraction rate at the center of BHE array gradually shifts towards the outer boundary. The greater the number of BHEs connected in the array, the more intensive is the shifting phenomenon. Further research is currently being carried out to reveal the impact of the load shifting phenomenon on the design of large-scale GSHP systems.

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