ZURICH, SWITZERLAND
6 - 10 OCTOBER 2025

EUROPEAN GEOTHERMAL CONGRESS 2025

Sensitivity assessment of shallow geothermal energy systems as basis for an improvement of planning procedures

Muhammad Asad[1], Kai Zosseder[1]

[1] Technical University of Munich, Chair of Hydrogeology, Arcisstraße 21, 80333 Munich

m.asad@tum.de

Keywords: shallow geothermal, borehole heat exchangers, numerical modelling, sensitivity analysis

ABSTRACT

Shallow geothermal energy is increasingly adopted for sustainable heating and cooling applications. Ensuring the long-term efficiency of borehole heat exchangers (BHEs) is essential for the reliable operation of such systems. In this study, a sensitivity analysis is carried out on an existing five-borehole heat exchanger system in Kranzberg, Germany. Six important parameters are examined to evaluate their impact on BHEs performance. The results provide practical insights into which parameters most strongly affect system behaviour, enabling a more focused approach for future BHE design and sizing.

1. INTRODUCTION

Shallow geothermal energy is the heat stored a few hundred metres down in the earth's surface that is available all year and all seasons. This heat can be used for both heating (in the winters) and cooling (in the summers) of the building. To efficiently harness geothermal energy, borehole heat exchangers play a crucial role and are essential for transferring thermal energy either into or out of a system, enabling the effective utilization of geothermal heat (Brettschneider and Perković, 2024). Heat exchangers facilitate both the extraction and dissipation of heat, making them indispensable in a wide range of thermal applications. Their use extends across various sectors, including industrial and agricultural domains. In agriculture, they support temperature regulation in greenhouses, maintain optimal water conditions in aquaculture systems, and assist in processes like crop drying and food dehydration. In industrial settings, heat exchangers contribute to energy conservation and process optimization, such as in water heating and thermal management systems. As the demand for sustainable and renewable energy solutions grows, the design and deployment of efficient heat exchangers remain central to maximizing the potential of geothermal energy systems (Ilyushin and Golovina, 2020; Martirosyan et al., 2021; van der Zwaan and Dalla Longa, 2019; Yildirim et al., 2019). The geothermal system can be implemented in different configurations depending on different parameters (geological, geographical, hydraulic, environmental) that influence its design.

More specifically, they can be classified as open loop, where the fluid that is sent to the heat exchanger is taken from an underground aquifer or from nearby lakes or rivers, recovery wells and return wells are made for the water to return to the source, in this case the fluid must not be contaminated; closed loop, the fluid circulates within probes, without mass exchanges with the external environment (Lund, 2003; Luo et al., 2019).

Another possible classification of geothermal systems is carried out according to the geometric arrangement of thermal exchange probes with the ground, so a geothermal system can be divided further into horizontal probes, where the pipes are placed horizontally in the ground up to a depth of about 3 to 4 m, they can be arranged in different geometries or hydraulic connections; for installation, they require a large free surface and are severely affected by seasonal thermal oscillations of the external environment. The exchanger can have a horizontal development and is laid in excavations, simple trenches or the exchangers are laid in excavations, with parallel or so-called "braid" connections, to reduce the space required for installation; vertical probes, arranged vertically in the ground can reach depths of 200 m; the probes are placed in holes drilled and filled with cement mortar (Pouloupatis et al., 2011; Zeng et al., 2003); they can be made with different shapes and sizes (U-tubes, double U tubes, coaxial).

As the use of shallow geothermal energy, mostly borehole heat exchanges (BHEs), continues to grow, especially in urban areas, the number of installations increases and can reach a critical density. This means that negative interactions between neighbouring systems can occur, leading to reduced overall efficiency as well as regulatory problems. In order to make the best possible use of near-surface geothermal potential, they must be optimally dimensioned and controlled but comparing planning and design of BHEs using the common planning tools with their monitored performance in the operation phase shows often a high divergence. The reasons of this variance can be uncertain input parameter information or approximations in the planning procedure and tools. Therefore, the project OptiGEOS, funded by the German Ministry of Economic Affairs and Climate Protection, is developing optimization procedures and tools for the planning of BHEs. In this framework a comprehensive sensitivity assessment considering six input parameters, impacting the performance of a BHEs has been conducted. For this study, a 3D numerical model using FEFLOW has been developed based on a real system of five BHEs to do its sensitivity analysis by using one at a time (OAT) parameter variation approach. In addition, this analysis will further include the interaction of geothermal systems between each other and as well as the impact of subsurface flow on the efficiency of the heat exchangers. The assessment identifies the critical parameter for the performance of BHEs and quantifies the potential impact of parameter increase or decrease. These findings have been compared and validated against the existing Kranzberg model data driven and based on real case monitoring provided by drilling and planning companies. These preliminary results will be finally implemented and development if a box model and will assist in development of the new planning tool for the optimization of BHE implementation in the framework of the OptiGeoS project.

2. METHODOLOGY

This section outlines the modeling approach used to evaluate the thermal behaviour of geothermal probe systems. Numerical model is built in FEFLOW, a finite element software designed to simulate heat and fluid flow in subsurface environments (DHI-WASY 2023), to simulate heat transport in the subsurface and assess the performance of BHEs. In the municipality of Kranzberg 30 km north of Munich there are five borehole heat exchangers of the company GeoKOAX with a length of 47 m installed. They are used for the heating and cooling of a residential house. The numerical model has been validated against the existing model of this facility to produce a synthetic model (**Figure 1**) that has been used to do the OVAT based sensitivity analysis.

2.1 Heat Transport Modeling

The initial and boundary conditions (BC) of the model are given below:

- Dirichlet BC is applied at the top layer to incorporate the surface temperature over the period.
- a constant 10˚C temperature BC which is applied on the right-side wall.
- Neumann BC is applied at the bottom layer to have the thermal gradient distribution across the domain before running the BHEs.
- the eastern model boundary, a value of 450.5 m above sea level is defined for the hydraulic head, while 447.5 m above sea level at the western model boundary of the domain.

Firstly, a short-term model for 2 months of simulation was performed to validate the numerical model against the existing Kranzberg model calibrated against the experimental data (**Figure 2 A**). To better visualize the data the outlet temperature time graph is converted to the cumulative time percentage graph (**Figure 2 B**), later the long-term model for five-year simulation period was developed using monthly average values of flow rates and extracted energy to evaluate the long-term thermal response of the BHEs.

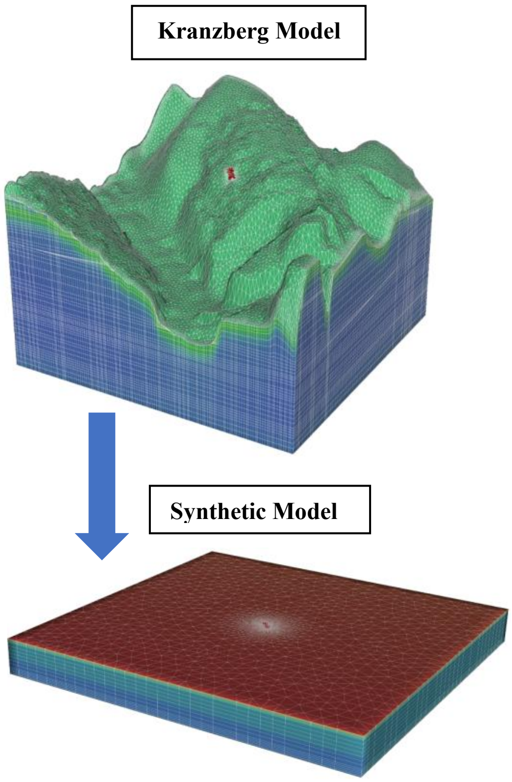

Figure 1: Conversion of existing Kranzberg model to a synthetic box model

Table 1: Parameters of the BHE

Property	Value
BHE Geometry	Coaxial (annular inlet)
Borehole Diameter	0.219 [m]
Inlet Pipe Diameter	0.14 [m]
Inlet Pipe Wall Thickness	0.0054 [m]
Outlet Pipe Diameter	0.04 [m]
Outlet Pipe Wall Thickness	0.0037 [m]
Pipe thermal conductivity	0.1,0.25,**0.42***,0.7,1[W/m/K]
Grout thermal conductivity	0.2, 0.7, **1***, 1.7, 2 [W/m/K]
Ground thermal conductivity	0.5, **1***, 2.2, 3.7,4.5 [W/m/K]
Ground heat capacity	1,2, **2.5***, 3, 3.5 [MJ/m^3/K]
Flow rate of working fluid	**0.42***, 1, 1.5, 2 [L/s]

Table 1 shows the BHE properties and different values for every varying parameter like ground, grout and pipe thermal conductivity ground heat capacity and flow rate. The steric sign (*) in **Table 1** represents the base model scenario values for each case and in **Table 2** properties of different working fluids have been described. It should be noted that flow rate was kept at the base model for all different scenarios.

Table 2: Working fluid properties

Fluid	λ_f [W/m/K]	c_f [J/kg/K]	ρ_f [kg/m³]	μ_f [mPa.s]
Glycol 25%	0.45	3974	1026	5.51
Ethanol 24.4%	0.426	4288	972	5.85
Glycol 33%	0.416	3899	1015	8.17
$CaCl_2$ 20%	0.54	3030	1186	4

3. RESULTS AND DISCUSSION

The model could reliably reproduce the thermal response of the subsurface and the fluid under realistic operational conditions for which the short-term model was developed and compared with the existing model of the facility as shown in the Figure 2A**,** average outlet temperature is governed by the thermal interaction between the circulating fluid and the surrounding ground. These values are highly sensitive to soil/rock thermal properties such as groundwater flow, initial subsurface temperature distribution, BHE operation parameters also play important role for instance flow rate and energy demand. The borehole mean fluid outlet temperatures were processed to calculate cumulative temperature distributions (Figure 2B**)** under heat extraction conditions—first for the initial 60 days and subsequently for the entire 5-year simulation period. These distributions serve as synthetic indicators for analyzing the sensitivity of different parameters and for drawing conclusions regarding the system's energy performance. By examining the fluid outlet temperature duration curves in Figure 2B**,** it is possible to determine how long the heat pump operates within specific source temperature ranges. For example, at a flow rate of 0.4 L/s, the mean outlet temperature remains ≤ 5 °C for approximately 791 days of the 5-year simulation (≈ 43.5% of the total period), whereas at 2 L/s, this condition occurs for only about 183 days (≈ 10% of the total period).

The subsurface temperature distribution around BHEs shown in Figure 3 which demonstrates the spatial influence of multiple BHEs on the surrounding ground. The top subfigure shows the overall 3D temperature field, where the temperature gradient remains nearly uniform across the broader domain except in the vicinity of the BHE region, indicating localized heat extraction. The zoomed-in view focuses on five BHEs, where distinct cooler zones (green to blue) are observed around each borehole. These regions represent the thermal plumes propagating from each BHE over a five-year simulation period. The overlapping of cooler zones reveals potential thermal interference between adjacent BHEs. When boreholes are spaced too closely, such interactions can reduce the system's efficiency, as the ground temperature around each borehole is already influenced by neighboring heat exchangers. These temperature contours provide valuable insights for optimizing borehole spacing and assessing the long-term thermal performance and sustainability of the BHE system.

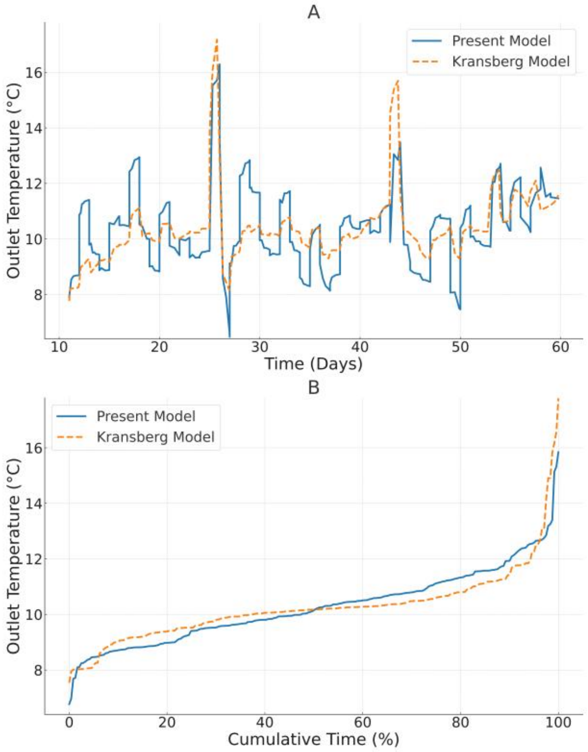

Figure 2: Model validation with the existing Kranzberg model (A); Conversion of outlet temperature to cumulative time distribution representation (B)

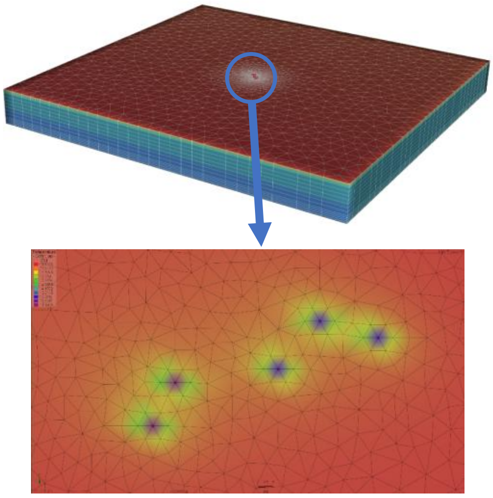

Figure 3: 3D and 2D FEFLOW simulation of subsurface temperature distribution around borehole heat exchangers (BHEs).

As it can be seen from Figure 2A that the outlet temperature of the numerical model follows consistent trends, which indicates that the model captures the overall thermal behaviour of the BHE system effectively but some deviations at the certain points, particularly during sharp transitions or spikes are also visible. These sudden transitions could be attributed to the sudden operational changes (e.g., flow or temperature variations at the initial days) or this could also be happened due to short-term environmental effects being not fully represented in the model (e.g., surface temperature fluctuations or precipitation events) as some simplifications and assumptions in the numerical model are present such as uniform material properties. The sensitivity analysis of six key elements have been show **Figure 5**, when Grout thermal conductivity is at increased from its lowest value to the next chosen value it shows a big jump in average outlet temperature due to which it had overall largest effect, as there is not so much increase in the average outlet temperature when it was increased further. When increased from its lowest tested value, the outlet temperature rose by approximately 3.3 °C across the examined range.

Ground thermal conductivity is observed to be strongly influential, yielding an improvement of about 2.7 °C and highlights the importance of thorough site characterization. The choice of working fluid meaningfully affected performance as well. Saline brines—such as 20% $CaCl_2$—possess lower viscosity than glycols or ethanol, which reduces hydraulic losses and increases outlet temperature by roughly 2.5 to 2.7 °C. Increasing the flow rate produced a smaller but measurable benefit, on the order of one degree Celsius on average, although any gain must be weighed against additional pumping energy and frictional losses; consequently, flow should be optimized rather than maximized. By contrast, pipe thermal conductivity had only a minor influence, with the curves remaining closely clustered, indicating that once typical pipe materials are used the contribution of the pipe wall to overall thermal resistance is limited. Ground volumetric heat capacity was the least influential parameter in this study, producing only modest changes in the outlet-temperature distribution.

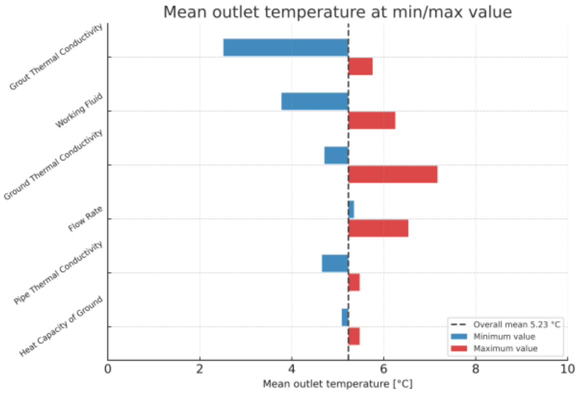

Figure 4: Influence of each parameter at its minimum (blue) and maximum (red) settings on the mean outlet temperature; all other parameters are held at their baseline values. The vertical dashed line marks the overall mean temperature (5.23 °C). Bars to the right of the line indicate warmer means, and bars to the left indicate cooler means. The largest deviations from the mean occur for ground thermal conductivity and working fluid / flow rate, while the smallest deviations are observed for pipe thermal conductivity and the ground's volumetric heat capacity.

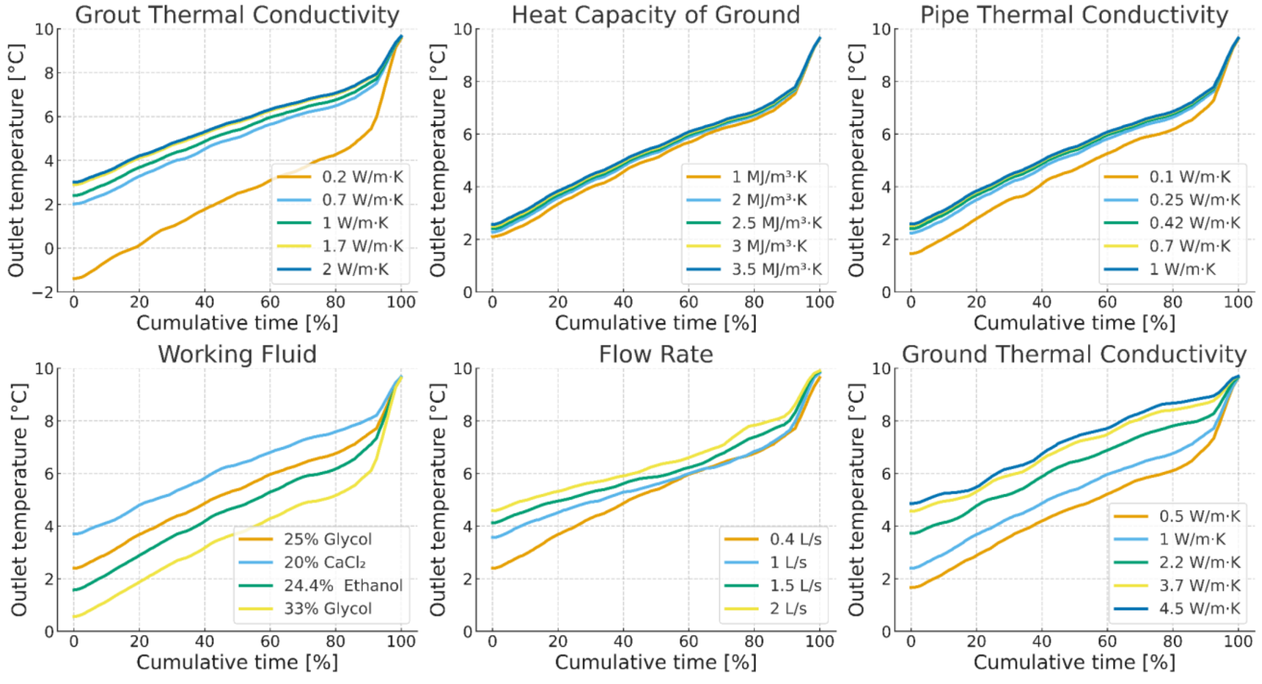

Figure 5: Sensitivity analysis of outlet temperature of six design parameters. Each subplot overlays five cases per parameter: flow rate, working fluid, ground thermal conductivity, grout thermal conductivity, ground volumetric heat capacity, and pipe thermal conductivity. Curves shifting upward indicate warmer outlets for a larger share of time.

4. CONCLUSIONS AND FUTURE WORK

In this work, A numerical model of a borehole heat exchanger (BHE) system was developed using FEFLOW and successfully calibrated against existing model based on experimental data from a real installation. The box model effectively reproduced the observed seasonal thermal dynamics and localized ground-cooling effects, confirming its reliability for long-term performance evaluation. Further, the sensitivity analysis of six key parameters demonstrated consistent behavior with literature findings that provide valuable guidance for future global sensitivity investigations.

Future research will focus on comprehensive sensitivity and uncertainty analyses to better quantify the influence of key factors such as subsurface thermal properties, groundwater flow, borehole spacing, and operational conditions. These efforts will strengthen the model's robustness and contribute to the development of optimized BHE design strategies suited to varying geological and climatic conditions.

REFERENCES

Brettschneider, A.L., Perković, L., 2024. Theoretical analysis of using multiple borehole heat exchangers for production of heating and cooling energy in shallow geothermal reservoirs with underground water flow. Appl Therm Eng 254, 123914. https://doi.org/10.1016/J.APPLTHERMALENG.2024.123914

Ilyushin, Y., Golovina, E., 2020. STABILITY OF TEMPERATURE FIELD OF THE DISTRIBUTED CONTROL SYSTEM 15.

Lund, J.W., 2003. The use of downhole heat exchangers. Geothermics 32, 535–543. https://doi.org/10.1016/j.geothermics.2003.06.002

Luo, Y., Guo, H., Meggers, F., Zhang, L., 2019. Deep coaxial borehole heat exchanger: Analytical modeling and thermal analysis. Energy 185, 1298–1313. https://doi.org/10.1016/j.energy.2019.05.228

Martirosyan, A. V., Martirosyan, K. V., Grudyaeva, E.K., Chernyshev, A.B., 2021. Calculation of the Temperature Maximum Value Access Time at the Observation Point, in: Proceedings of the 2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, ElConRus 2021. Institute of Electrical and Electronics Engineers Inc., pp. 1014–1018. https://doi.org/10.1109/ElConRus51938.2021.9396287

Pouloupatis, P.D., Florides, G., Tassou, S., 2011. Measurements of ground temperatures in Cyprus for ground thermal applications. Renew Energy 36, 804–814. https://doi.org/10.1016/J.RENENE.2010.07.029

van der Zwaan, B., Dalla Longa, F., 2019. Integrated assessment projections for global geothermal energy use. Geothermics 82, 203–211. https://doi.org/10.1016/j.geothermics.2019.06.008

Yildirim, N., Parmanto, S., Akkurt, G.G., 2019. Thermodynamic assessment of downhole heat exchangers for geothermal power generation. Renew Energy 141, 1080–1091. https://doi.org/10.1016/j.renene.2019.04.049

Zeng, H., Diao, N., Fang, Z., 2003. Heat transfer analysis of boreholes in vertical ground heat exchangers. Int J Heat Mass Transf 46, 4467–4481. https://doi.org/10.1016/S0017-9310(03)00270-9