Numerical simulation of thermal response test under high groundwater advection and evaluation of thermal properties of the subsurface in the practice of Hans-Rehn-Stift case study

M.Sc. Matin Liaghi, Universität Stuttgart
Prof. Dr.-Ing. habil. Bernhard Westrich, Universität Stuttgart
Univ.-Prof. Dr.-Ing. habil. Christian Moormann, Universität Stuttgart

A thermal response test (TRT) is considered as the most common method to provide reliable information about the underground thermal properties, which are significantly important for an efficient and optimized design of BHE. In this study, a three dimensional thermo-hydro coupled model of BHE has been developed to simulate the performed TRT test in a BHE and its surrounding soil, which is installed in different geological layers under high groundwater advection effect. Comparison of the temperature profiles' development due to the TRT test between numerical simulation and recorded data in the field are presented. The results show the success of the numerical model in reproducing the performed TRT test. Moreover, the verified model has been used for further investigations to achieve a better estimation of subsurface thermal properties and especially the groundwater velocity.

1 Introduction

The shallow geothermal systems absorbed more and more attention in recent years. Ground source heat pump (GSHP) systems are considered as supplies of the energy to diminish the primary energy use in commercial and residential buildings for space heating and cooling. Several studies are performed in this field, which considering a GSHP in cold climate region Bakirci (2010) as well as a mild climate region Pulat et. al. (2009). Providing an efficient and optimized design of BHE for a specific site location strongly depends on the level of the detailed information about the underground thermal properties. Subsurface thermal properties are specific parameters corresponding to each site location. Thermal response test (TRT) is the most common method to assess the thermal properties of the subsurface. The exact evaluation of a TRT, especially in complex conditions like high groundwater advection is tremendously important for designing a BHE. A TRT is performed on a heat exchanger probe, by circulating fluid with a defined heat input using heat pump over a period of time. The inlet and outlet water temperature along with water flow rate are measured continuously which later used to analyze the reaction of the subsurface to the temperature. By using TRT, it is possible to evaluate the effective thermal conductivity, which is a combination of subsurface and filling material thermal conductivity. The effective thermal conductivity resulting from TRT considers all the heat transport in the subsurface including both conduction and convection (in the presence of groundwater). Based on Sanner et. al. (2005) the theoretical basis of TRT and its further interpretation has been studied in many investigations since 19th such as Hellström (1991), Claesson & Eskilson (1988) and many others.

The line source theory is known as the most popular method to evaluate a thermal response test. This theory is based on Kelvin line source equation Carslaw & Jaeger (1959). In this model, the subsurface is considered as a homogeneous and isotropic medium with a uniform initial temperature, which the BHE is implemented inside that as an infinite line source with radial purely conductive heat flux per unit length.

Another approach to analyze the heat transfer between the BHE and its surrounding domain is the cylindrical heat source approach. In this method, the BHE with a specific diameter is considered to be placed in an infinite homogeneous domain. This approach considers a constant initial temperature for the whole domain and a definite heat flux per unit surface from the cylinder to the adjacent medium. These TRT interpretation methods depict some deficiencies due to different reasons as following:

(1) Ignoring the heterogeneity of the subsurface.
(2) Assuming a constant initial temperature for the whole domain and neglecting the natural temperature gradient of the earth Signorelli (2004).
(3) Neglecting axial heat flux especially at the surface of the ground due to the ambient temperature fluctuations.
(4) Purely conductive heat transport and ignoring convective heat transport due to groundwater flow Signorelli et. al (2007).

A numerical simulation can assist the investigation to overcome the limitations and achieve high accuracy of TRT interpretation.

2 Hans-Rehn-Stift case study

The Hans-Rahn-Stift is a residential facility for elderly people, which is placed in Stuttgart. It's evaluation is part of the "GeoSpeicher" project in Baden Württemberg state of Germany.

2.1 Project conditions

The heat supply of the facility is ensured by various types of heat supply such as a combined heat and power plant, solar thermal energy and an air heat pump. In addition, the base load of the heat demand is covered by a geothermal probe field consisting of 21 (double U-pipe) geothermal probes. 20 of these BHEs have the depth of about 90 m and one of them is extended up to 190 m and used for thermal response test and studying the geology and hydrology properties of the field and later operated as a part of the system for energy production.

The underground along the BHEs is formed mainly by 2 layers of limestone and sandstone and a narrow layer of clay. The thermal properties of the soil layers were chosen based on VDI-RICHTLINIEN (VDI 4640) (2015) and are shown in table 1.

Table1

Soil layers thermal properties

Properties	Thermal Conductivity	Volumetric heat capacity
Unit	$W/m \cdot K$	$J/kg \cdot K$
Sandstone	2.8	1181
Limestone	2.7	1000
Clay	2.2	1000

Noteworthy to mention that above thermal properties belong to the saturated soil and not dry soil.

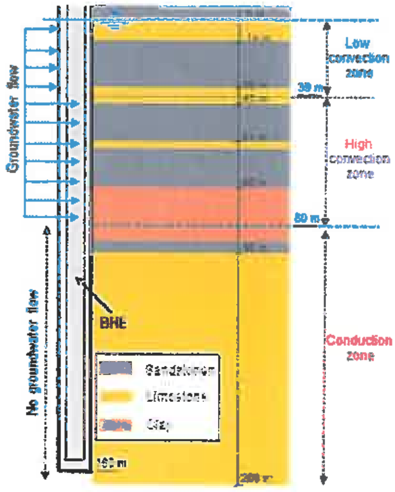

Figure 1: Geological stratification of subsurface and different underground zones.

Fig 1 shows the geological stratification of subsurface soil layers. There is a groundwater flow in the upper layer of the subsurface, from 6 m depth near the surface and stretches up to 80 m depth. The hydraulic conductivity is varying and is estimated about $3 * 10^{-7}\ m\ /\ s$ for the depth between 6 m until 18 m, $7 * 10^{-7}\ {}^{m}/_{s}$ for the depth between 18 m until 39 m and further down up to 80 m the value is $4 * 10^{-6}\ {}^{m}/_{s}$. Because of varying hydraulic conductivity, it is reasonable to divide the subsurface into three different zones: Low convection zone with weak effect of groundwater flow, high convection zone with high groundwater velocity and correspondingly high convective heat transport effect in this section (39 up to 80 m) (Fig 1) and Conduction zone without groundwater flow. The details information regarding the probe, which has been used for the TRT test are shown below in table 2.

Table2

Details information of TRT probe

BHE diameter	mm	200
BHE depth	m	190
thermal conductivity	$W/m \cdot K$	2.2
Volumetric heat capacity	$J/kg \cdot K$	2300
Pipe diameter	mm	20.4

2.2 TRT condition

To obtain the natural temperature profile of the subsurface before any TRT operation, the temperature of the fluid inside the pipe through the 190 m depth of the BHE is measured. To ensure an undisturbed temperature profile along with the depth of the ground, it has been waited long enough after installation of the BHE that the whole system reaches to the steady state condition. This phase of study is called initial state.

Afterwards, The TRT test has been performed in Hans-Rehn-Stift. Most important information for the TRT test is shown in table 3.

Table3

Details information of TRT test

Average thermal input	W	10,000
Avergae volume rate	m^3/h	1.32
Average flow velocity in pipes	m/s	0.21
Average Reynolds number	Re	7,150
Type of flow		Turbulent
TRT duration	h	162

After completion of the TRT, two measurements have been carried out: first one after 2 h and the second one after 26 h. As it is explained above, these measurements performed inside the inlet pipe of the probe through the whole depth using NIMO-T temperature device.

The TRT results are interpreted using line source theory and an effective thermal conductivity of 8.7 $W/m\cdot K$ obtained. It is concluded that this significantly high thermal conductivity is due to groundwater velocity. A groundwater flow of 1.2 m/d is estimated for this field. However, groundwater flow makes it difficult to interpret the thermal response test with regard to the absolute value of the heat conductivity, since the convective portion of the heat transport is not taken into account in the evaluation model. Therefore, the importance of the numerical investigation to assist the interpretation of the TRT becomes more significant. The numerical model can provide a better possibility to quantify more accurately the effective thermal conductivity of the subsurface under the effect of high convection groundwater flow. Furthermore, it can provide a better estimation of groundwater velocity.

In this paper, a numerical simulation has been used to study the thermal response test in Hans-Rehn-Stift to propose a better estimation for subsurface thermal properties as well as groundwater velocity using parameter study.

3 Numerical model

A numerical thermal-hydraulically coupled model was developed in the software environment COMSOL Multiphysics version (5.3).

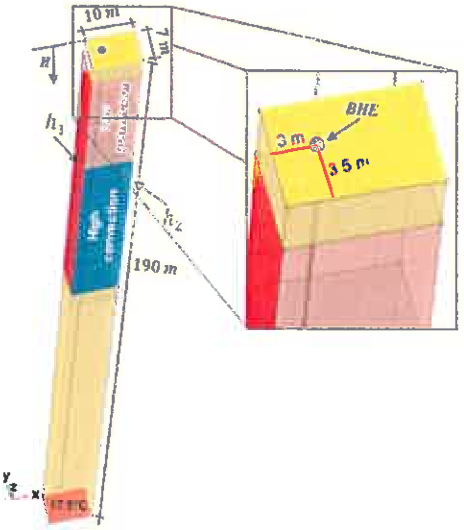

Figure 2: Numerical model domain geometry and boundaries.

3.1 Basic approach

The model geometry as shown in Fig 2 includes a calculation section with 200 m depth, 10 m length, and 7 m width. Within the three-dimensional calculation domain, a geothermal probe (BHE) with 190 m depth and 20 cm diameter was implemented in the coordinates of $X = 3\,m$, $Y = 3.5\,m$. The dimension was chosen so that the temperature distribution of the BHE is not influenced by the model boundaries. The groundwater flow into the model domain is applied using the different hydraulic head on the two sides of the domain (h_1, inlet boundary) and (h_2, outlet boundary) based on Darcy's law (Eq.1) to have the target filter velocity of 1.2 m/d in the high convection zone.

$$V_f = k_f \cdot i \tag{1}$$

No flow condition ($-n \cdot \rho u = 0$) is set for the rest of the domain. In the numerical model, the heat transfer in the porous medium is coupled with the groundwater flow (Eq 2), considering equilibrium temperature for the combination of porous medium and water.

$$(\rho C_P)_{eff}\frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot \dot{q} = \dot{Q} \tag{2}$$

$$q = -\lambda_{eff} \nabla T$$

The temperature of the groundwater flow is applied as a constant temperature boundary of 11 °C at the inflow. Based on the field measurements at the initial state before performing any TRT test Fig. 3, 11 °C is considered as the initial temperature of the domain in the groundwater zones (5 – 80 m) and top section (0 – 5 m) of the model. For the depth from 80 m up to 200, the natural temperature gradient of the subsurface in this region is applied using Eq 3.

$$T_H = -0.04 \cdot H + 9.2 \tag{3}$$

Where H is the depth in each specific location in the subsurface. The effect of the ambient temperature on the near surface depth is considered into the model by applying a heat flux boundary temperature, which contains temperature, air pressure and wind velocity based on recorded data of the nearest weather station to the project site (Leinfelden-Echterdingen). At the bottom of the model, based on the natural temperature gradient computation a constant temperature boundary of 17 °C has been defined. Thermal insulation boundary is set for the remaining surfaces as ($-n \cdot q = 0$).

For conducting the mesh structure of the numerical model, the top surface of the model is discretized by means of free triangle mesh and then it is swept down to the bottom of the domain, generating 292,210 prism elements. Based on the fact, that temperature gradient in the radial direction is significantly higher than the vertical gradient; accordingly, the mesh distribution is also much finer in radial direction in comparison to the axial direction. To prove the property of the discretization, the final mesh structure has been chosen according to the convergence of the outlet temperature within 0.7%.

3.2 Initial state

Based on a geohydrological report for this project the groundwater velocity of 1.2 m/d was defined for the numerical model by means of constant potential heads. The model was simulated as a transient problem with a simulation duration of 5 months. For this phase of the study, there is no fluid circulation in the pipes of the BHE, therefore the temperature profile within the pipes should be representative of the initial temperature profile in the subsurface before TRT test. Figure 3 shows the comparison between the measured temperature profile in the field and calculated temperature profile within the geothermal probe pipe before the start of the TRT test.

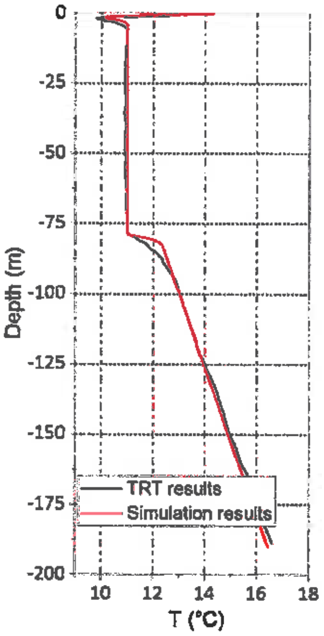

Figure 3: Initial temperature profile of the subsurface before the start of the TRT test.

Fig. 3 depicts a good agreement between the numerical results and field measurements. The influence of the groundwater flow can be seen in depth from 6 m up to 80 m, causing a constant temperature of 11 °C in this part. The lower section from 80 m until 190 m, where located in the conduction zone without any groundwater effects, the natural geothermal temperature gradient is formed. Furthermore, the numerical model was successful to capture the infiltration of the ambient temperature which leads to temperature anomaly up to 6 m depth near the surface. Temperature profile of fig. 3 was taken as initial temperature for the TRT phase.

3.3 TRT state

Considering TRT operation in the field, the numerical model was conducted to simulate the exact same condition as the field. 162 h circulation of the fluid and 10000 W energy input in each time step were implemented into the numerical model. For comparison between the numerical model and the TRT test, two measurements were used, one after 2 h and the second one after 26 h after the end of the heat supply. The results of the measurements and the simulation are shown in Fig. 4.

As can be seen in fig. 4, there is a better agreement between the simulation and field measurement after 26 h (b) than the measurement after 2 h (a). The reason is that, as the more time passes after the stop of the test, the system is getting more close to the steady state situation especially due to the high convection effect (39 m – 80 m), which transports the excess heat around the BHE due to the TRT test to downstream. The stepwise reduction of the temperature between 6 m until 18 m and 18 m until 39 m is due to different hydraulic conductivity values and accordingly different groundwater velocity. The wavy shape of the TRT temperature profile at the surface could be due to mixing of the fluid inside the pipe during the measurement. Difference between the exact time of the measurement in the field and extracting the results from the numerical model especially after 2h, could mention as another source of the deviation. During this time the system exposed to the fast transition to the steady condition.

On the other hand, seems that 2 h was not enough time for the simulation to reduce the temperature of the fluid inside the pipe. Therefore, a parameter study was conducted to investigate the influence of two important parameters, i.e. thermal conductivity and groundwater velocity. The parameter study was focused on the situation 2h after TRT because of the fact that the heat transfer between BHE and ambient soil is much higher than after 26h and hence more suitable to detect the sensitivity of the thermodynamics parameters which are to be separately quantified.

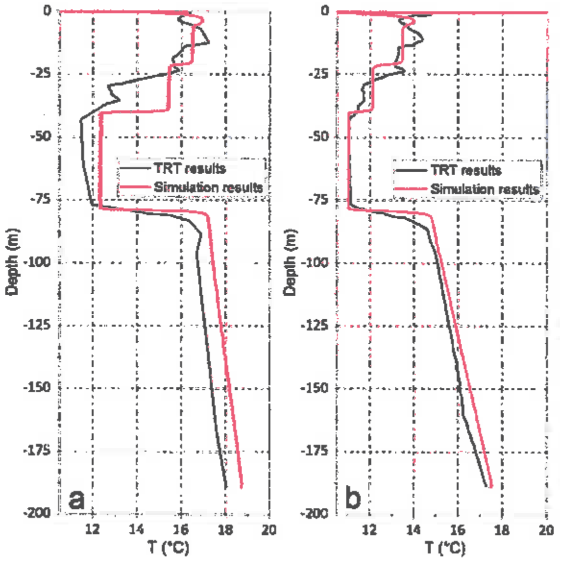

Figure 4: Comparison of TRT field measurements vs. numerical simulation: (a) after 2 h and (b) after 26 h.

3.3.1 Thermal conductivity

As shown in Fig 1, the thickness of the clay layer in comparison to the entire domain is very small and accordingly its effect is negligible. Therefore in the numerical simulation, just the main layer of limestone and sandstone were considered. Based on VDI criteria (Table 1) the offered saturated thermal conductivity mean values for these soils are 2.70 and 2.80 $W/m \cdot K$. Therefore the value of 2.70 $W/m \cdot K$ is considered as the thermal conductivity value for the entire domain. For the parameter study, the thermal conductivity with the range of 2.4 $W/m \cdot K$ up to 3.6 $W/m \cdot K$ was considered for these type of soils based on VDI table. The results of the parameter study for the critical case (2h after TRT) are shown in Fig. 5.

Based on Fig. 5, the influence of thermal conductivity is limited due to high convection effect in high ground water zone and it is negligible. Figure 5 (a) shows the nonlinear relation between the thermal conductivity and the temperature inside the pipe of the BHE. 50 % increase in thermal conductivity value leads to 2.2 % changes in temperature values. On the other hand, results show almost a linear relation between the thermal conductivity value and temperature change inside the pipe in the conduction zone. Fig. 5(b) illustrates 7.4 % changes in the temperature inside the pipe due to a 50 % change in thermal conductivity values. Correspondingly, the higher influence of thermal conductivity in low convection zone due to lower groundwater velocity can be explained.

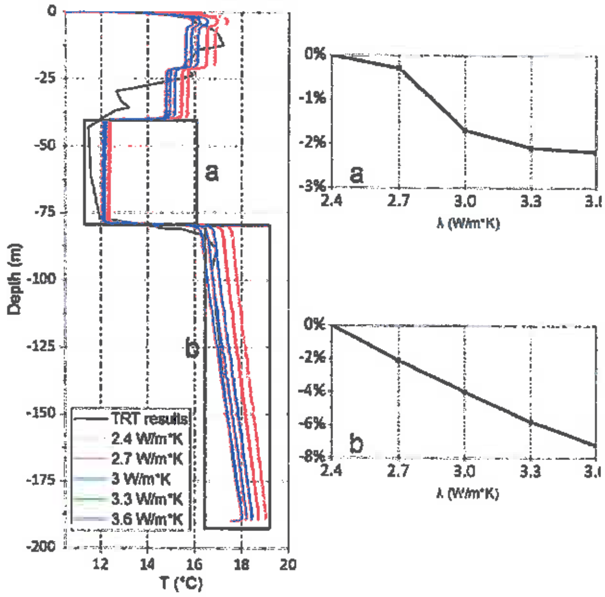

Figure 5: Parameter study on thermal conductivity effect (2h after TRT).

3.3.2 Groundwater velocity

To investigate the influence of the groundwater velocity on the TRT, the range of the velocity between 1.2 m/d up to 2 m/d in high convection zone was studied by adjusting different hydraulic head and the results are shown in Fig 6.

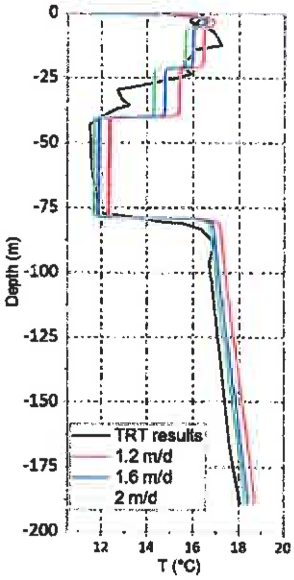

Figure 6: Parameter study on groundwater velocity effect (2 h after TRT).

Despite the thermal conductivity, Fig. 6 shows the influence of groundwater velocity in the entire domain, especially in convection zones. 33 percent increase in groundwater velocity from 1.2 $\mathrm{m/d}$ to 1.6 $\mathrm{m/d}$ leads to 3.7 % and 2.3 % percent decrease in temperature in high convection and conduction zones respectively. Furthermore, this effect is even more significant in low convection zone between the depths 21 m until 40 m, where the influence reaches up to 4.4%. The reason is that in lower convection zone the groundwater velocity is small and therefore there is a low convective transport effect. Consequently, the system is further from the steady condition and has more potential for the change due to higher groundwater velocity.

This proves the importance of the right estimation of groundwater velocity due to its significant impact on the heat transport process and accordingly on designing of the ground heat exchangers. At the end, by considering the parameter study using a numerical model, the values of 3.3 $W/m \cdot K$ and 1.7 m/d have been chosen for the thermal conductivity and groundwater velocity respectively. Fig. 7 shows the final results and improvement of the numerical simulation especially for the critical case of 2 h after TRT (Fig 7, a).

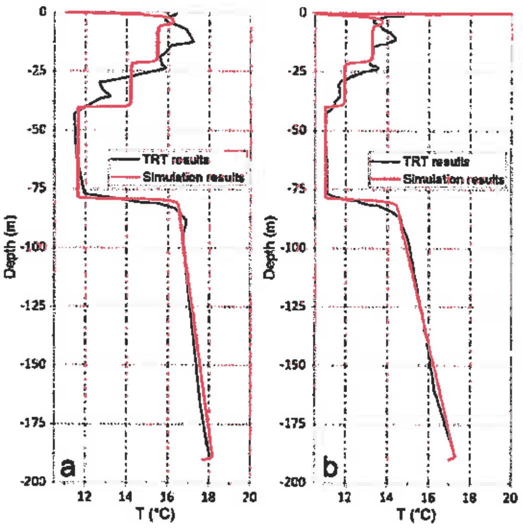

Figure 7: Comparison between numerical simulation final results and TRT test: (a) after 2 h and (b) after 26 h.

Conclusion

A numerical model approach was developed to simulate the heat transport due to a TRT test in a BHE under high groundwater flow velocity. The numerical model was successfully compared with the recorded temperature data of a TRT test in Hans-Rehn-Stift project. The model was used for further investigation on this case study, where the line source assumptions illustrate several shortages in case of interpretation of the TRT.

It is shown that, in the absence of groundwater flow or low convection effect, thermal conductivity plays a significant role in the heat transport and should be taken into account as a decisive parameter. On the other hand its influence is negligible under high groundwater flow advection effect.

Despite the thermal conductivity, groundwater velocity must be considered as a decisive parameter in both convection and conduction zones. Numerical simulations show that the filter velocity is the only parameter with significant effect in high groundwater convection effect situation. Based on the numerical investigation the groundwater of 1.7 $\mathrm{m/d}$ has been estimated for the groundwater velocity in Hans-Rehn-Stift project.

References

Bakirci, K. (2010). *Evaluation of the performance of a ground-source heat-pump system with series GHE (ground heat exchanger) in the cold climate region.* Energy 35, pp. 3088-3096.

Pulat, E., Coskun, S., Unlu, K., Yamankaradeniz, N. (2009). *Experimental study of horizontal ground source heat pump performance for mild climate in Turkey.* Energy 34, pp. 1284–1295.

Sanner, B., Hellström, G., Spitler, J., Gehlin, S. (2005). *Thermal Response Test – Current Status and World-Wide Application.* Proceedings World Geothermal Congress, Tukey.

Hellström, G. (1991). Ground heat storage, thermal analysis of duct storage systems, I.Theory. 262 p., LTH.

Claesson, J. and Eskilson, P. (1988). *Conductive heat extraction to a deep borehole, thermal analysis and dimensioning rules.* Energy 13/6, pp. 509-527.

Carslaw, H. S. and Jaeger, J. C. (1959). *Conduction of heat in solids.* Second edition, Oxford University Press, Oxford.

Signorelli, S. (2004). *Geoscientific investigations for the use of shallow low-enthalpy Systems.* Doctoral thesis. ETH Zürich.

Signorelli, S. Bassetti, S. Pahud, D. Kohl, T. (2007). *Numerical evaluation of thermal response test.* Geothermics, vol. 36, pp.141-166.

VDI-RICHTLINIEN, (2015). *Thermische Nutzung des Untergrunds Erdgekoppelte Wärmepumpenanlagen. VDI 4640, Blatt 2.*