RGNZ/MGPB

Numerical Analysis of Borehole Heat Exchanger Performance in Shallow Gravel Aquifers and Clay-dominated Soil

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 550.8
DOI: 10.17794/rgn.2024.2.6

Original scientific paper

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Abstract

The performance of geothermal heat extraction in shallow aquifers depends on both Borehole Heat Exchanger (BHE) and soil or aquifer properties. In this work, an analysis of the thermal yield of a shallow geothermal reservoir was made numerically with the finite element method used to simulate heat and mass transfer in the three-dimensional reservoir. The main parameters for analysis which have been considered are the geometry and physical parameters of the BHE and grout, as well as aquifer matrix and groundwater fluid. Physical parameters are thermal conductivity, flow conductivity, expansion coefficient, porosity, volumetric heat capacity, anisotropy and dispersivity. The numerical tests have been performed in single BHE line source configuration representing numerically modelled thermal response test for the estimation of sustainable heat extraction. The domain size was a 100x100 meter rectangle with a depth of 200 meters. Three main lithological configurations have been modelled: gravel aquifer with low and high convection of groundwater fluid, as well as a shallow geothermal reservoir dominated by clay material without convection. For selected cases, the analysis for temporal and spatial discretization was also made. Three-dimensional transient modelling was made in FEFLOW® software with pre- and post-processing done in user-defined Python scripts. The results show the most influential parameters to be considered when setting up the real case simulation of geothermal heating and cooling, as well as optimal temporal and spatial discretization set-up with respect to expected thermal gradients in the reservoir.

Keywords:
Borehole Heat Exchanger (BHE); shallow geothermal reservoir; geothermal heating and cooling

1. Introduction

Ground Source Heat Pumps (GSHP's) are widely used for heating, and cooling, in many areas, especially North America and Europe (Omer, 2008). There are two types of GSHP, open and closed loop. Although open loop has more annual energy savings and CO$_2$ reduction in combined heating and cooling than closed loop (Boahen et al., 2017), closed loop is more used due to suitability for small residential buildings, there is no possibility of clogging and environmental pollution, and no need for an abundant aquifer (Singh et al., 2019).

Closed loop GSHP uses borehole heat exchangers to transfer heat from or into the ground. Borehole heat exchangers represent one of the main elements of GSHP. Their thermal performance (thermal conductivity of the ground and thermal resistance within the borehole) can be determined with the Thermal Response Test (**Pahud and Matthey, 2001**). The thermal response test is an in-situ test commonly used nowadays to avoid under- and oversizing of ground heat exchangers (**Spitler and Gehlin, 2015**). It consists of an electric heater (or heat pump), fluid pump, temperature sensors and a flow meter (**Beier et al., 2021**). The thermal response test can be done in two ways, by circulating fluid that is warmer or colder than the surrounding ground. Fluid is pumped through a pipe and the ground exchanges heat with the fluid while both the inlet and outlet temperatures are measured. **Wang (2014)** and **Quaggiotto et al. (2019)** analysed the energy performance of double-U and coaxial vertical borehole heat exchangers. They concluded that under equal boundary conditions, the coaxial BHE exchanges more energy in both heating and cooling mode, than the double-U BHE. The energy exchange rate of coaxial BHE rises with an increase of ground thermal conductivity.

Thermal conductivity of grout has a large impact on heat transfer and is directly related to a system's efficiency. Bentonite and cement are the most used (high mechanical strength), but grout selection depends on the selected location and the system to be used, so it is dif-

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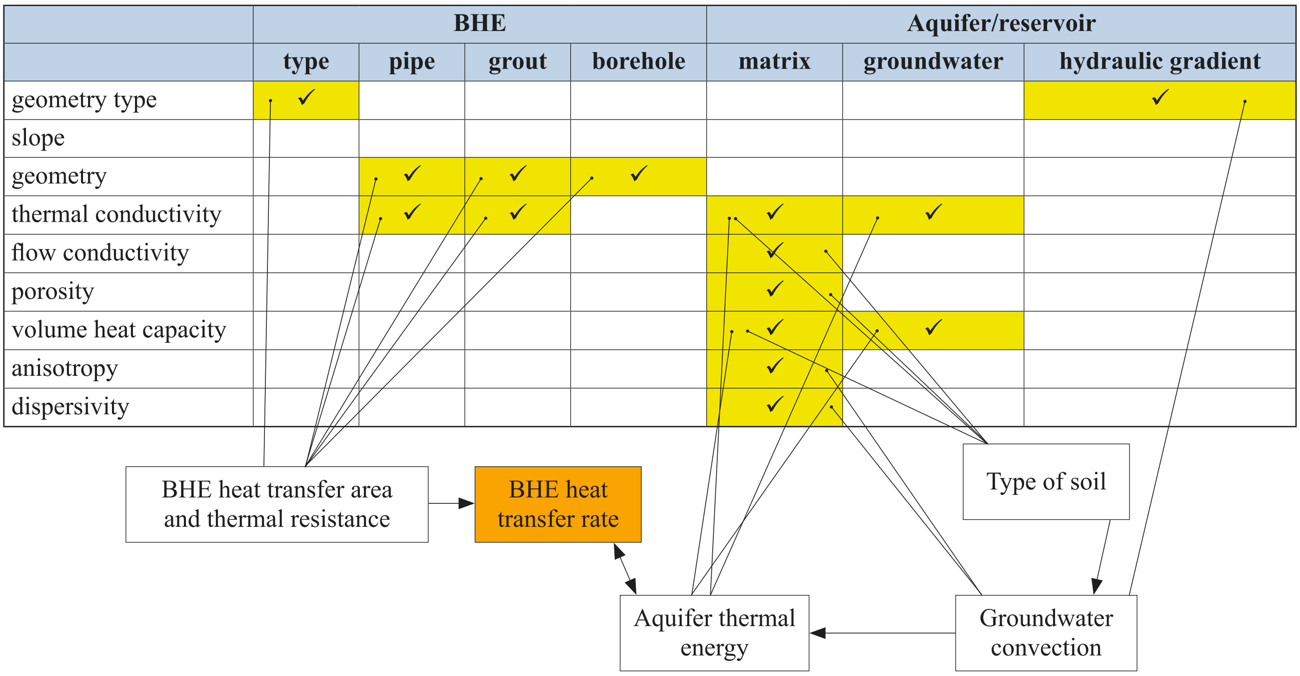
Table 1: BHE and aquifer/reservoir parameters and their mutual influences



	BHE				Aquifer/reservoir		
	type	**pipe**	**grout**	**borehole**	**matrix**	**groundwater**	**hydraulic gradient**
geometry type	✓						✓
slope							
geometry		✓	✓	✓			
thermal conductivity		✓	✓		✓	✓	
flow conductivity					✓		
porosity					✓		
volume heat capacity					✓	✓	
anisotropy					✓		
dispersivity					✓		

Table 2: Type of BHE used in simulations and their description

BHE type	**Description**
Double-U D32	Double-U with pipe diameter 32 mm and SDR 11
Double-U D40	Double-U with pipe diameter 40 mm and SDR 11
Coaxial D63/32	Coaxial with outer pipe diameter 63 mm SDR 17 and inner pipe 32 mm SDR 11
Coaxial D63/40	Coaxial with outer pipe diameter 63 mm SDR 17 and inner pipe 40 mm SDR 11

SDR – standard dimensional ratio, nominal outside diameter/nominal wall thickness

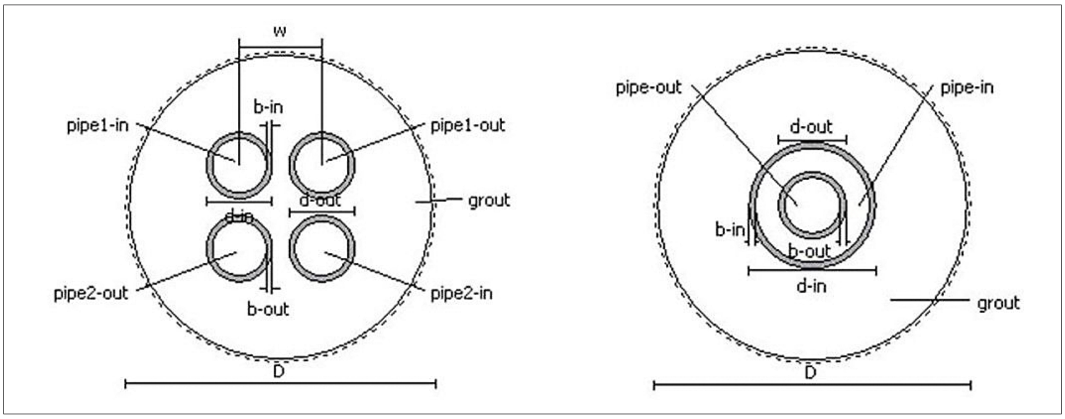


Figure 1: Configurations of double-U and coaxial borehole heat exchangers (from **FEFLOW® software**)

Table 3: Shallow geothermal reservoir parameters

Case	***R1***	***R2***	***R3***
Description	Gravel with hydraulic gradient 1m/1000 m	Gravel with no hydraulic gradient	Clay
Hydraulic gradient, m/m	0.001	0	0
Porosity, -	0.15	0.15	0.6
Hydraulic conductivity, m/d	500	5	0
Volumetric heat capacity – matrix, MJ/m^3/K	2.4	2.4	3
Thermal conductivity – matrix, W/m/K	3	3	1.66

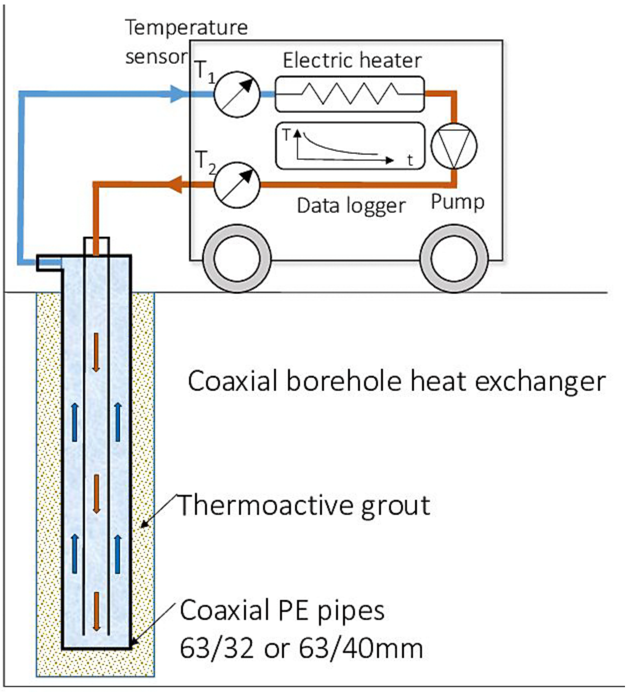


Figure 2: Equipment for Thermal Response Test (TRT) (from **Kurevija et. al., 2018**)

ficult to say which material is the best. Grout thermal conductivity can be improved by using sand and graphite due to its higher thermal conductivity (**Mahmoud et al., 2021**). The coefficient of performance depends on the system design, the parameters of the soil (heat transfer) and the case study (**Ahmadi, 2018**).

2. Method

Before implementation of the analysis, it is necessary to determine the parameters that affect heat transfer in the geothermal heat pump system, and their mutual influence. Setup parameters can be divided into borehole heat exchanger and aquifer/reservoir parameters. Furthermore, some parameters are geometry or domain-related (type of borehole heat exchanger, the slope of the hydraulic gradient, pipe/grout/borehole geometry), some are physical properties (thermal conductivity and volume heat capacity), and some are related to the aquifer/reservoir (flow conductivity, porosity, anisotropy, dispersivity). All parameters and their mutual influences are presented in **Table 1**.

Heat transfer of borehole heat exchangers depends on the type and geometry of borehole heat exchangers, flow

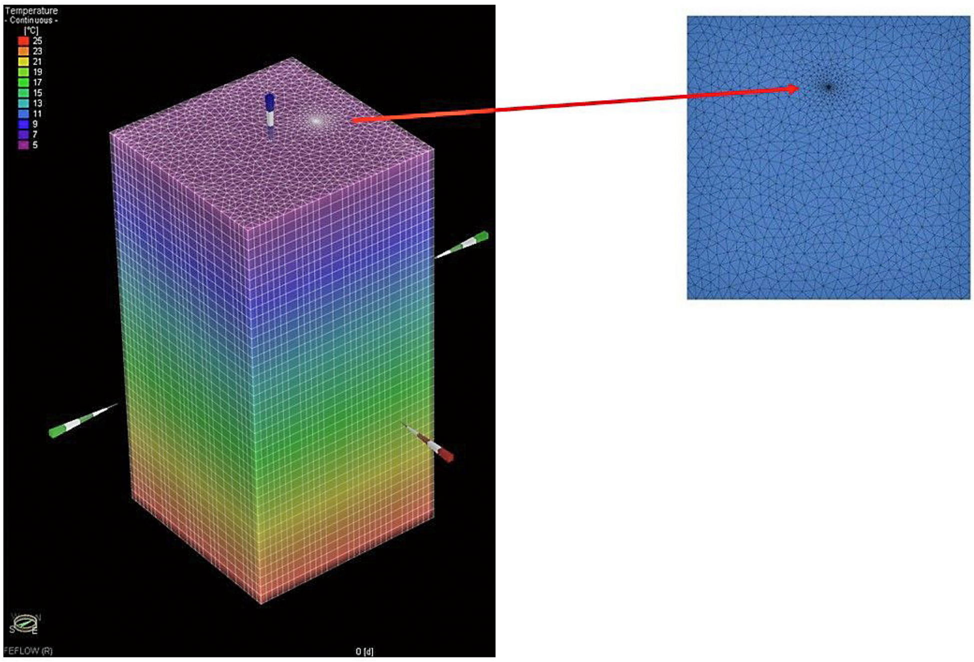


Figure 3: Domain layout and mesh refinement (from **FEFLOW® software**)

Table 4: BHE nondimensional numbers and heat transfer coefficient

BHE type	**Re, -**	**Flow type**	**Nu, -**	**α, W/m²K**
Double-U D32	4681	transitional	45	830
Double-U D40	3746	transitional	29	428
Coaxial D63/32 (annulus/central)	1405/4697	laminar/transitional	7.4/45.5	64/926
Coaxial D63/40 (annulus/central)	1287/3759	lamina/transitional	7.4/29.4	64/906

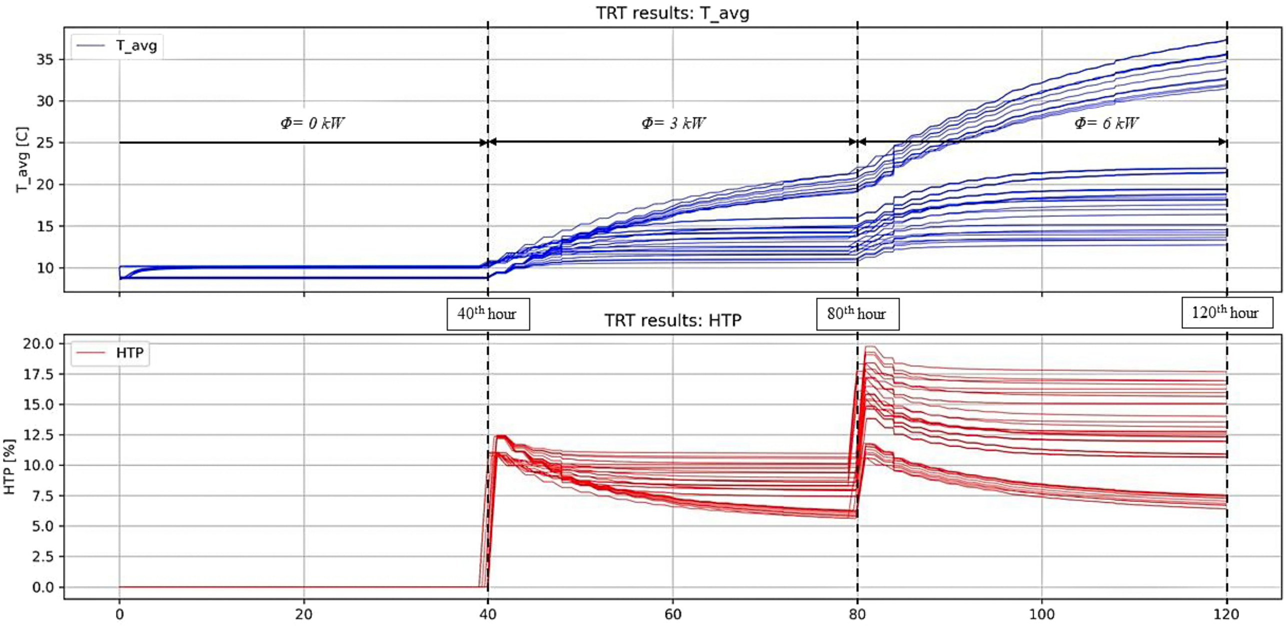


Figure 4: Numerical Thermal Response Test results

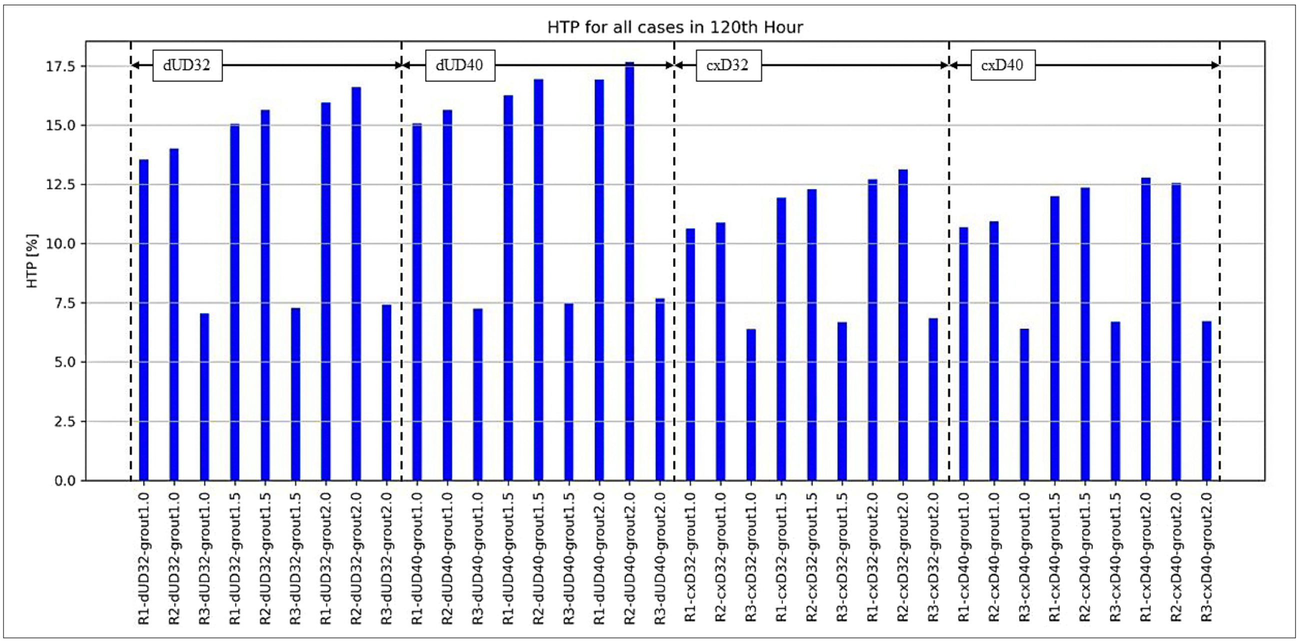


Figure 5: Heat transfer potential (*HTP*) for all 36 scenarios at the endtime (120th hour)

regime (turbulent, laminar) and physical properties (i.e. thermal conductivity) of the pipe and grout. Heat transfer between the fluid and the pipe depends on regime of the flow. If it is turbulent, the HTC is greater than in the case of laminar. It depends on the local Nusselt number which depends on Reynold and Prandlt numbers, as described in **FEFLOW® White papers (2010)**. From the reservoir point of view, the type of soil and groundwater convection are important, and they define the amount of the aquifer thermal energy. Flow conductivity, porosity, thermal conductivity, and volume heat capacity define type of soil. Groundwater convection is influenced by the type of soil, anisotropy, dispersivity and hydraulic convection. At the end, the resulting heat transfer rate of borehole heat exchanger is influenced by the borehole heat exchanger thermal resistance and transfer area and aquifer thermal energy. The aim of this work is to estimate heat transfer rate of the borehole heat exchangers with respect to the borehole heat exchanger parameters and available aquifer thermal energy. If analysis is done with all 15 main parameters, with at least 3 different values for each parameter, it would result in more than 14 million combinations, which is an unreasonably large number of calculations. Therefore, a reduction of the pa-

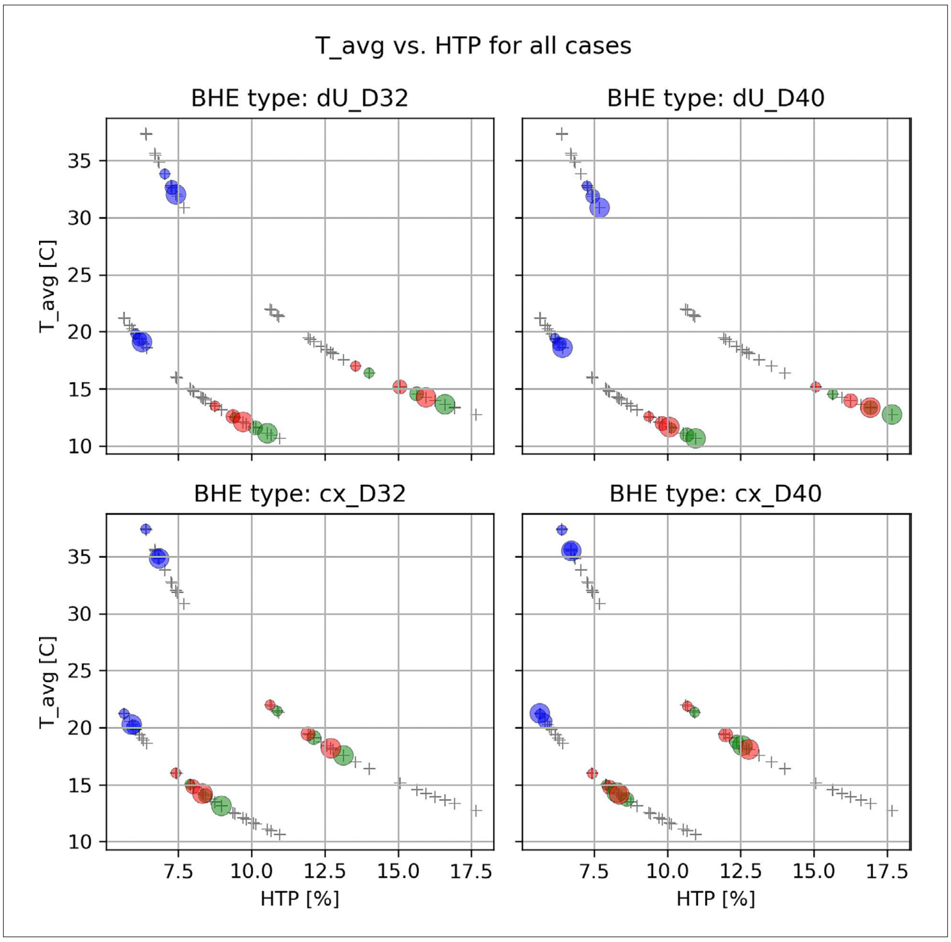


Figure 6: Average temperature vs *HTP* for 80th and 120th hour (red dot – *R1*, green dot – *R2*, blue dot – *R3*)

rameters must be done according to expert knowledge on types of possible aquifers and the expected geometries of borehole heat exchangers.

Four standard types of borehole heat exchangers will be analysed: 1. Double-U D32 (*d-in* = 32 mm, *d-out* = 32 mm), 2. Double-U D40 (*d-in* = 40 mm, *d-out* = 40 mm), 3. Coaxial D63/32 (*d-in* = 63 mm, *d-out* = 32 mm), 4. Coaxial D63/40 (*d-in* = 63 mm, *d-out* = 40 mm). Their description is shown in **Table 2**. All these configurations are provided by FEFLOW® simulation software (see **Figure 1**).

Grout thermal conductivity (λ) is a very important parameter since higher values of grout thermal conductivity reduce the thermal resistance between the primary fluid and the aquifer. Three values will be tested: 1.0, 1.5, and 2.0 W/m/K – these values fall inside the expected range.

Anisotropy (angle 0), and dispersivity (longitudinal 5 m, transversal 0.5 m) are kept constant. Shallow geothermal reservoir parameters are listed in **Table 3**. Three types of shallow geothermal reservoirs will be tested: *R1* and *R2* present aquifers with higher and lower value of hydraulic conductivity. Hydraulic conductivity is a parameter that parametrizes the ability for fluid movement - the higher the conductivity, the higher potential for fluid movement. On the other hand, the movement of the fluid will not occur if there is no hydraulic gradient. The third shallow geothermal reservoir, *R3*, is 100% clay. The values of parameters are set based on expert knowledge, since a wide span of parameters can be associated to each type of soil.

Some values are kept constant, like thermal conductivity of pipe (0.42 J/m/s/K) and groundwater parameters. The number of combinations is now reduced, with a total of 36 different options (4 BHE types · 3 values of grout thermal conductivity · 3 types of shallow geothermal reservoir = 36 options). Naming the convention for all 36 scenarios is RX_YY_groutZ, where X denotes type of reservoir according to **Table 3** (*R1*, *R2* or *R3*), YY denotes type of BHE according to **Table 2** (dUD32, dUD40, cxD32 and cxD40) and Z denotes value of thermal conductivity of the grout (1.0, 1.5 or 2.0 W/mK), as presented in **Supplementary data**.

To quantify the possibility of heat utilization from shallow geothermal reservoir, the Thermal Response Test (TRT) must be applied. We will use the naming convention where 'outlet' refers to the outlet from the BHE (inlet towards the TRT equipment), while 'inlet' refers to the inlet towards the BHE (outlet from the surface TRT equip-

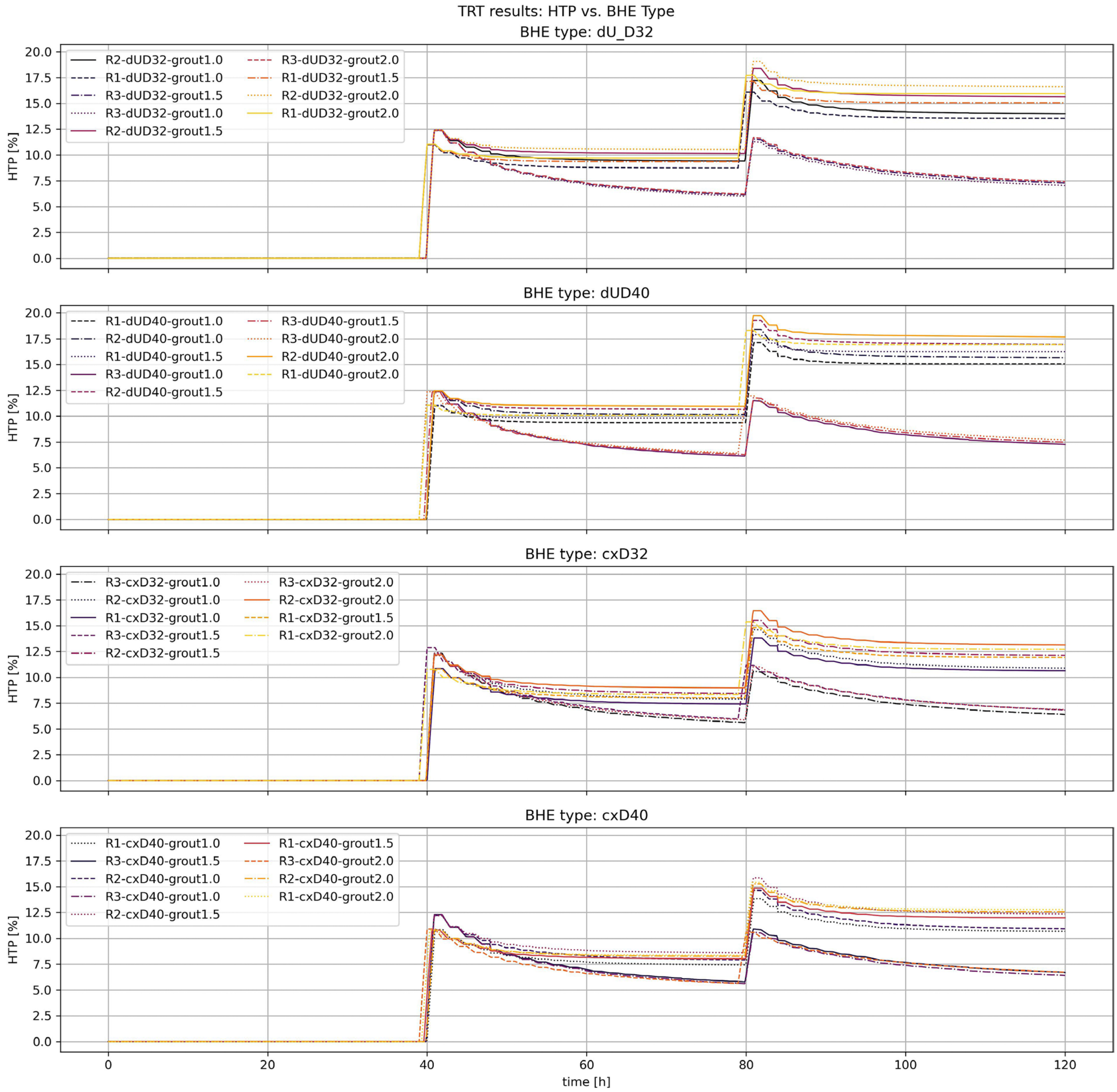


Figure 7: Thermal response test analysis based on BHE type

ment). The outlet temperature (T_1) is raised by an electric heater in the loop and circulated through the BHE as inlet temperature (T_2). The reservoir is absorbing part of that heat and returns the fluid at lower value again as T_2 (see **Figure 2**). The difference between inlet and outlet temperature is directly proportional to heat absorption, or more precisely heat transfer towards the shallow geothermal reservoir. The ability of the reservoir to absorb heat is also directly pointing to the ability of the reservoir to give heat to the fluid during the heating season. At the beginning the problem is non-stationary, but after some time, the temperature increase stabilizes, indicating the steady-state performance of the reservoir.

Borehole heat exchanger performance will be quantified with the use of two parameters: average temperature T_{avg} and heat transfer potential *HTP*. Average temperature is defined as the arithmetic mean between the inlet and outlet temperature:

$$T_{avg} = \frac{1}{2} \cdot \left(T_2 + T_1 \right) \tag{1}$$

Heat transfer potential is defined as relative change in temperature between inlet and outlet temperature, while relative change is with respect to temperature inlet:

$$HTP = \frac{\left(T_2 - T_1 \right)}{T_2} \cdot 100\% \tag{2}$$

Where:

T_{avg} – average temperature (°C),
T_1 – outlet temperature (°C),
T_2 – inlet temperature (°C),
HTP – heat transfer potential (-).

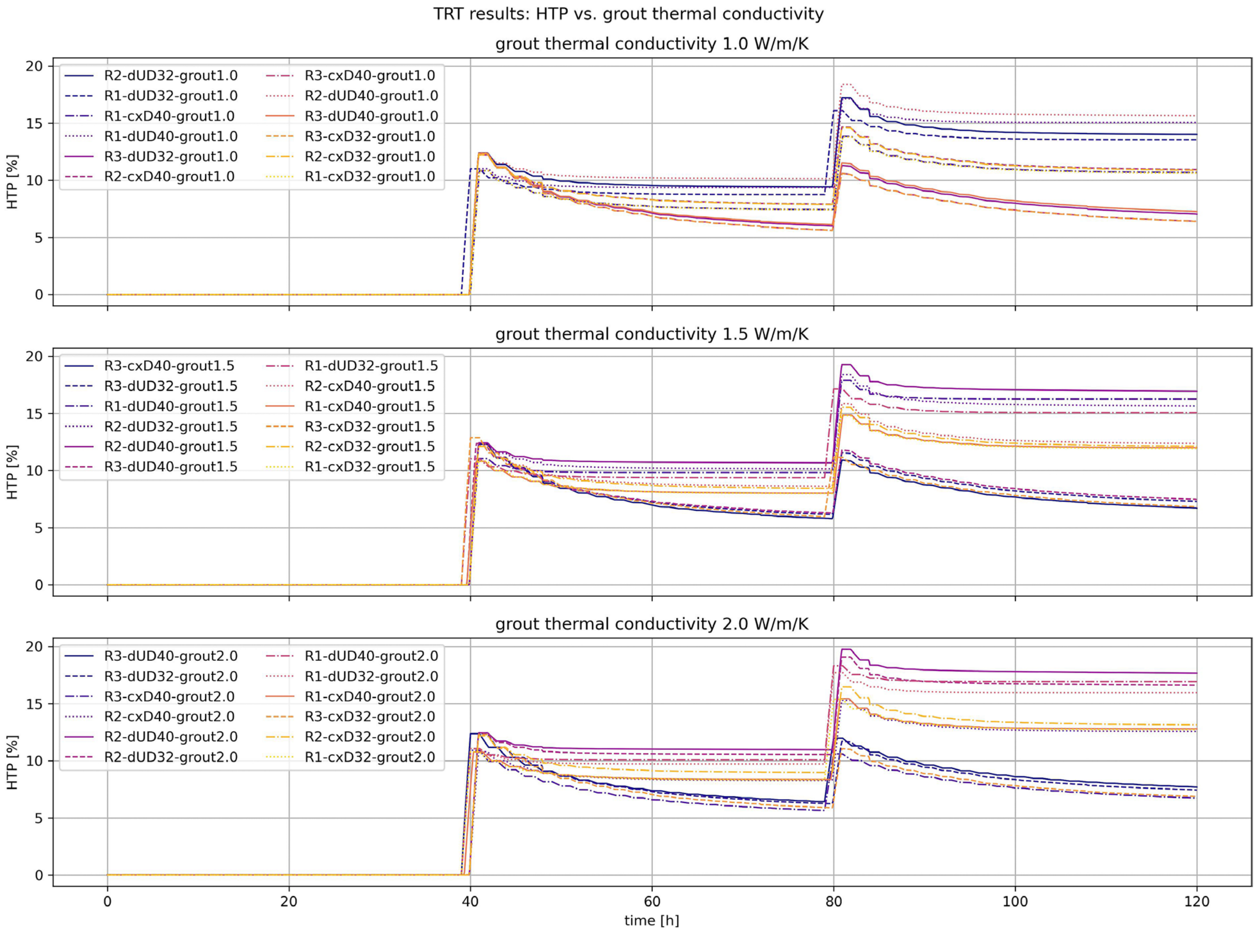


Figure 8: Thermal response test analysis based on grout thermal conductivity

Heat transfer potential, defined according to **Figure 2**, will in the numerical cases presented in this work, always be positive with the heater on or equal to zero when the heater is turned off. Higher values of *HTP* indicate that the borehole heat exchanger is capable of transferring heat to the reservoir at a higher rate than in the case with lower values of *HTP*. It is expected that higher values of grout heat transfer coefficient, higher convection rates in the reservoir and a larger diameter and exchange surface of borehole heat exchanger led to higher *HTP*. Due to the inability to transfer heat to the reservoir, systems with lower *HTP* will lead to higher values of outlet temperature, and therefore higher average temperature.

3. Simulation

Thermal response test simulation for all 36 cases has been done in FEFLOW®. FEFLOW® is a software product developed from DHI Group for analysis, modelling and simulation of groundwater and porous media (**FeFlow, 2023**).

Figure 3 shows the domain modelled in FEFLOW®. The domain is a rectangular shape with a square base 100x100 m and 200 m in depth, with isothermal boundary conditions (the temperature increases linearly with depth). Simulation has been done with one BHE with a depth of 100 m. Also, the mesh refinement in the vicinity of borehole heat exchangers can be seen. The spatial resolution around the borehole heat exchanger is approximately 10 cm, as recommended from the FEFLOW®. The volume flow rate of the primary fluid is 50 m^3/day, which corresponds to 0.578 kg/s if the assumed primary fluid density is 1000 kg/m^3. The corresponding resulting non-dimensional numbers and heat transfer coefficient are given in **Table 4**.

Simulations were performed over a period of 120 hours (5 days). The first 40 hours of simulation there was no heater power added to the primary fluid (water). From the 40th to the 80th hour, the heater power was 3 kW, and from the 80th to the 120th hour, the heater power was 6 kW.

4. Results

As can be seen in **Figure 4**, the simulation showed a large span of resulting values of average temperatures. The most important parameter is the ratio *HTP* at the endtime. The curves are grouped into two groups, clay and gravel. The gravel line values range from approximately 13 to 23°C, while clay lines range from approximately 32 to 37°C (the highest temperature applies to coaxial heat exchangers). The reason for this is that clay

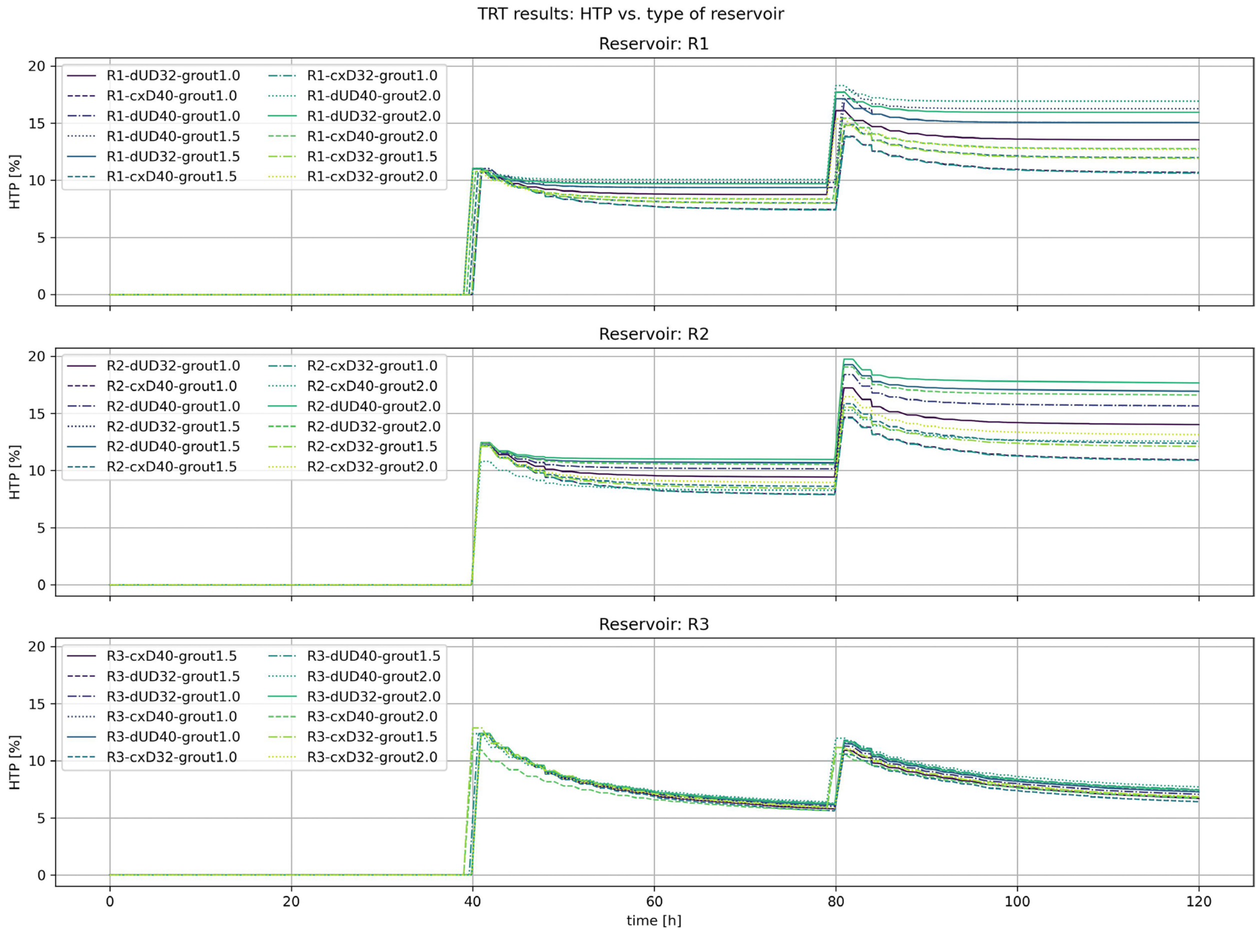


Figure 9: Thermal response test analysis based on type of shallow geothermal reservoir

has a higher thermal conductivity than gravel (2.05 W/mK for clay and 1.78 W/mK for gravel (**Pahud, 2002**)).

The *HTP* parameters at endtime (120th hour) in Figure 5 show the span from 5% to 17.5%. The higher the *HTP*, the better the performance of the shallow geothermal reservoir since higher values of *HTP* mean that the shallow geothermal reservoir has absorbed more heat and will be able to give more heat during the heating season without affecting the overall shallow geothermal reservoir temperature. The clay shallow geothermal reservoir (*R3*) has the lowest values of *HTP*, meaning that the absorption of heat is at a minimum. This is due to the inability of the shallow geothermal reservoir to remove heat from the borehole heat exchanger zone due to lack of convection which leads to overheating. Other parameters show that an increase in grout thermal conductivity and diameter of borehole heat exchanger pipe (increase of borehole heat exchanger area) are beneficial for heat exchange and result in higher *HTP*. This is valid for all three types of shallow geothermal reservoirs (*R1*, *R2* and *R3*).

If T_{avg} is plotted against *HTP*, as shown in **Figure 6**, the distinction between clay and gravel-based shallow geothermal reservoirs is visible. Also, increased gravel thermal conductivity and BHE's with a higher surface area (double-U type with larger diameter) lead to lower T_{avg} and higher *HTP*. The same trend is visible for the 80th hour (lower position), as well as the 120th hour (higher position) (corresponds to 3 kW and 6 kW of heater power).

The results of the thermal response test analysis based on BHE type, grout thermal conductivity and shallow geothermal reservoir type can be seen in **Figures 7, 8** and **9**. We can conclude that the double-U BHE type shows better results for all cases than the coaxial BHE type. Also, the clay shallow geothermal reservoir (*R3*) for all cases has the lowest *HTP* due to the absence of hydraulic conductivity, i.e. the heat cannot be removed or dispersed within the shallow geothermal reservoir. Moreover, the steady state solution for shallow geothermal reservoir *R3* is not achieved, meaning that the overheating effect would be even more emphasized if the process were to continue.

5. Conclusions

The paper analyses the significance of the numerical thermal response test in evaluating the performance of heat exchangers of a shallow geothermal reservoir. First, it is necessary to determine which parameters occur in nature, which parameters we can influence, and which parameters we cannot influence. The performance indicators are average temperature between the outlet and inlet temperatures and heat transfer potential towards the shallow geothermal reservoir.

The results showed that the clay shallow geothermal reservoir, although it has a higher thermal conductivity than the gravel, due to the absence of hydraulic conductivity, has a lower HTP than the gravel shallow geothermal reservoir. This means that the reservoir will receive heat and accumulate it in the BHE area, which will ultimately lead to overheating of the reservoir. The fact that the steady state was not achieved, which is visible in the figures, speaks of this. The higher the thermal conductivity of the grout, the better the heat exchange. Double-U BHEs showed better results than coaxial BHEs (both types of coaxial BHEs have the same results due to the same dimensions of the outer tube). The best performance for all shallow geothermal reservoir types was the BHE double-U D40.

Acknowledgement

This research has been supported by the project PLIGES (Mapping of shallow geothermal systems in the Republic of Croatia - Mapiranje plitkih geotermalnih sustava u Republici Hrvatskoj) financed by Iceland, Liechtenstein, and Norway through the Financial Mechanism of the European Economic Area (EEA) 2014-2021 with national co-financing by the Republic of Croatia within the "Energy and Climate Change" Program.

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SAŽETAK

Numerička analiza učinkovitosti bušotinskoga izmjenjivača topline u plitkim vodonosnicima šljunka i tlu u kojemu dominira glina

Učinkovitost korištenja geotermalne topline u plitkim vodonosnicima ovisi o bušotinskome izmjenjivaču topline (BHE) i svojstvima tla ili vodonosnika. U ovome radu numerički je napravljena analiza osjetljivosti toplinskoga prinosa plitkoga geotermalnog ležišta metodom konačnih elemenata korištenom za simulaciju prijenosa topline i mase u trodimenzionalnome ležištu. Glavni parametri za analizu osjetljivosti koji su uzeti u obzir jesu geometrija i fizički parametri BHE-a i cementne obloge te matrice vodonosnika i podzemne vode. Fizički su parametri toplinska vodljivost, vodljivost protoka, koeficijent ekspanzije, poroznost, volumetrijski toplinski kapacitet, anizotropija i disperzivnost. Numerički testovi provedeni su u konfiguraciji jednoga bušotinskog izmjenjivača topline koji predstavlja numerički modelirani test toplinskoga odziva za procjenu održivoga korištenja topline. Domena je bila pravokutnoga oblika 100 x 100 metara s dubinom od 200 metara. Za svaku analizu osjetljivosti modelirane su tri glavne konfiguracije: šljunčani vodonosnik s niskom i visokom konvekcijom podzemne vode te ležište u kojemu dominira glinoviti materijal bez konvekcije. Za odabrane slučajeve također je napravljena analiza osjetljivosti na vremensku i prostornu diskretizaciju. Trodimenzionalno modeliranje napravljeno je u softveru FEFLOW® uz prethodnu i naknadnu obradu u korisnički definiranim skriptama za Python. Rezultati pokazuju najutjecajnije parametre koje treba uzeti u obzir pri postavljanju stvarne simulacije slučaja grijanja i hlađenja geotermalnim izvorom, kao i optimalnu postavku vremenske i prostorne diskretizacije s obzirom na očekivane toplinske gradijente u ležištu.

Ključne riječi:
bušotinski izmjenjivač topline, plitko geotermalno ležište, geotermalno grijanje i hlađenje

Author’s contribution

Amalia Lekić Brettschneider (1) (M. Sc., doctoral candidate) defined the model and domain, analysed the results of the simulation, and wrote the paper. **Luka Perković (2)** (PhD, Associate Professor) defined the model and domain, performed the simulation, and coordinated.