Interpretation of the first thermal response test in Central Asian countries

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ABSTRACT

Ground Source Heat Pumps (GSHP) systems have been widely distributed in several regions of the world due to the low operation costs and environmentally-friendliness. In Central Asian countries, however, the number of installations is very limited due to the low recognition of the GSHP system and its advantages.

Akita University, Japan and the National Science Academy of Tajikistan are currently carrying out a five-years joint project for the promotion of GSHP systems in the Republic of Tajikistan (hereafter, called as Tajikistan) with the sponsorship by the Japanese government. To demonstrate the applicability of the systems in dry countries like Tajikistan, a closed-loop GSHP system of 10kW cooling and heating capacity will have been installed in the capital city, Dushanbe in Autumn, 2024. For the evaluation of the heat exchange capability of the ground at the location, a Thermal Response Test (TRT) was carried out in September 2023 at a Ground Heat Exchanger (GHE) of 105 m deep near one of the buildings in the Academy. The TRT consists of a heating period of 2 days followed by a temperature recovery period of 2 days. The inlet and outlet temperatures of circulation fluid were measured every 1 minute, while the temperature distributions in the GHE were measured using an optical fiber sensor. The graphical interpretation of the TRT showed that the average thermal conductivity of the ground is around 1.9 W/m/K, which is reasonably high to introduce GSHP systems. The thermal resistance of the GHE, on the other hand, was estimated quite high in the shallow part of the formation due to the low groundwater level which exists 50 m below ground level.

Based on the geological information and GHE specifications, an analytical simulation model of the GHE based on the cylindrical source function was constructed and was validated using the TRT results. A case study on the thermal properties of grouting material of the GHE was then carried out using the model for improving the performance of the GSHP system. The simulation indicated that the heat exchange capacity of the GHE could be improved by 20% by improving the thermal conductivity of the grouting material.

1. INFORMATION ON PROJECT

This research has been carried out to evaluate the thermo-physical properties of shallow ground for the optimum design of GSHP systems in the capital city of Tajikistan, Dushanbe. The research is one of the research themes of the Science and Technology Research Partnership for Sustainable Development (SATREPS) project, which is in progress between Japan and Tajikistan. The outline of the project is described in the following section. The geological conditions of the target area and the methodology of TRTs is also given in the following sections.

1.1 SATREPS project

SATREPS project is an international R&D project between Japan and developing countries sponsored by the Japan International Cooperation Agency (JICA) and the Japan Science and Technology Agency (JST). Akita University, Japan and the National Science Academy of Tajikistan (hereafter, called as Academy) are jointly carrying out the project for a period of five years. The project aims to contribute to regional stabilization and global warming mitigation by improving the energy situation and creating jobs in Tajikistan focusing on the use of abundant groundwater resources in Tajikistan for heating and cooling purposes. Specifically, the following three research topics will be conducted by constructing and disseminating an "Advanced Ground Source Heat Pump (GSHP) system for arid regions (Tajikistan model)" that integrates ICT technologies such as artificial intelligence. (1) Development of groundwater flow and heat transport models based on field surveys, GIS data, and artificial intelligence, and construction of geothermal and groundwater heat utilization potential maps; (2) Implementation of long-term heating and cooling tests using demonstration plants with multimodal measurement and artificial intelligence; and (3) Institutional design for dissemination of the "Tajikistan Model." Through (1) and (2), the research group will develop an optimal geothermal heating and cooling system based on artificial intelligence and will reflect it in the institutional design.

Figure 1: Location of Tajikistan and Japan.

1.2 Geological information

The first GSHP system in Tajikistan is currently being constructed in one of the buildings of the Academy located in the central part of the capital city, Dushanbe. The locations of Tajikistan, Dushanbe and Japan are shown in Fig. 1.

The graben where Dushanbe exists is located in western Tajikistan, about 280 km west of the Pamir Plateau, which was formed by the collision of the Indian and Eurasian plates. The Hissar-Kokshaal fault, which has an east-west strike, is located to the north of the graben. The Ilyak-Vaksh fault, which also has an east-west strike, is located to the south of the graben. This graben, similar to the strike of fault, extends

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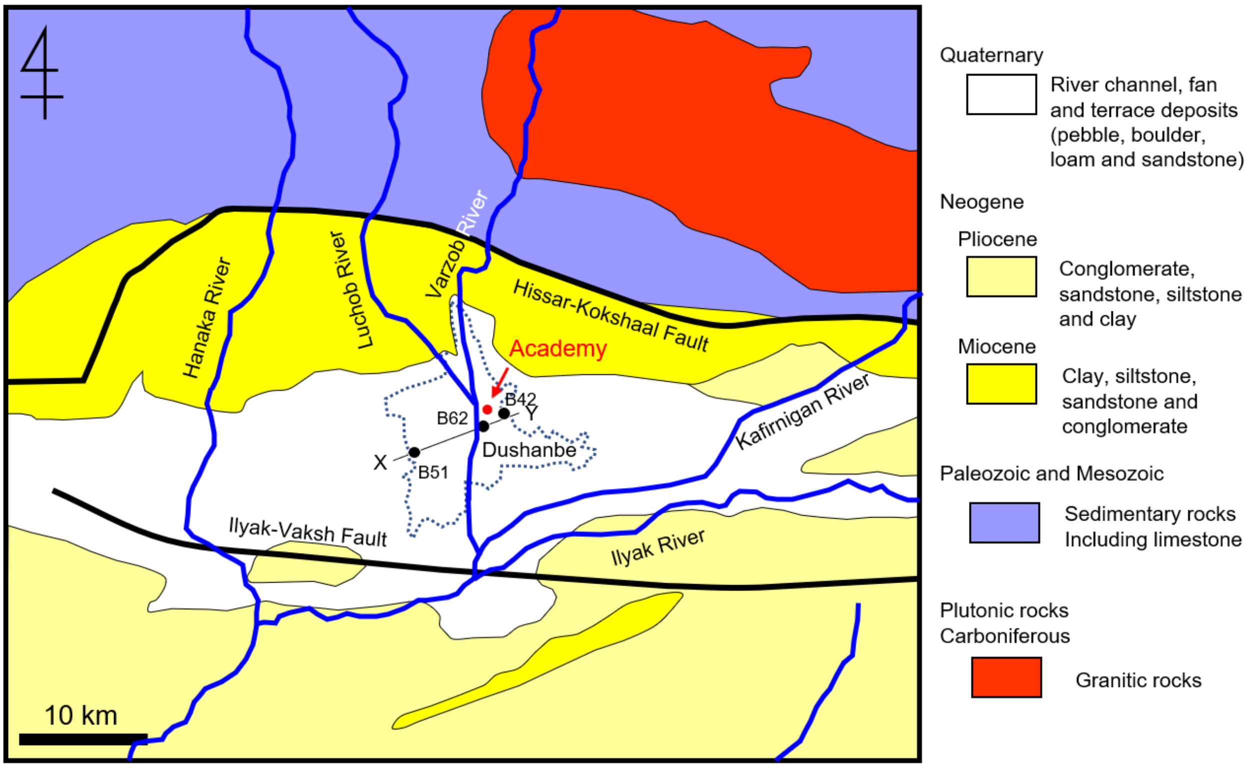

Figure 2: Schematic geologic map around Dushanbe, Tajikistan. This geologic map was simplified from the geologic maps of Vlasov et al. (1986) and Hakimov et al. (2020).

from east to west (Fig. 2). The size of graben is about 70 km long and 20 km width (Hakimov et al., 2021). There are mountain ranges to the north and south of the graben. The northern mountain range (Hissar range) is higher in elevation than the southern mountain range. Rivers flowing into this graben flow north to south or northeast to southwest across the Hissar range and the Hissar-Kokshaal fault, which are located north of the graben. The main river in this graben is the Kafirnigan River, which flows from northeast to southwest. The Varzob River, Luchob River, and Hissar Canal flow into this river as tributaries (Hakimov et al., 2021) (Fig. 2).

The geology of the Dushanbe area is composed of Paleozoic to Mesozoic sedimentary and igneous rocks and Cenozoic sedimentary rocks (Vlasov et al., 1986) (Fig. 2). The Paleozoic to Mesozoic sedimentary and igneous rocks are distributed in the mountain range north of the Hissar-Kokshaal fault. The geology of the mountain range is composed of Carboniferous basaltic to rhyolitic volcanic rocks and sedimentary rocks, Jurassic sedimentary rocks mainly composed of limestone and Carboniferous granites (Vlasov et al., 1986). The geology of the graben between the Hissar-Kokshaal and Ilyak-Vaksh faults consists of Miocene, Pliocene, and Quaternary strata (Vlasov et al., 1986. Hakimov et al. 2021).

The Miocene strata consist of clay, siltstone, sandstone and conglomerate. Sandstone tends to dominate in the upper part of the formation. The Pliocene strata is composed of conglomerate, sandstone, siltstone and clay. In the upper part of the Pliocene strata, sandstone and siltstone tends to predominate (Vlasov et al., 1986). The Quaternary strata consist of river channel, fan and terrace deposits. Each deposit is composed of pebbles, boulders and loams (Fig. 3). The thickness of the Quaternary strata is estimated to be up to 300 meters (Hakimov et al., 2021). The Academy, where the GSHP system is constructed, is located in the central part of

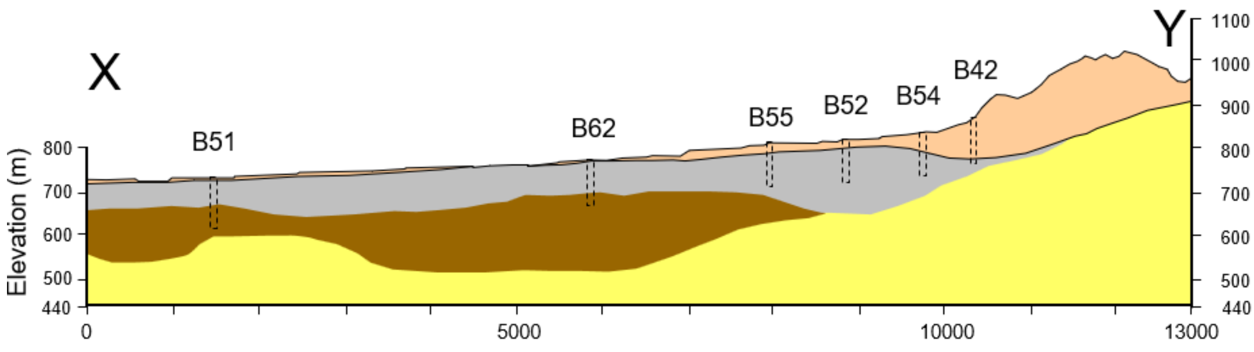

Figure 3: Schematic cross-section of the line X-Y in Fig. 2. In this cross-section, the four loam layers that were classified by thickness in the cross-section of Hakimov et al. (2021) are combined into a single loam layer.

the graben as shown using a red circle in Fig. 2. The groundwater necessary for the use of the GSHP system is mainly present in the Quaternary strata.

1.2 Theory of thermal response tests

TRTs are commonly carried out in the designing stage of GSHP systems to estimate the thermal conductivity of the ground (λs) and thermal resistance of the GHE (R) and determine the optimum GHE length. TRT consists of the circulation of heated water through the U-tunes in the GHE for 2 to 3 days and the observation of the temperature recovery after the heating period for a few days. The recovery period is omitted if the vertical distribution of λs is not estimated. The water temperature at the inlet and outlet of the GHE and the circulation rate are measured during the heating period and the vertical temperature distribution in the GHE is measured using an optical fiber thermometer or multi-point temperature sensors during the recovery period.

The graphical interpretation of the temperature data during the heating period is commonly performed using a semi-log plot of time vs. average water temperature at GHE inlet and outlet. The average thermal conductivity of the GHE is calculated based on the slope, m, of the temperature increase and heat exchange rate using Eq. (1). The thermal resistance of the GHE, R, is an indicator of the efficiency of GHEs, determined by specifications of U-tubes, grouting materials, etc. defined by Eq (2).

$$\lambda s = 0.0183\dot{q}/m \quad (1)$$

$$T_{ave} - T_{ff} = \frac{\dot{q}}{4\pi\lambda_s}\left(-\ln\frac{{r_o}^2}{4\alpha_s t} - 0.5772\right) + \dot{q}R \quad (2)$$

where, α_s: thermal diffusivity of soil (m^2/s)

λ_s: thermal conductivity of soil (W/m/K)

m: slope of straight line (˚C/cycle)

$\dot{q}$: heat exchange rate per GHE length (W/m)

r_o: outer radius of heat exchanger (m)

R: thermal resistance (mK/W)

t: time (s)

T_{ave}: average water temperature (˚C)

T_{ff}: far-field temperature (˚C)

For the analytical modeling of TRT, the cylindrical source function G (Ingersoll et al., 1954) as shown in Eqs. (3) to (6) is used to simulate heat conduction in the ground around the GHE.

T_{ff} -T_{ro} = $\dot{q}/\lambda s/L$ **Error! Bookmark not defined.**G(Z,P) (3)

$$Z = \alpha_s t/r^2 \quad (4)$$

$$P = r/r_o \quad (5)$$

$$G(Z,P) = \frac{1}{\pi}\int_0^\infty \frac{e^{-\beta^2 Z}-1}{J^2{}_1(\beta)+Y^2{}_1(\beta)} J_0(P\beta)Y_1(\beta)\text{-}J_1(\beta)Y_0(P\beta)\frac{d\beta}{\beta^2} \quad (6)$$

where, G: cylindrical source function (-)

J_0, J_1: Bessel functions of the first-kind (-)

Y_0, Y_1: Bessel functions of the second-kind (-)

L: length of heat exchanger (m)

T_{ro}: temperature at outer face of U-tube (˚C)

To obtain the vertical distribution of λs, the ground is divided into sub-layers of 1 to 2 m thick to which the cylindrical source function is applied; this allows for a vertical variation in thermal conductivities, initial temperatures and heat exchange rates. Details of the TRT interpretation using the temperature profiles by optical fiber thermometers is described in Fujii et al. (2009).

2. RESULTS AND DISCUSSION

2.1 Drilling information of GHE

The GHE in the Academy was drilled in June through July 2023 using a rotary drilling machine. Photo 1 shows a photo taken during the drilling operation. A GSHP system is currently being installed in the 4th floor of the blue building on the left in the photo.

Photo 1: A photo of the drilling operation.

The diameter of the borehole is 216mm. The drilling operation encountered a fluid loss around 25 m, 34 m and 56-63 m below GL, indicating the existence of highly permeable zones. The groundwater level at the well was observed quite deep, around 50 m below GL. This would probably be due to the excessive groundwater pumping in the surrounding area. This is inferred from the fact that there are several dry old water pumping wells in Dushanbe. The geological column at the well and the schematic of well completion are shown in Fig. 4. The well was drilled to 105m below GL and two sets of U-tube (ID/OD=26mm/32mm) were installed followed by a grouting with silica sand to be completed as a double U-tube GHE. The U-tube could be run to 102m below GL though the hole condition was not very good.

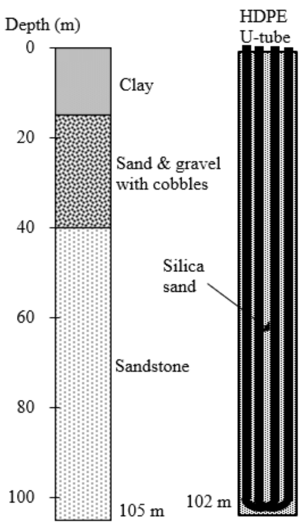

Figure 4: Geological column of the GHE (left) and well completion of the GHE (right).

2.1 Results and interpretation of thermal response test

The TRT consisted of a heating period of 2 days followed by a temperature recovery period of 2 days. The heat load and circulation rate during the heating period were set as 3.87 kW (38.0 W/m) and 19.9 L/min, respectively. The average ground temperature in the GHE was measured as 16.5 °C. The temperature profiles in the GHE were measured using an optical fiber thermometer, which is set in one of the U-tubes. Fig. 5 shows the measured temperatures during the TRT. Due to the bending of U-tube, the optical fiber sensor could not reach the bottom of GHE, but stopped at 86 m below GL. The time in the legend of the figure indicates the elapsed time after the end of heating period. Quick recovery of ground temperature to the initial temperature was observed due to the relatively high λ.

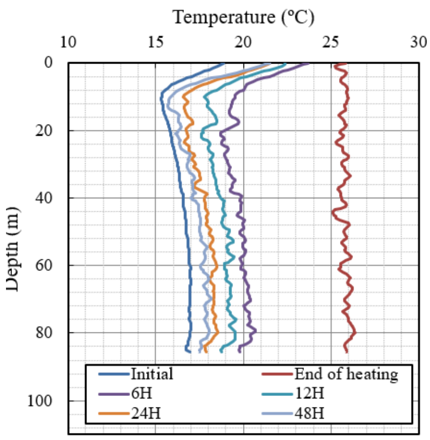

Figure 5: Measured temperatures in GHE during TRT.

First, the interpretation of the heating data was carried out using the semi-log plot of time vs. average water temperature at GHE inlet and outlet as shown in Fig. 6. A clear straight line was observed after heating of 10 hours. The average λs is estimated as 1.88 W/m/K from the slope of the straight line. The thermal resistance was estimated as 0.17 mK/W using Eq. (2), which is a relatively large value for a double U-tube GHE. This is due to the low λ of the grouting material (λg) between the land surface and the groundwater level of 50 m below GL where the pore space of the grouting material is unsaturated with water and is instead saturated with air.

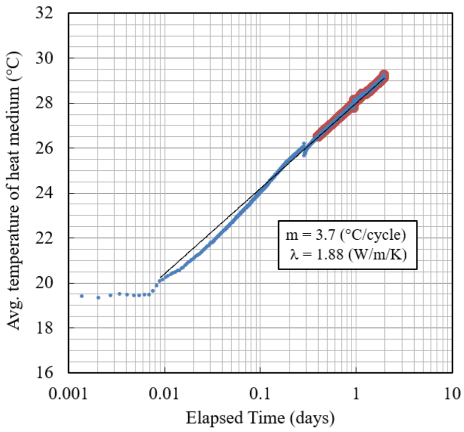

Figure 6: Graphical interpretation of heating data.

Next, the interpretation of the recovery data was performed based on the analytical modeling procedure described in Section 1.3. An iterative calculation was made treating the λs of every 2 meters depth as matching parameters. In the iteration procedure, the error between the measured and calculated water temperatures and the error between the measured and calculated well temperature profiles were minimized simultaneously using a nonlinear regression method. In the calculation of GHE performance, measured inlet temperatures were input and outlet temperatures and temperature distribution in the GHE were calculated every 30 minutes during the heating period. Then, the temperature recovery performance in the formation was calculated for 2 days by setting the heat exchange rate and circulation rate as zero. The λ of the grouting material (λg) was determined with trial and errors until a good matching was obtained between the measured and calculated temperature profiles. Fig.7 shows the matching of the outlet temperatures of circulating water during the heating period. Fig. 8 shows the matching results of the formation temperatures 12 hours and 24 hours after the end of heating period. Reasonably good matching was obtained on outlet temperatures and formation temperatures. The matching of formation temperature below 82 m was not considered due to the lack of temperature measurement, but the temperature measured at 82 m is extended to the bottom of the GHE. The λg was determined as 1.0 W/m/K and 2.0 W/m/K for surface to 50 m (above groundwater level; unsaturated) and 50 m to bottom (below groundwater level; water-saturated), respectively, after several attempts. The good matching results as shown above indicate that the analytical model for the GHE at this location can simulate the heat exchange performance and temperature distribution at the GHE reasonably well.

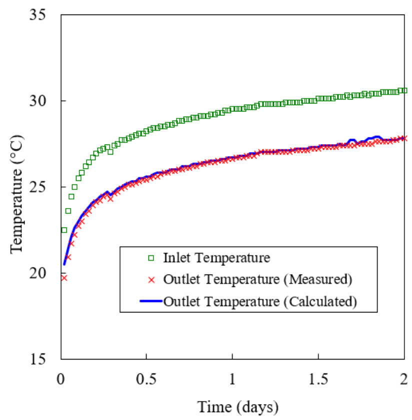

Figure 7: Matching result of outlet temperatures.

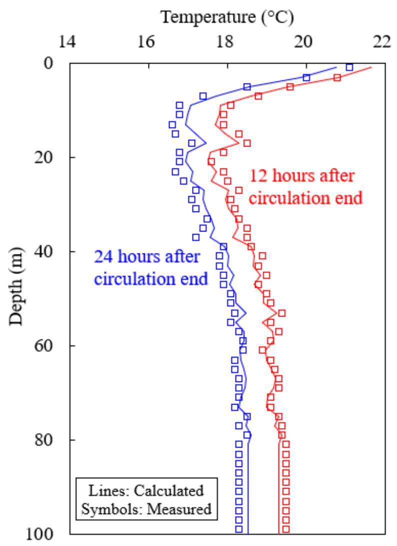

Figure 8: Matching result of formation temperatures.

As the result of the above history matching, the vertical distribution of λs was determined obtained as shown in Fig. 9. High λs zones were estimated through intervals between 20 m and 40 m (sand and gravel layer with cobbles) and between 50 m and 70 m (sand layer). The average λs of the entire GHE depth is calculated as 2.02 W/m/K, which is reasonably close to the value from the graphical method, 1.88 W/m/K. The high λs zone between 50 m and 70 m agrees well with the third fluid loss zone between 56 m and 63 m, observed in the drilling operation. The high λs would be due to the existence of groundwater flow through the permeable layer.

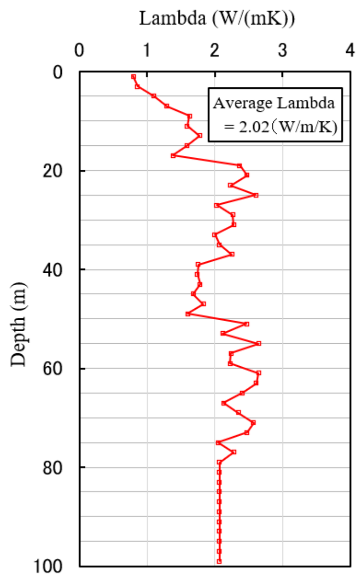

Figure 9: Vertical distribution of thermal conductivity of the GHE.

2.3 Sensitivity study

In the current GHE, the space between the U-tube and the well wall was filled with locally produced silica sand (Photo 2). No mineral analysis was made for this sand, but the color of the sand in the photo indicates that the quartz content is not very high and hence the λ of the silica sand could not be very high. Actually, the λ was measured as 0.37 W/m/K and 1.60 W/m/K in dry and water-saturated conditions, respectively, in the laboratory of Akita University. Both values are relatively low for silica sand. The λ values of Japanese domestic silica sand of high quartz content and a cement mortar mixed with the same silica sand were measured 3.0 W/m/K and 2.5 W/m/K, respectively, in water-saturated conditions in the laboratory (Fujii et al., 2003). In a ground with low groundwater levels, as seen in Dushanbe, the heat exchange capability of the GHE could be improved using a silica sand of high λ.

Photo 2: A photo of the silica sand filled in the GHE.

Based on the above, the improvement of heat exchange rate by replacing the grouting material with the above high-λ silica sand is evaluated using the analytical model. In the calculation, the λg values above and below the groundwater level were set as 2.5 W/m/K and 3.0 W/m/K, respectively. The λg of 2.5 W/m/K above the groundwater level assumes the cement mixed with the silica sand for minimizing the volume of pore space and avoid the existence of air in the filling material. The λg of 3.0 W/m/K below the groundwater level assumes the filling of silica sand saturated with groundwater. Fig. 10 compares the outlet temperatures of the original TRT and the simulated TRT using the improved grouting material. The GHE design, circulation rates, inlet temperatures are set as equal to the original TRT. As can be seen from the figure, The outlet temperatures decreased about 0.5 ° C, indicating the improvement of the heat exchange capacity. The average heat exchange rates during the heating of 2 days in the two cases are 3.74 kW and 4.50 kW, respectively, resulting a significant enhancement of heat exchange rate of 20%.

The above sensitivity study shows that the use of highly thermally conductive grouting material is quite important when installing a GHE in a location of low groundwater levels, which would be encountered when planning a GSHP system in a dry region like the Central Asian countries.

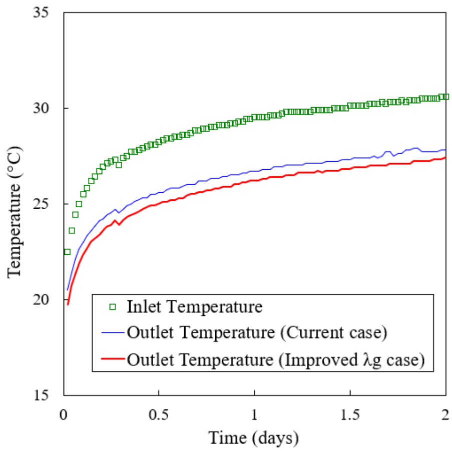

Figure 10: Comparison of outlet temperatures before and after the change of grouting materials.

3. CONCLUSION

Akita University, Japan and the National Science Academy of Tajikistan have carried out a TRT at a GHE of 105m deep in the Academy in the capital city, Dushanbe. The TRT consists of a heating period of 2 days followed by a temperature recovery period of 2 days. The interpretation using a graphical method showed that the average thermal conductivity of the ground was around 1.9 W/m/K, which is a favorable value for introducing GSHP systems. The thermal resistance of the GHE was estimated high in the shallow part of the formation due to the low groundwater level of 50 m below ground level.

Based on the geological information and GHE designs, an analytical simulation model of the GHE based on the cylindrical source function was constructed and was validated using the TRT results. A case study on the thermal properties of grouting material of the GHE was then carried out using the model to investigate the possibility of improving the performance of the GHE. The simulation indicated that the heat exchange capacity of the GHE could be improved by 20% by replacing the current grouting material with the one rich in quartz content.

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