Numerical Simulation of Large-Scale GCHP Systems in the Presence of Groundwater Flow

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Keywords

Ground-coupled heat pump, numerical simulation, groundwater flow, thermal response test

ABSTRACT

Heat exchange performances of ground heat exchangers (GHEs) in Ground-Coupled Heat Pump (GCHP) systems are more or less affected by the advection of groundwater flow, if groundwater flows exist in the stratum. Under the influence of groundwater flow, heat exchange rates can be enhanced, while thermal interferences between GHEs should be considered if a large number of wells are drilled with a short spacing. In this paper, the heat exchange performances of large-scale GCHP systems with groundwater flow in a shallow stratum, in Akita Plain, Japan, are predicted with numerical simulation for determining the optimum operation strategies of the GCHP systems.

Introduction

In the past few years, the number of installations of GCHP systems has remarkably increased in northern Japan. This is mainly due to the increasing recognition of the advantages of GCHP systems and also due to the reduction of installation costs with the technical development by drilling companies. In Japan, many of the residential areas are located on alluvial deposits, where groundwater flow could influence the performance of GCHP systems. Researches have been made to examine the effects of groundwater flow on heat exchange performances of GHEs. Kimura et al. (1988) developed an integral solution to predict the relationship between groundwater flow velocities and heat exchange rates. Fujii (2002) quantified the improvements in heat exchange rates by groundwater flow using a 2D finite-difference numerical simulation model. Gehlin and Hellström (2003) predicted the influences of groundwater flow on heat exchange performance in hard rocks with vertical fractures using 3D finite difference model. In the above studies, the enhancements of heat exchange rates by groundwater flow were confirmed with analytical and numerical computations. The overall performances of GHEs in large-scale GCHP systems, however, have not been intensively studied using actual field data.

In this paper, the performances of a large-scale GCHP system, constructed in the central part of Akita Plain, Japan, are simulated using finite-element groundwater flow and heat transport simulation program, FEFLOW (Diersch, 2002). For estimating the distribution of groundwater flow velocities and temperatures in Akita Plain, a field-wide groundwater flow model of Akita Plain is constructed on the basis of groundwater levels and groundwater temperatures obtained through field measurements. Then, a single GHE model is developed according to the geological and groundwater information at the GCHP system location. The GHE model is validated with thermal response test results conducted at the same location. Finally, the GHE models are grouped to construct a multi-well model including 75 GHEs, which were completed for the GCHP system in 2003. The multi-well model predicts the long-term performance of the GCHP system to optimize the future operation plan of the GCHP system.

Field-wide Modeling of Groundwater Flow System in Akita Plain

The Akita Plain is an alluvial plain in northern part of Japan, developed along the Sea of Japan with a north-south extension of approximately 16 kilometers as shown in Figure 1, overleaf. The plain is surrounded by hills to the north and south, by ranges of higher than 1,000m in elevation to the east. In the center of plain, Omono River flows from south-east to north-west, along which Quaternary system are deposited above the Tertiary system. The thickness of Quaternary system ranges from 0m to 70m. The Quaternary system mainly consists of the intercalation of silt and fine sand, while the Tertiary system mainly consist of siltstones and mudstones.

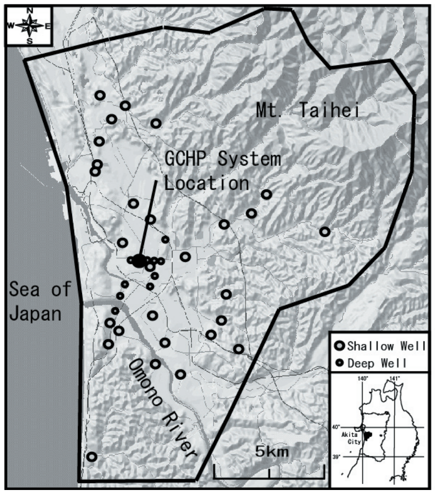

Figure 1. Area of field-wide model.

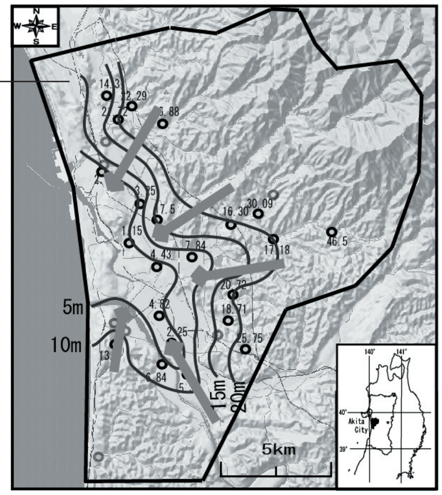

Figure 2-1. Contour map of measured groundwater levels.

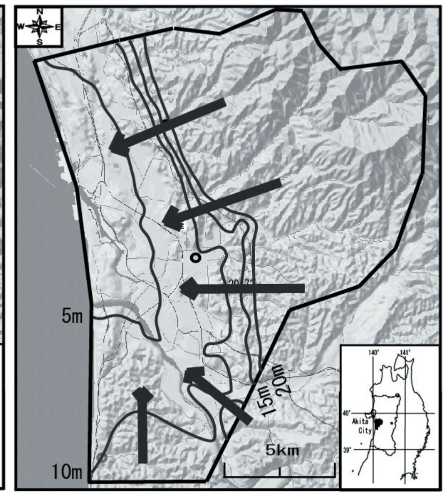

Figure 2-2. Contour map of calculated groundwater levels.

In the field data sampling, 12 deep (50-80 m) wells and 21 shallow (<10 m) wells were selected in the Akita Plain as shown in Figure.1. Water table and groundwater temperatures were measured in summer 2002. The water table and the contour map of temperature at –50m are shown in Figure 2-1 and Figure 3-1, respectively. The water table shows similar trend with surface elevation. In the central part of the plain, water table locate shallower than -10m. The groundwater temperature shows an increasing trend as approaching from the hills or ranges to the central part of the plain. At the center of the plain, the groundwater temperature at –50m is nearly 15°C.

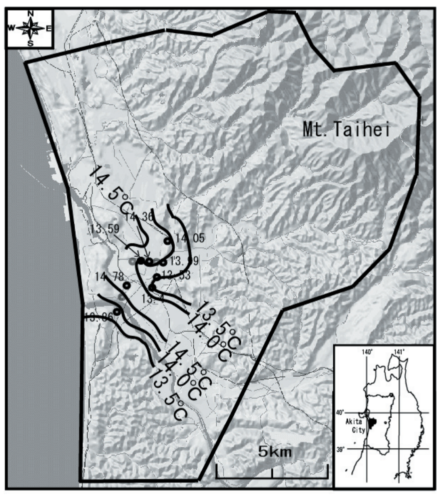

Figure 3-1. Contour map of measured groundwater temperatures.

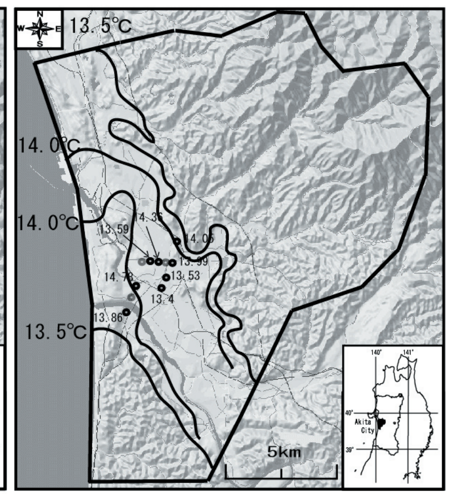

Figure 3-2. Contour map of calculated groundwater temperatures.

To construct a field-wide groundwater flow model in the Akita Plain, finite element grids as shown in Figure 4 were constructed using FEFLOW. Bold lines in the figure denote the boundary of the model area. The model covers the entire Akita Plain and the dividing ranges in the east. The sizes of the model are 32km and 28km in the north-south and in east-west directions, respectively. Layer 1 to Layer 5 represent the Quaternary system with variable thickness depending on actual layer thickness (0-70 m). Layer 6 to Layer 17 represents the Tertiary system with a total thickness of 480m.

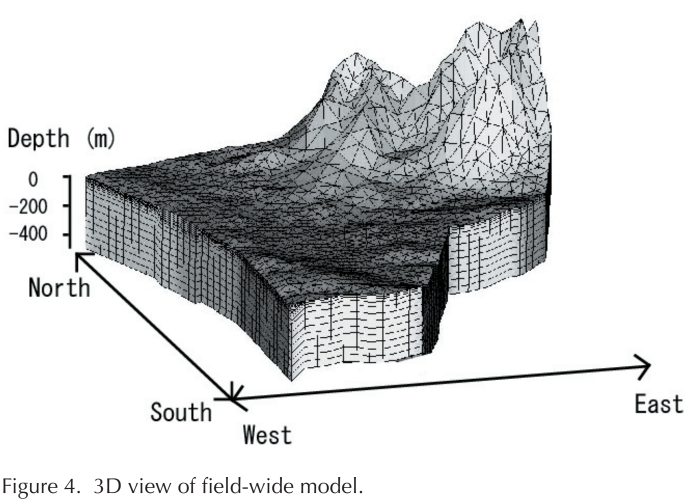

Figure 4. 3D view of field-wide model.

In the first stage of field-wide modeling, natural state simulations were conducted. Calculated groundwater levels were matched with measured data using hydraulic conductivity and groundwater level at the model boundaries as matching parameters. The simulation period was set 10^6 years when chronological changes became negligible. Calculated groundwater table in Figure 2-2 shows good agreement with the measured ones as shown in Figure 2-1. The hydraulic conductivity values of the Quaternary and Tertiary systems were determined to be 1.0×10^{-6}m/s and 1.0×10^{-8}m/s, respectively. Based on the groundwater flow simulation, in the next stage, groundwater temperatures were also matched with measured temperatures. Matching parameters were thermal conductivity of stratum and heat flux from the bottom of the model. With reference to Thermophysical Properties Handbook (1990), heat capacity and porosity in each system were determined on the basis of formation types as shown in Table 1. Surface temperatures were determined

Table 1. Properties of strata.

Thermal conductivity (W/(mK))	Quaternary	1.20
	Tertiary	1.50
Hydraulic Conductivity (m/s)	Quaternary	1.0×10^{-6}
	Tertiary	1.0×10^{-8}
Heat capacity (J/(m^{3}K))	Quaternary	4.919×10^{6}
	Tertiary	4.919×10^{6}
Porosity (-)	Quaternary	0.15
	Tertiary	0.05

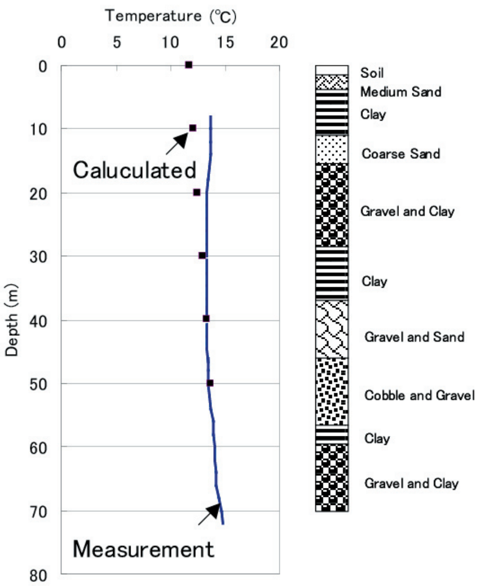

Figure 5. Comparison of measured and calculated well temperature profiles.

using the annual average temperature in Akita City (11.8°C@6m) and a decrease rate of ambient temperature with elevation (7.0°C/1000m). The calculated groundwater temperature at -50m shown in Figure 3-2 agreed well with the measured data shown in Figure 3-1. Figure 5 shows the comparison of measured and simulated well temperature profile in one of the deep wells located in the central part of the plain. Sufficiently good match was obtained except the intervals shallower than –20m, where ground temperatures are affected by seasonal changes of atmospheric temperatures. In other deep wells, the calculated temperature profiles fitted the measured data reasonably well. Thermal conductivity values of the Quaternary system and the Tertiary system were estimated to be 1.2W/(m·K) and 1.5W/(m·K), respectively. The heat flux from the bottom was determined as 0.047 W/m^2.

From the good agreement of water table and temperatures as shown above, the large-scale numerical model could successfully represent the groundwater flow system in Akita Plain. The numerical model estimated the groundwater velocity at the GCHP system location (shown with a large circle in Figure 1) to be $1.4\text{x}10^{-4}$ m/day in the Quaternary system, in which GHEs of the GCHP system were completed. The arrows in Figure 2-2 show the groundwater flow direction from east to west at the GCHP location.

Development of GHE Model and Sensitivity Studies

A 3D GHE model was constructed for simulating the heat exchange performance of a GHE at the GHCP system location. The area of the model was a square of 5m x 5m, while only half of the area was simulated considering the symmetry of the model as shown in Figure 6. The number of layers is five, with a total thickness of 50m, which is equal to the length of the GHEs in the GCHP system. The direction of the groundwater flow is shown in the figure. Based on simulation results of large-scale model, a groundwater flow of $1.4\text{x}10^{-4}$ m/day was specified in the well model. The GHE model was validated using the results of thermal response test (TRT) conducted in January 2003 at the site. For the TRT, a GHE of 50m deep was drilled and completed with a single polyethylene U-tube. The hole was grouted with cement mixed with silica sand. During the test, heated water of 30°C was circulated at 25liter/min through the U-tube for 72 hours. Inlet and outlet temperatures of the water were recorded throughout the test. Heat exchange rates were history matched using the thermal conductivity of the formation as matching parameters. Using a thermal conductivity of 1.18 W/(m·K), which was obtained using Horner Plot method (Fujii et al., 2002), good agreements between measured and calculated heat exchange rates were obtained as shown in Figure 7, validating the reliability of the well model.

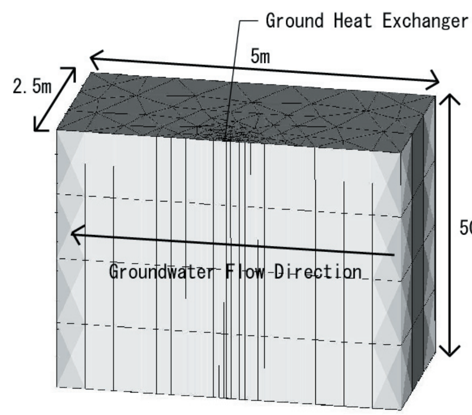

Figure 6. 3D view of GHE model.

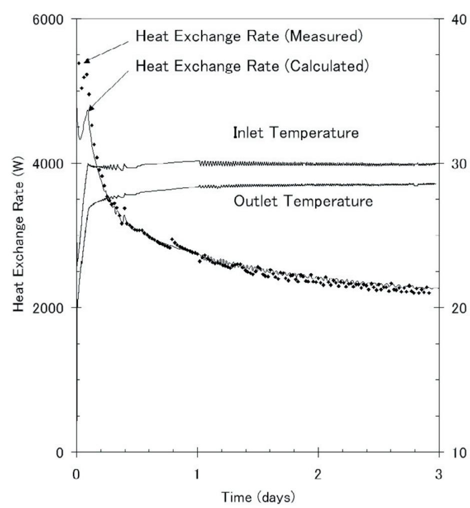

Figure 7. History matching result of thermal response tests.

Next, the well model was validated using the cylindrical function G (Ingersoll et al., 1954) as shown in Equation-1 through Equation-4.

$$T_{ff} - T_{ro} = \frac{q_{gc}}{\lambda_s L} G(Z,P) \quad (1)$$

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

$$P = r/r_o \quad (3)$$

where,

L : length of heat exchanger

q_{gc} : heat exchange rate between formation and heat exchanger

r : radius

r_o : outer radius of heat exchanger
t : time
T_{ff} : formation temperature
T_{ro} : temperature at outer wall of GHE
Z : Fourier number
α_s : thermal diffusivity of formation
λ_s : thermal conductivity of formation

No groundwater flow was assumed in the numerical model for simulating only heat conduction. Figure 8 compares the chronological change of differences between formation temperatures (T_{ff}) and outer wall temperatures of the GHE (T_{ro}), which is proportional to the heat exchange rate at the GHE. The figure shows that the numerical model is able to model the heat conduction around the GHE reasonably well.

The relationship between groundwater velocity and heat exchange rate was evaluated using the GHE model as shown in Figure 9. Peclet number (Pe) in the X axis is defined as follows:

$$Pe = 2r_oU/\alpha_s \qquad (5)$$

where, U is the groundwater velocity. Pe=1 corresponds to U=0.38 m/day in case r_o =0.034m and α_s=3.0x10^{-7}m^2/s. Figure 9 shows that groundwater effects on heat exchange rates are negligible in the ranges of Pe<0.1. Similar observations were obtained in the analysis by Kimura et al. (1988) using integral solutions. In case Pe>0.1, improved heat exchange rates are expected due to the advection of the groundwater.

In the previous section, the groundwater velocity at the GCHP systems location was estimated to be 1.4x10^{-4} m/day. α_s =3.0x10^{-7}m^2/s and r_o =0.034m gives a Pe of 3.7x10^{-4} at the GCHP system location, which indicates that the improvement in heat exchange rates is not expected.

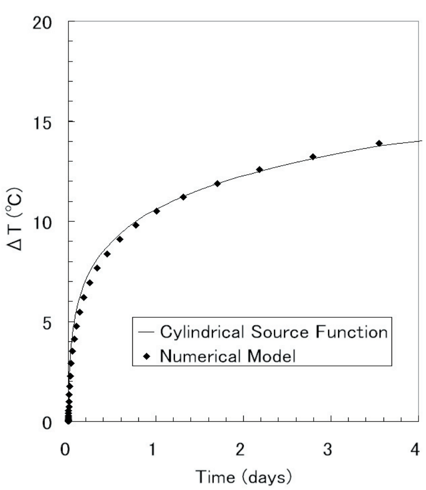

Figure 8. Comparison of temperatures calculated by numerical and analytical models.

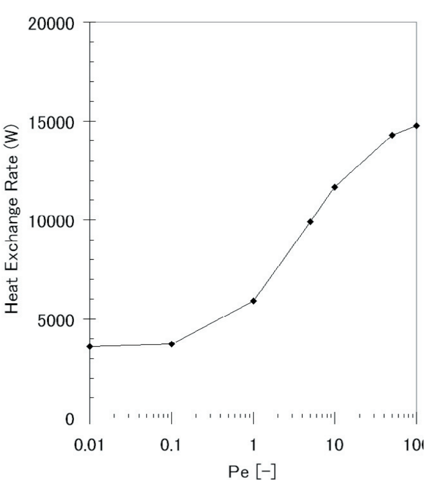

Figure 9. Peclet number vs. heat exchange rate.

Simulation of a Large-Scale GCHP System

The GHCP system was installed in 2003 in the basement of a gymnasium of a public school in the central part of Akita Plain. The location of the GHCP system is shown in Figure.1. Seventy-five GHEs of 50m deep were drilled and completed with double 2.5cm U-tube for space heating during winter seasons. The arrangement of GHE is shown in Figure 10. Though operations in summer seasons are not planned at this moment, heat storage operations would be necessary considering the small groundwater velocity and low thermal conductivity of formation at the GCHP location. To predict the performance of each GHE and to quantify the requirement of heat storage, multi-well model was developed using FEFLOW.

The grid system of the multi-well model is shown in Figure 11. The sizes of the model are 100m, 140m and 50m in X, Y and Z directions, respectively. The number of layers was set five, each of which has a thickness of 10m. Same thermophysical parameters as were used for the GHE model were used for the multi-well model. The heat flux from the bottom was specified as 0.047 W/m^2 based on the natural state simulation results of the field-wide model. The velocity of groundwater flow was set at 1.4x10^{-4} m/day based on the above model studies, flowing from east to west as shown in Figure 10. Simulation runs were conducted for 50 years to predict the long-term performance of the GCHP system. The average temperatures of heat medium are set at 0°C and 30°C for heat extraction and heat storage, respectively. Four cases of simulation runs with different heat storage periods were carried out as follows:

Case 1 — 120 days' heat extraction (no heat storage) each year
Case 2 — 120 days' heat extraction and 30 days' heat storage each year

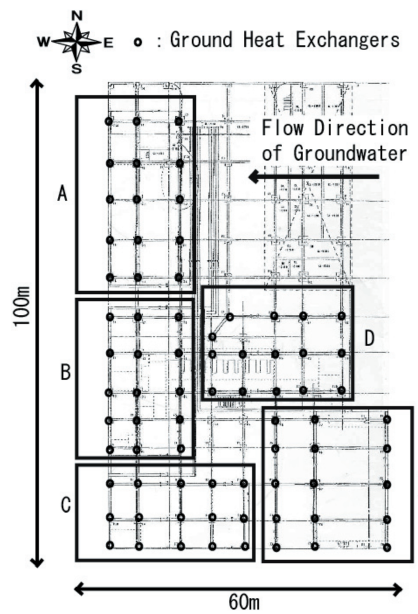

Figure 10. Well arrangements in multi-well model.

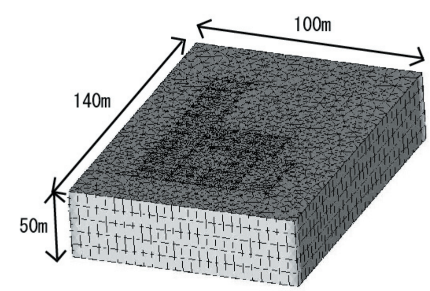

Figure 11. 3D view of multi-well model.

Case 3 — 120 days' heat extraction and 60 days' heat storage each year
Case 4 — 120 days' heat extraction and 90 days' heat storage each year

Figure 12 compares the performance of average heat extraction rate per GHE in each case during the 50 years. In Case 1, the heat extraction rate was reduced by 57.6% in 50 years. As the period of heat storage increases, the rate of decrease in heat extraction became small since heat storage operations recover the drop in ground temperature. In Case 3, the heat extraction rate at 50 years showed a drop of only 4.4% from the initial rate. In Case 4, the heat extraction rate at 50 years showed an increase of 10.0% from the initial rate indicating a stable system operation. The above shows that the GCHP system requires heat storage of at least two months to maintain the original heating capacities since the energy supply by groundwater flow is not expected at the GCHP system location.

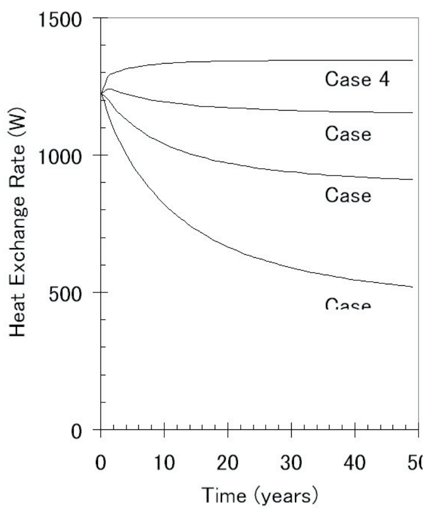

Figure 12. Comparison of heat exchange profiles.

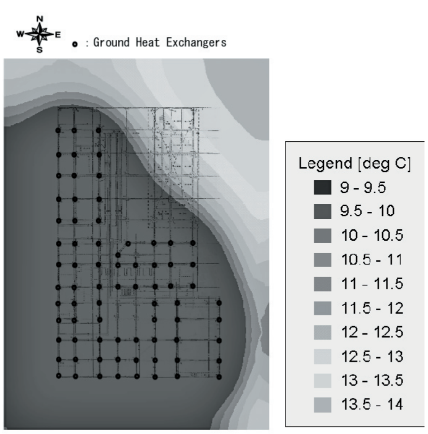

Figure 13-1. Temperature distributions at 50 years (Case 1).

Figure 13-1 and Figure 13-2 show the temperature distribution at –50m in Case 1 and Case 4 at 50 years. In Case 1, the temperature around GHEs dropped from the initial temperature of 13.5°C to 9.0-9.5°C, resulting in the decrease in heat extraction rates. In Case 4, on the other hand, the temperatures around GHEs at 50 years are 13.5-14.0 °C indicating no loss of heat extraction. Figure 13-2 shows that the temperature drop is more widely spread to the west direction due to the advection of groundwater, though groundwater velocity is small. As was shown by the GHE model, the groundwater velocity of 1.4×10^{-4} m/day is not large enough to enhance the heat exchange rate at the GHE, but it affects the distribution of ground temperature, which could result in differences in heat exchange rates depending on well locations after long-term operations. To clarify this, 75 GHEs are divided into five groups according to locations as shown in Figure 10. GHEs in Groups A, D and E are located upstream of the groundwater flow direction, while GHEs in Groups C and D are located downstream. Table 2 summarizes the rank of heat extraction rates in each group after 50 years. In Cases 1, 2 and 3, the groups located upstream showed higher heat extraction rates than the downstream groups, indicating the effect of groundwater flow on heat exchange performances. At the first year, the average heat extraction rate in Group A is 2.7% higher than those in Group B, while the difference becomes 44.5% after 50 years. The above shows that more heat storage operations should be conducted in downstream GHEs than in upstream GHEs to maintain uniform heat extraction rate from GHEs.

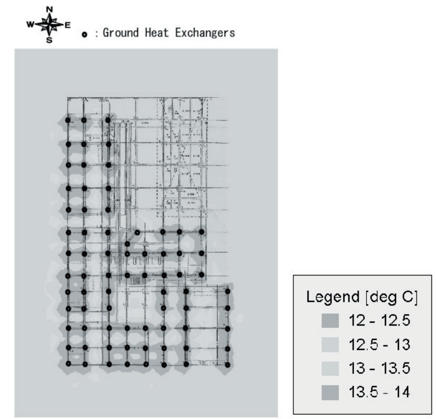

Figure 13-2. Temperature distributions at 50 years (Case 4).

Table 2. Ranks of well groups in heat exchange rates.

Heat Extraction Rate after 50 yrs	small ⟷ large				
Case 1	B	C	D	E	A
Case 2	B	C	D	A	E
Case 3	B	C	A	D	E
Case 4	C	A	B	D	E

In cases with long heat storage period, the stored heat does not flow out through the faces of each group adjacent to other groups since the face acts like a no-flow boundary. On the other hand, stored heat is lost to the formation through faces that are open to the formation. As the period of heat storage increases, the superiority of Group A becomes smaller since Group A faces other groups only in the south direction, and is open to the formation in other directions. In a GCHP system with heat storage plans, therefore, arrangement of wells should be carefully designed to avoid the loss of stored heat to the formation.

Summary

A field-wide groundwater flow model, a single GHE model and a multi-well models were developed for the prediction of the performance of large-scale GCHP systems, in Akita City, Japan using finite-element groundwater and heat simulation program, FEFLOW. The following conclusions were made from the model studies:

1) Enhancement in heat exchange rate can be realized when Peclet number of groundwater flow is greater than 0.1.
2) Heat storage period should be carefully determined depending on the groundwater flow velocity to avoid significant deterioration in heat exchange rates with time.
3) More heat storage operations should be made in the wells

located downstream of the groundwater flow.

4) For planning heat storage, arrangement of wells should be carefully designed to avoid the loss of stored heat to the formation.

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