

Study on Shallow Geothermal and Hydrogeology at Fukushima Renewable Energy Institute, AIST

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ABSTRACT

Ground-Source Heat Pump System (GSHP system) was increasingly installed in Europe and the United States when the oil shock occurred in the 1970's. Initial cost of the GSHP system in Japan, however, is higher than that of air-source heat pump system. Therefore, such systems are still not widely utilized in Japan. One of the causes is that thickness of Quaternary system in Japan is different from continental countries.

Most of the topography of major towns in Japan is alluvial plain or basin, therefore, basement of Quaternary system is deeper than that of continental countries. Thickness of Quaternary system in Kanto Plain, the largest plain in Japan, is estimated to be deeper than 3000m. Quaternary system has high value of hydraulic conductivity and includes fine aquifers.

Subsurface thermal regime is affected not only by thermal conduction but also by advection owing to groundwater flow. The effect of thermal advection is especially large in shallow sedimentary layer with active groundwater flow. This paper introduces some researches on GSHP System considering evaluation of installation potential for GSHP System based on hydrogeological data at Fukushima Renewable Energy Institute, AIST (FREA).

1. INTRODUCTION

In order to promote the development of renewable energy, the reduction of energy consumption till now and the cooperation of consumers with the supply side are expected to obtain lower cost and significant results. Low enthalpy geothermal energy has been focused as the air conditioning system to households that can possibly reduce the significant amount of electrical energy.

Worldwide use of GSHP system has extensively grown after the oil shock occurred in the 1970's. GSHP system may achieve higher coefficient of performance (COP, thermal output / power input) than conventional air-source heat pumps that may contribute to energy savings and environmental protection. Since initial cost of the GSHP system in Japan, however, is higher than that of air-source heat pump system, such systems are still not widely utilized in Japan. For example, installed GSHP system capacity of USA (12,000 MWt) corresponds to 1,000,000 GSHP systems (12kWt) for domestic purpose (Lund, 2010). On the other hand, number of GSHP system installed in Japan until 2011 reached 990 (Ministry of Environment, 2014).

Most of the topography of major towns in Japan is alluvial plain or basin, therefore, basement of Quaternary system is deeper than that of continental countries. For example, thickness of Quaternary system in Kanto Plain around Metropolis of Tokyo, the largest plain in Japan, is estimated deeper than 3,000 m. Thermal conductivity of Quaternary system is lower than that of Tertiary system in continental areas. Therefore, Quaternary system has disadvantage for using GSHP system from the aspect of thermal conductivity in geological setting. Quaternary system, however, has high value of hydraulic conductivity and includes fine aquifers. Groundwater flow causes thermal advection which increases value of effective thermal conductivity. It means that making good use of groundwater flow is the best way to operate GSHP system in Japan.

National Institute of Advanced Industrial Science and Technology (AIST) established the Fukushima Renewable Energy Institute in Koriyama, Fukushima Prefecture in April 2014, to promote research and development (R&D) into renewable energy. The Fukushima Renewable Energy Institute, AIST (FREA) has two basic missions: The promotion of R&D into renewable energy, which is open to the world; and to make a contribution to industrial clusters and their reconstruction.

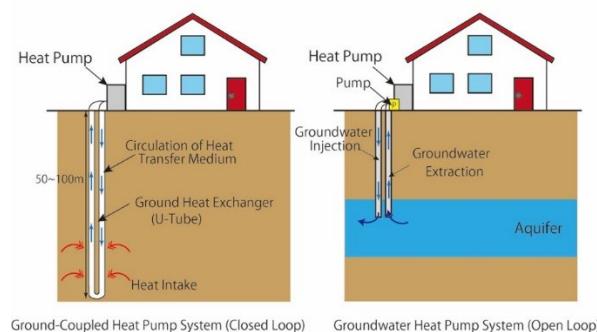


Figure 1: Ground Source Heat Pump System

For optimal use of GSHP systems, Shallow Geothermal and Hydrogeology Team, FREIA, is compiling potential maps for the installation of GSHP systems based on results of groundwater flow and heat exchange simulations. Heat exchange rate and preferred drilling depth of a GSHP system are influenced by local hydro-geological settings. Therefore, we are conducting groundwater and geological surveys to perform numerical simulation on groundwater flow and local heat exchange, in order to compile potential maps for GSHP systems' installation. These maps can improve GSHP system's design so that high system performance and cost reduction can be realized.

2. GROUNDWATER FLOW SYSTEM AND THEIR EFFECTS ON SUBSURFACE THERMAL REGIME

It is known that subsurface temperature distribution is generally affected not only by thermal conduction but also by advection owing to groundwater flow (Uchida et al., 2003). The effect of thermal advection is especially large in shallow sedimentary layer with high groundwater flux. Groundwater temperature measured in an observation well is assumed to be identical to subsurface temperature, because there exists thermal equilibrium between the water in a borehole and its surrounding subsurface layers. Temperature profiles are one-dimensional sequential data arrays so that areally distributed temperature profiles provide three-dimensional subsurface information.

Figure 2 shows groundwater flow system and subsurface thermal regime (modified from Domenico and Palciauskas, 1973). If there is no groundwater flow or static groundwater condition (Figure 2a), subsurface thermal regime is governed only by thermal conduction and subsurface temperature gradient is constant (Figure 2b). When a simple regional groundwater flow system due to topographic driving (Figure 2c) is assumed, thermal regime will be disturbed by thermal advection owing to groundwater flow (Figure 2d). In the groundwater recharge area, subsurface temperatures and gradients are lower than that under static groundwater condition (Figure 2b). In the discharge area, on the other hand, temperatures and gradients are larger than that under static condition.

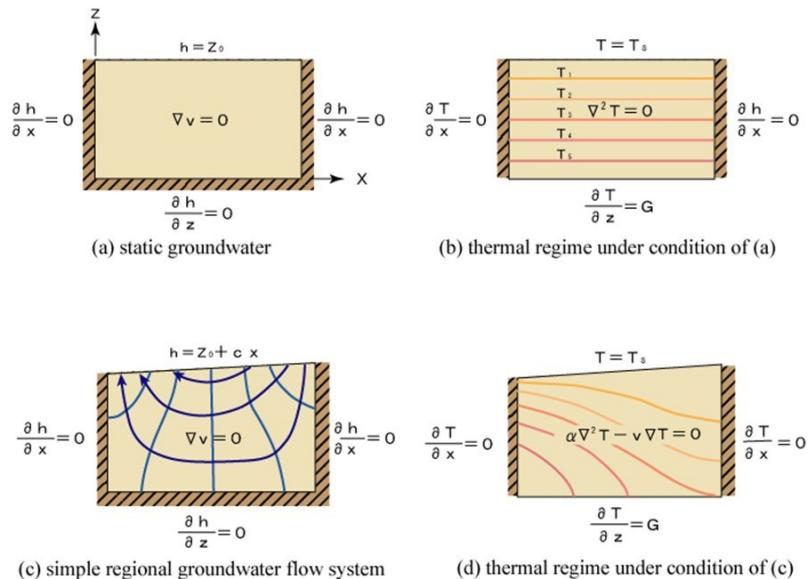


Figure 2: Subsurface thermal regime affected by a groundwater flow system (modified Domenico and Palciauskas, 1973)
(a) static groundwater, (b) thermal regime under condition of (a), (c) simple regional groundwater flow system, (d) thermal regime under condition of (c)

There are many observation wells in Japan which are used for monitoring groundwater level and land subsidence. Each observation site has two or three nested observation wells, and these wells are designed for single screen well. Each screen depth is set at the different aquifer, therefore we can get three-dimensional distribution of hydraulic head and estimate groundwater flow system. We have measured groundwater level and groundwater temperature at 2 m intervals in those observation wells and constructed database of subsurface temperature in Japan. The precision of thermometer which we used is 0.01 degree C.



Photo 1: Observation well for monitoring land subsidence in Japan

3. POTENTIAL MAPPING OF GSHP SYSTEMS BASED ON HYDRO-GEOLOGICAL MODELING

We have compiled potential maps based on hydrogeological data obtained by field work and groundwater flow / heat exchange simulations for optimal use of GSHP systems. The purpose of this study is to develop the suitable maps for GSHP system reflecting large-scale groundwater flow/heat transport environment. Yoshioka et al. (2010) showed heat exchange rate maps in Fukui Plain, Japan, reflecting large-scale modeling.

3.1 Large-Scale Model of Groundwater Flow / Heat Transport System in Fukui Plain

Fukui Plain is located in northern part of Fukui prefecture, Japan (Figure 3). It is surrounded by the Niu Mountains, Kaetsu Mountains and Kaetsu Chuou Mountains, Kaetsu Plateau and some large and small mountains to the south. In this area, summers are hot and winters are cold, and this area has heavy snow. GSHP system, therefore, can be applied to both the air-conditioner and the snow melting system.

Field surveys were performed to obtain data of groundwater level and subsurface temperature profiles using wells for snow melting system and observation wells. Groundwater flow/heat transport simulation in Fukui Plain was conducted using FEFLOW (Diersch, 2002).

Finite-element grids used in the model were shown in Figure 3. It was assumed that the model was closed to fluid flow and heat transport at its top and bottom. In this calculation, the groundwater level at outer boundary of the model was determined as a function of surface elevation. The physical properties of the model layers were assigned through the matching of measured and calculated groundwater levels and temperature profiles by adjusting the hydraulic and thermal conductivities.

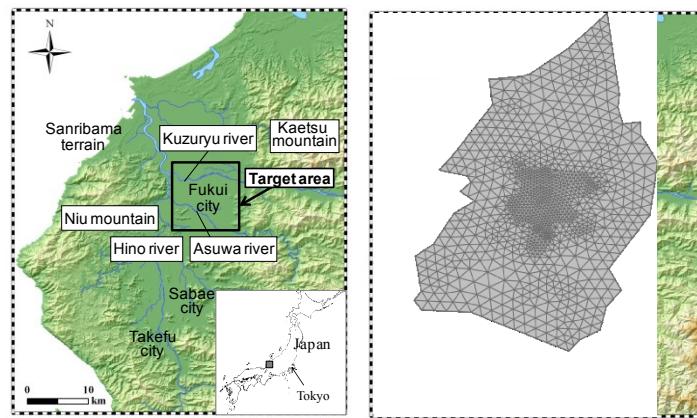


Figure 3: Map of Fukui Plain (left) and finite-element grids (right).

3.2 Small-Scale Single Heat Exchanger Model for Heat exchange Rate Maps

In order to develop heat exchange rate maps for GSHP system, single BHE (Borehole Heat Exchanger) models were constructed at 13 points surrounding Fukui city. In this city, residential areas and commercial buildings are concentrated and the demand for GCHPs is expected.

Figure 4 shows a 3D view of BHE grid model as an example, which is approximately 80 m depth and 20 m square. The center of the rectangle is assumed to be assigned with the 50 m long heat exchanger. Closed fluid flow and heat transport boundaries were assumed at the top and bottom of the BHE model. The groundwater velocities in the BHE model were determined by adjusting the hydraulic heads at lateral boundaries so that the velocity profiles at center of the grid model matched with the results of large-scale modeling.

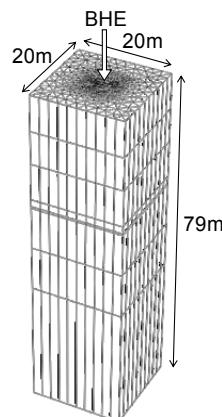


Figure 4: An example of the grid model of the single BHE mode (Diersch, 2002)

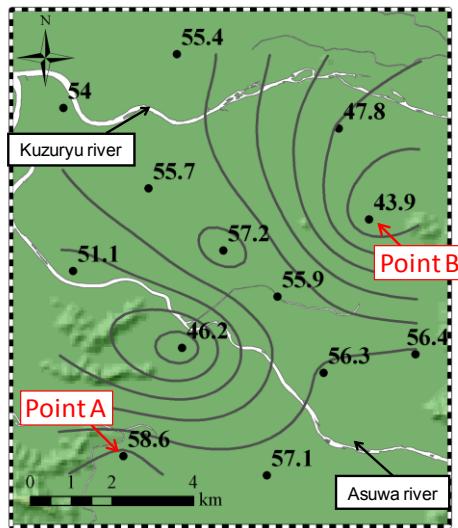


Figure 5: The heat exchange rate map (unit: [W/m])

A constant-temperature boundary condition was applied to the top of the model and the heat influxes at the bottom of every BHE were estimated by the calculated temperature profile in large-scale modeling. The heat transfer coefficient between the heat transfer medium and the outer face of the BHE is set at 19.7 W/ (m²K) (Fujii et al., 2005). The single heat exchange modeling was carried out assuming two different scenarios; the snow melting as Case1 and cooling/heating as Case 2. This paper describes only Case 1 due to space limitation. In Case 1, the BHE grids were set at a constant temperature of 5 degree C with operating time of 5 hours per day for 90 days per year. Total calculation period was 10 years.

Figure 5 shows the heat exchange rate map on the basis of the single BHE models at 13 points after a 10 year operation for Case 1. The maximum heat exchange rate is approximately 58.6 W/m at the southwest part (point A), and the minimum is approximately 43.9 W/m at the northeast part of the area (point B). The maximum heat exchange rate is 1.3 times as large as the minimum rate in the target area. This indicated that the length of BHE at point A can be 0.7 times less than that at point B.

4. STUDY ON SYSTEM OPTIMIZATION TECHNOLOGIES

A study has been conducted to develop innovative technologies for the optimization of GSHP system's design and installation that will be suitable for various hydro-geological characteristics. Collaboration with universities and local business enterprises within Fukushima prefecture is given a higher priority. Demonstration of these systems to general public with a real-time data exhibition panel may help to promote GSHP system.

We installed GSHP systems consisting of two boreholes (40 m depth) and three sheet type heat exchangers (2 m depth) in both AIST Tsukuba Center and FREJA (Figure 6 and Photo 2). There is a difference in hydrogeological setting between Tsukuba Center and FREJA. The geological setting in Tsukuba Center is sedimentary layer of the Quaternary System, on the other hand, in FREJA is shale in the Tertiary System. Moreover, water table in Tsukuba Center is higher than that in FREJA. The purpose of this experimental test is to understand effects of hydrogeological condition on the performance of GSHP system.

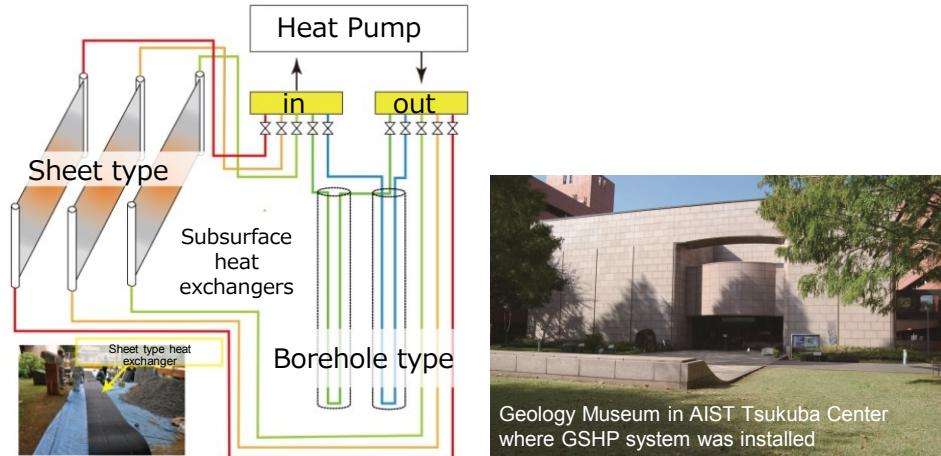


Figure 6: Borehole and sheet type heat exchangers installed in AIST Tsukuba Center and FREJA to compare the system performances in different hydrogeological settings

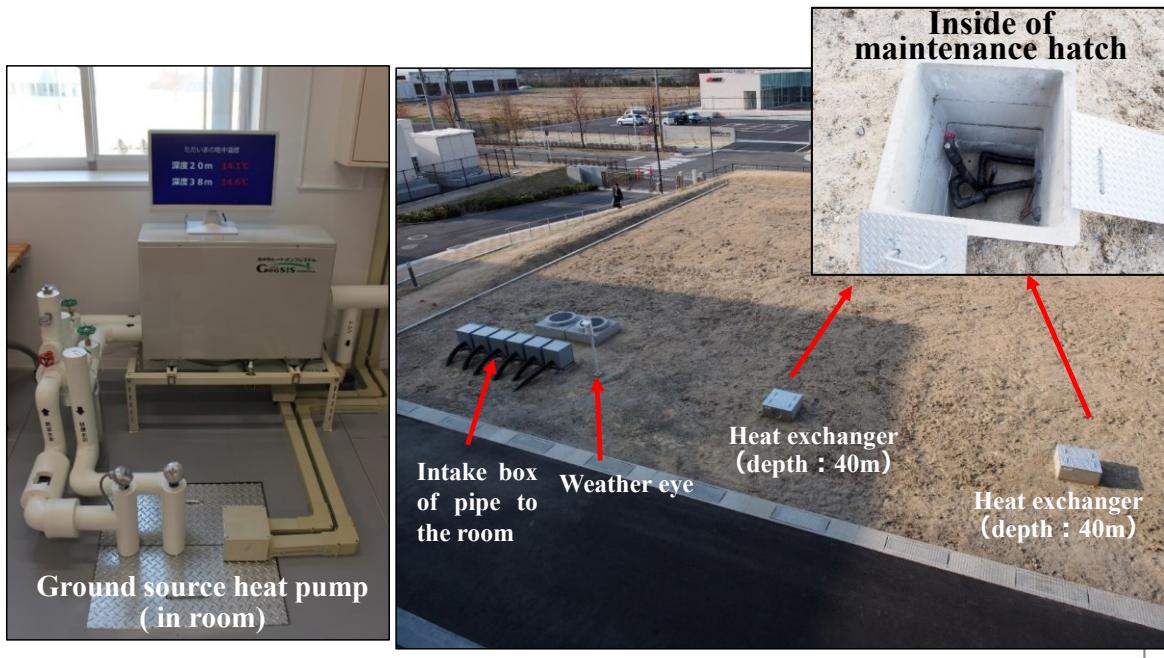


Photo 2: Ground source heat pump (left side) and arrangement of borehole heat exchangers at test filed in FREA

We are compiling and analyzing the field test data of GSHP system in both Tsukuba Center and FREA to compare the system performances in different hydrogeological settings. These test data can contribute to optimize GSHP system for various geological settings in Japan.

5. CONCLUSIONS

In this paper, we introduced some researches on GSHP System considering evaluation of installation potential for GSHP System based on hydrogeological data at Fukushima Renewable energy Institute, AIST (FREA).

1. AIST established the Fukushima Renewable Energy Institute in Koriyama, Fukushima Prefecture in April 2014 to promote R&D into renewable energy.
2. For optimal use of GSHP systems, Shallow Geothermal and Hydrogeology Team, FREA, is compiling potential maps of GSHP systems based on results of groundwater flow and heat exchange simulations.
3. Borehole and sheet type heat exchangers are installed in both AIST Tsukuba Center and FREA to compare the system performances in different hydrogeological settings.
4. These test data can contribute to optimize GSHP system for various hydrogeological settings in Japan.

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