The effects of groundwater flow on vertical-borehole ground source heat pump systems in a semi-cold climate, Fukushima, Japan

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Abstract

Heat advection by groundwater flow is known to improve the performance of a ground heat exchanger (GHE), but the performance effect of groundwater advection is not yet fully understood. This study examined how parameters related to groundwater flow, such as aquifer thickness, porosity, lithology, and groundwater flow velocity, affect the performance of a borehole GHE. Among these parameters, groundwater flow velocity has the greatest effect on heat flux. With a groundwater flow velocity of 10^{-4} m/s or more through a low-porosity aquifer filled with gravels with high thermal conductivity, the heat flux of a GHE can be as much as 60% higher than that of non-aquifer GHE. However, groundwater seldom flows with such a high velocity, and porosity, gravel size, and aquifer thickness, vary regionally. Thus, groundwater advection might be expected to improve GHE performance by up to 20%.

***Keywords**:* Ground source heat pump (GSHP), ground heat exchanger (GHE), semi-cold region, groundwater

1. Introduction

Ground source heat pumps (GSHP) are systems that combine a heat pump with a ground heat exchanger (GHE, a closed loop system that may be dozens of meters long) or that are fed by groundwater from a well (open loop systems). In operating mode, they use the ground as a heat source, and a fluid medium (water or a water–antifreeze mixture) transfers heat from the ground to the heat exchanger of the heat pump. Thus, they are able to utilize ground heat energy. Because the ground temperature changes less seasonally than the air temperature does, a GSHP can achieve greater energy savings than a conventional air source heat pump system.

In general, heat advection by groundwater flow significantly enhances heat transfer in geologic materials with high hydraulic conductivity, such as sand, gravel, and rocks exhibiting fractures or solution channels [1]. Finite element method (FEM) numerical simulations predicting the effect of groundwater flow on the long-term performance of large GHE fields with unbalanced winter and summer loads have indicated that groundwater flow does not reduce the effects of hourly peak loads on heat transfer, but notably improves long-term performance [2].

In the absence of groundwater flow, when multiple GHEs are used, the temperature decrease in the surrounding ground is greater than in the case of a single GHE, even if the GHEs are spaced 7.5 m apart. After 30 years of operation, the heat recovery time is about 70 years [3].

In the presence of groundwater flow, GHE fields can be sustainable even when the seasonal heat loads are completely unbalanced [1]. For a single GHE experiencing a constant heat flux for 2 years, a groundwater flow velocity of 60 m/year (about 2×10^{-7} m/s), a typical velocity in coarse sand, had a considerable effect on the predicted time evolution of the mean temperature of the GHE [4]. FEM numerical simulations of the long-term performance of large fields of GHEs (6 m apart) with groundwater flow [5] have shown that a groundwater flow velocity of 10^{-7} m/s is sufficient to ensure long-term sustainability of a single line or two staggered lines of infinite GHEs, and a velocity of 10^{-6} m/s ensures the long-term sustainability of four staggered lines of infinite GHEs. If the Peclet number is sufficiently large, the groundwater flow can effectively carry away excess heat accumulated in the ground [6].

In Japan, most towns and cities are located along the coast or in basins where the underlying sediments consist of clastics of various sizes, from gravel to clay. Gravel and sand layers are usually good aquifers. Thus, when designing GHEs in Japan, it is very important to calculate the effect of groundwater on GHE operation. This effect depends on parameters such as groundwater flow velocity, aquifer thickness, geological parameters (e.g., porosity, clast size and composition), and thermal conductivity.

The relationships among these parameters and how they affect the heat flux of a GHE has yet to be systematically explained. Moreover, the thermal conductivity of water, 0.56 W/mK, is considerably lower than that of clastics (e.g., 1.65 W/mK for wet sand) [7]. Thus, it is difficult to utilize groundwater efficiently, which is a consideration in the design and operation of a GHE.

This study used 3-D numerical simulation modeling to clarify the effects of parameters related to groundwater flow on GHE performance, and then evaluated possible ways to enhance GHE functioning.

2. 3-D Numerical Simulation of a 3-D GHE

2.1 Model and Fundamental Equation

A schematic diagram of a borehole GHE is shown in Fig. 1. (Symbols are defined at the end of the text.) The sediments are separated into aquifer and other layers. The top of the aquifer is 10 m below ground level. The GHE is rectangular (0.2 m by 100 m) with an isothermal wall of 5 °C. In the simulations, the GHE was operated continuously for 250 h.

The groundwater flow is assumed to be horizontal and unidirectional. The *groundwater* flow *velocity* is described by a form of the Laplace equation as 2-D *potential flow*. Ground temperature is calculated using Eq. (1). Values of constants used in the calculations are shown in Table 1.

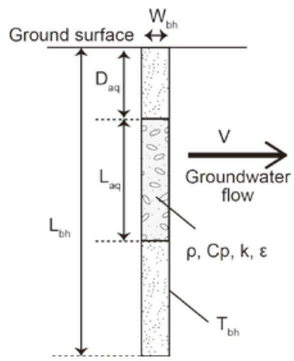

Fig. 1. Schematic diagram of a GHE.

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p u\frac{\partial T}{\partial x}+\rho C_p v\frac{\partial T}{\partial y}=\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(k\frac{\partial T}{\partial z}) \quad (1)$$

Table 1. Values of constants

D_{aq}	m	10
L_{bh}	m	100
T_{bh}	°C	5
w_{bh}	m	0.2

2.2 Effective Thermal Properties of Aquifers

Gravel was assumed to consist of granite or tuff. Both are common at the study site (Nihon University, Fukushima, Japan), and they have different thermal properties (Table 2). The material composing other layers was assumed to be soil, and its properties were measured at the study site [8]. The values used for parameters allowed to vary in different simulations are listed in Table 3.

Table 2. Thermal properties

	ρ (kg/m^3)	C_p (kJ/kgK)	k (W/mK)
Water	1000	4.2	0.6
Soil	1960	1.2	2.1
Granite	2650	1.1	4.3
Tuff	1400	1.7	0.8

The effective thermal properties of an aquifer are calculated as follows [9]:

$$\frac{k_e}{k_p}=\varepsilon+\frac{1-\varepsilon}{\phi+\frac{2}{3}\left(\frac{k_f}{k_p}\right)} \quad (2)$$

$$\rho_e=(1-\varepsilon)\rho_p+\varepsilon\rho_w \quad (3)$$

$$C_{p,e}=(1-\varepsilon)C_{p,p}+\varepsilon C_{p,w} \quad (4)$$

Table 3. Calculation conditions (variable values)

L_{aq}	m	0, 10, 30 , 50
v	m^3/s	0, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}
ε	%	0, 10, 20, 45

3. Results

3.1 Effect of Water on the GHE Heat Flux

A GHE with a non-gravel aquifer (water only) was investigated to clarify the effect of groundwater advection on the heat flux across the GHE wall. The calculated heat flux for different groundwater flow velocities in a 10-m-thick aquifer is shown in Fig. 2. With a flow velocity of zero, there is no groundwater advection effect and the heat flux at all depths of the GHE is lower than that of a non-aquifer GHE (soil only), because the thermal conductivity of water is lower than that of soil (Table 2). With a flow velocity of 10^{-5} m/s, the heat flux is almost the same as that of a non-aquifer GHE. When the velocity is 10^{-3} m/s, groundwater advection increases the average heat flux by 3% after 250 h of operation compared with a non-aquifer GHE. Thus, if flow velocity exceeds 10^{-5} m/s, groundwater advection is effective, and after long-term continuous operation, the heat flux of a GHE with an aquifer is much higher than that of a non-aquifer GHE.

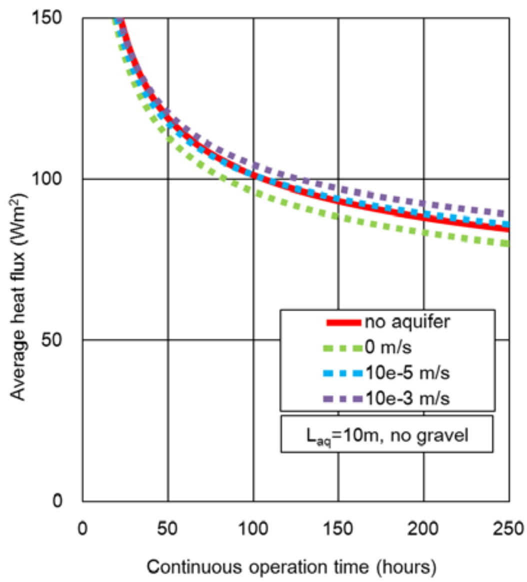

Fig. 2. Heat flux changes for different water flow velocities.

The effect of the thickness of a non-gravel aquifer was also investigated under a constant groundwater flow velocity of 10^{-5} m/s (Fig. 3). After 100 h of continuous operation, the heat flux of the GHE with an aquifer 10, 30, or 50 m thick begins to exceed that of a non-aquifer GHE. After 250 h of continuous operation, the heat flux of GHE in a 50-m-thick aquifer is about 5% higher than that of a non-aquifer GHE. Thus, the thicker the aquifer, the higher heat flux of the GHE becomes.

The aquifer does not become as cool as the soil layer, because advection by groundwater is lower than that by soil (Table 2). In a GHE with a 10-m-thick aquifer, after 250 h of continuous operation, the heat flux of the soil layers decreases from 90 to about 60 W/m^2, whereas that of the aquifer layer remains at around 80 W/m^2 (Fig. 4). As a result, the heat flux of the whole GHE is higher than that of a non-aquifer GHE.

These results indicate that a high groundwater flow velocity and a thick aquifer enhance heat advection by groundwater flow, improving the thermal performance by up to 5%.

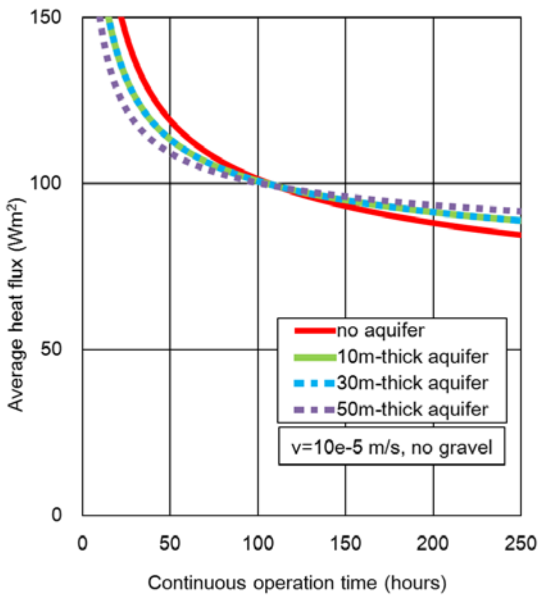

Fig. 3. Heat flux changes for different aquifer thicknesses.

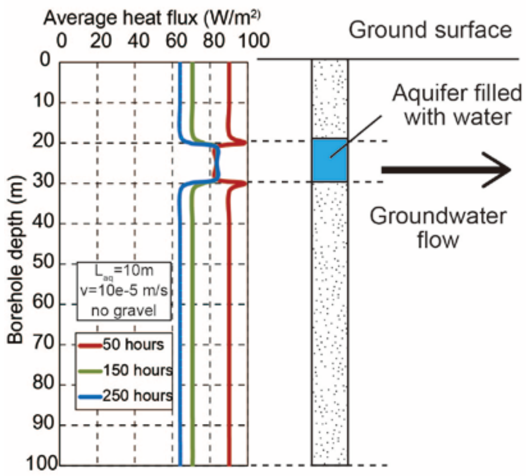

Fig. 4. Heat flux profiles of a GHE with a water-filled aquifer after continuous operation for 50, 150, and 250 h.

3.2 Effect of a Gravel-filled Aquifer on the GHE Heat Flux

Next, the effect of a gravel-filled aquifer on GHE thermal performance was examined. Heat flux profiles for operation times of 50, 150, and 250 h of a GHE with a granite-gravel-filled aquifer are shown in Fig. 5. In the soil layers, the heat flux profiles are the same as before (Fig. 4): the heat flux decreases from 90 to 60 W/m^2 after 250 h. In the aquifer layer, however, the heat flux is about 250 W/m^2, five times the flux with a water-filled aquifer. The thermal conductivity of granite is about seven times that of water (Table 2). This result indicates that, because of its high thermal conductivity, gravel improves heat advection more than groundwater flow alone.

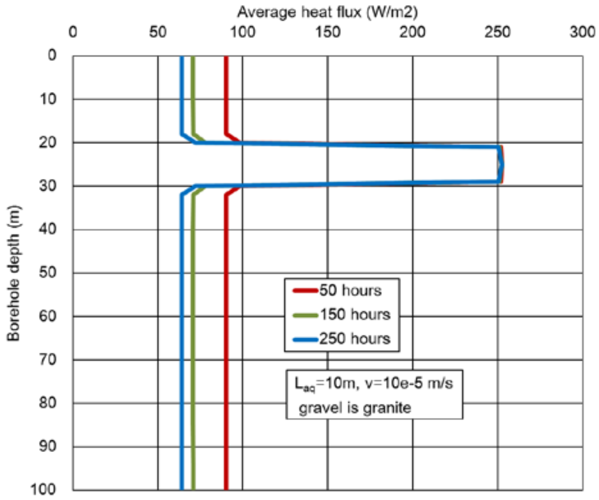

Fig. 5. Heat flux profiles of a GHE with a granite-gravel-filled aquifer after continuous operation for 50, 150, and 250 h.

The effects of other parameters on heat flux of a GHE with a gravel-filled aquifer (aquifer thickness, porosity, lithology, and groundwater flow velocity) were also examined. Heat flux changes for a GHE with an aquifer with different porosities and lithology were calculated. In general, gravel layer porosity ranges from 25% to 40% [9]. In the simulation, the porosity was set to 20% and 45%. Granite was chosen for the aquifer gravel filling. The groundwater flow velocity was set to 10^{-5} m/s.

Fig. 6 shows the simulated heat flux changes. When the aquifer porosity was 20%, the heat flux of the GHE was higher than when the aquifer porosity was 45%. Compared with a non-aquifer GHE, the heat flux of a GHE with a 20% porosity aquifer was 20% higher. Thus, lower aquifer porosity leads to a higher heat flux.

Heat flux of a GHE with a aquifer of tuff gravel, which has low thermal conductivity, was also examined. The porosity and groundwater flow velocity were set to 20% and 10^{-5} m/s, respectively. In the simulation result, the heat flux was almost the same as that of a non-aquifer GHE (Fig. 6).

These results suggest that aquifer gravel with high thermal conductivity, such as granite, increases the heat flux when groundwater advection is constant. Also, low aquifer porosity enhances advection.

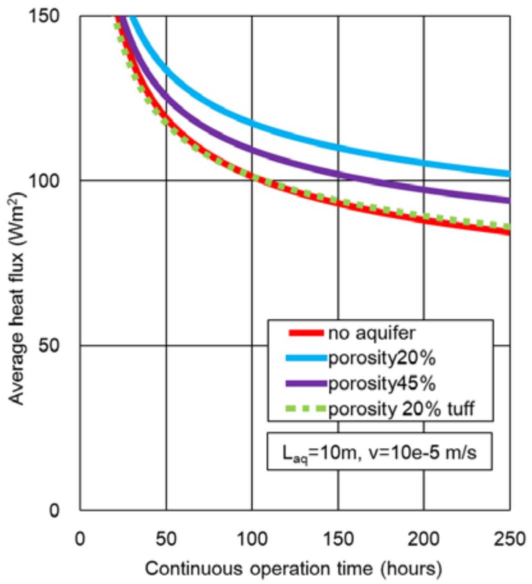

Fig. 6. Heat flux changes with different aquifer porosity and lithology.

Finally, the effect of the groundwater flow velocity in a granite-gravel-filled aquifer was investigated. Aquifer thickness was set to 10 m.

In general, groundwater in Japan flows at velocities from about 10^{-5} to 10^{-6} m/s [10-12]. Here, the velocity was set to 0, 10^{-6}, 10^{-5}, 10^{-4}, or 10^{-3} m/s (Fig. 7). When the velocity was 0 or 10^{-6} m/s, the heat flux was similar to that of a non-aquifer GHE, whereas when the velocity was 10^{-5} m/s, the heat flux increased by 20% compared with a non-aquifer GHE. At velocities of 10^{-4} and 10^{-3} m/s, the heat flux exceeded 140 W/m^2 after 250 h of operation. This heat flux is about 60% higher than that of a non-aquifer GHE.

Thus, groundwater flow velocity has a greater effect on advection than the other parameters examined and the higher the velocity, the more advection is enhanced.

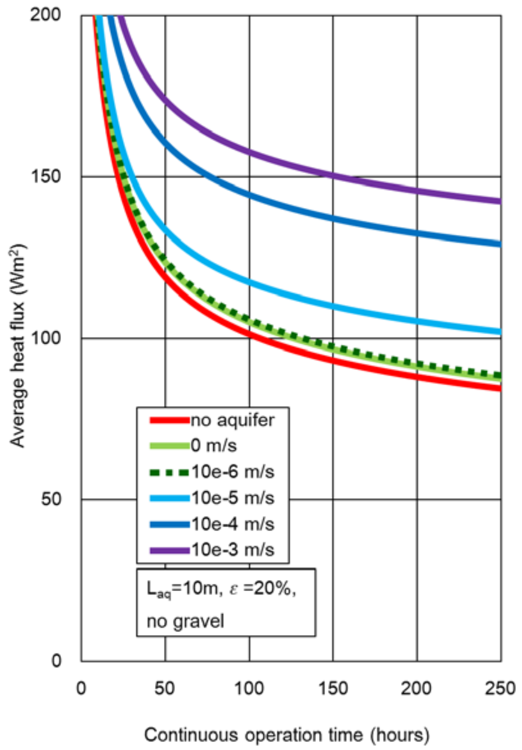

Fig. 7. Heat flux changes with different groundwater flow velocities.

4. Discussion

4.1 Parameter Effects on the GHE Heat Flux

The heat flux of a GHE with an aquifer consisting of only a water-filled space and a groundwater flow velocity of more than 10^{-5} m/s is much higher than that of a non-aquifer GHE. After continuous long-term operation, groundwater advection effectively increases the heat flux of the whole GHE (Figs. 2 and 3). However, even with a thick aquifer, the heat flux increases by no more than 5% because of the low thermal conductivity of water.

The heat flux of a GHE with a granite-gravel-filled aquifer is five times that of a GHE with a water-filled aquifer after continuous, long-term operation (Figs. 4 and 5). If the aquifer porosity is varied while keeping the geology and groundwater flow velocity the same, smaller porosity leads to a higher heat flux (Fig. 6). With the same porosity and same groundwater flow velocity, the heat flux is much higher in a granite-gravel-filled aquifer than in a tuff-gravel-filled aquifer. These results suggest that the high thermal conductivity of granite improved the thermal performance of the whole GHE.

With a granite-gravel-filled aquifer and a groundwater flow velocity of more than 10^{-4} m/s, the heat flux of a GHE is about 60% higher compared with a non-aquifer GHE (Fig. 7). Thus, a high thermal conductivity and a high groundwater flow velocity have an effect that is greater than the sum of their individual effects.

4.2 Designing a GHE with Groundwater Effect

An aquifer is typically a water-filled stratum composed of large clastics such as gravel and sand. The 3-D numerical simulations showed that in the case of a gravel-filled aquifer, thermal performance of a GHE is enhance by low porosity, high thermal conductivity of the gravel, and a high groundwater flow velocity.

If the groundwater flow velocity is higher than 10^{-5} m/s, groundwater advection enhances heat transfer in the geologic materials and leads to the GHE's having a high heat flux [12]. However, groundwater conditions are complicated. A high groundwater flow velocity of more than 10^{-4} m/s is seen only in some alluvial fans [13], and usually only in simulations. Therefore, the effect of groundwater advection is likely to be less than 20%.

Moreover, geological conditions, such as porosity, gravel size, and aquifer thickness are often unknown and vary regionally. Thus, in the design of a GSHP system, it would not be appropriate to assume a large groundwater effect.

5. Conclusion

The effects of groundwater flow-related parameters, aquifer thickness, porosity, lithology, and groundwater flow velocity, on the thermal performance of a GHE were examined. Among these parameters, the most effective parameters were groundwater flow velocity and thermal conductivity. With a groundwater flow velocity of more than 10^{-4} m/s, a granite gravel with high thermal conductivity, and a low porosity of 20%, can increase the heat flux of a GHE by 60% compared with a non-aquifer GHE.

However, a groundwater flow velocity exceeding 10^{-4} m/s is rare in Japan, and geological conditions such as porosity, gravel size, and aquifer thickness are often unknown and highly variable. Thus, even if geological conditions are favorable, the effect of groundwater advection is likely to be no more than 20%.

Symbol definitions and units

C_p	kJ/kgK	Specific heat
$C_{p,e}$	kJ/kgK	Effective specific heat
$C_{p,p}$	kJ/kgK	Specific heat of particles
$C_{p,w}$	kJ/kgK	Specific heat of water
D_{aq}	m	Depth of the aquifer top
k	W/mK	Thermal conductivity
k_e	W/mK	Effective thermal conductivity
k_f	W/mK	Thermal conductivity of fluid
k_p	W/mK	Thermal conductivity of particles
L_{bh}	m	Borehole length
L_{aq}	m	Aquifer thickness
T_{bh}	°C	Borehole temperature
v	m^3/s	Groundwater flow velocity
w_{bh}	m	Borehole width
ε	%	Aquifer porosity
ρ	kg/m^3	Density
ρ_e	kg/m^3	Effective density
ρ_p	kg/m^3	Particle density
ρ_w	kg/m^3	Water density

6. Acknowledgements

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