Importance of Groundwater Flow on Life Cycle Costs of a Household Ground Heat Pump System in Japan

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Summary

This paper analyzed life cycle costs of a ground source heat pump system used in a residence of Japan considering an advection effect of groundwater flow of eight different Darcy velocity. The required length of a single borehole heat exchanger was determined in each seven area of different heating/cooling loads to minimize the life cycle cost during 20 years through heat pump simulations. This study revealed that the effect of groundwater flow appeared when the velocity was more than 10 m/y and was almost converged when the velocity reached at 200 m/y. The cost decreased almost linearly according to the logarithms of the velocity. The velocity range was possible in steep valleys and alluvial fans of Japan. This study also showed that the costs were related mainly to the total loads, and secondarily to the groundwater flow conditions for the household system. Among seven areas, the household system was economically suitable relative to conventional air source heat pump systems in the cold areas 1 and 2 without initial cost reduction. The moderately warm areas 3 to 5 also became suitable when the initial costs would be reduced by 20 % as a common target of current R&D projects.

Keywords: Ground source heat pump system, Groundwater, Life cycle cost, Sensitivity analysis

1. Introduction

Ground source heat pump systems (GSHPs) are available as energy-saving systems for heating/cooling demands in buildings due to the relative stability of ground temperatures. GSHPs potentially contribute to the purpose of the Japan government; a total CO2 emission should be reduced by 26 % until 2030. Actually in Japan, the number of installed GSHPs has been growing up rapidly since 2000s1). However, the number is not enough as compared with other countries, because initial costs of the system are high relative to conventional systems such as air source heat pump systems (ASHPs). As an example, the national agency showed that the capital cost of GSHPs for a residence in Japan is almost 1.5 times of that in USA2). On the other hand, GSHPs would reduce their life cycle costs (LCC) through the efficient operations and the reduction could potentially cover the economic disadvantage at the implementation.

Japan has a large amount of groundwater resources over the land. In mountains and hills where groundwater flows actively according to the steep topography, heat transfer around a borehole heat exchanger (BHE) is generated not only by conduction but also by advection. Fig. 1 shows the water table slopes in a regular 1-km grid of Japan, from the grid data3). Groundwater flows actively except in flat areas of <1 % (white zones). For example, when hydraulic conductivity is ranged in $10^{-5}$ and $10^{-3}$ m/s in the averaged hydraulic gradient of 6.1 %, the Darcy velocity (specific discharge of groundwater flow) is estimated at 2- 200 m/y. Such velocity indicates that the groundwater contributes to enhance GSHPs, as shown in previous studies4). On the other hand, the economic contribution of groundwater flows on GSHPs has been discussed at each typical site because the analysis of GSHPs needs various factors regarding heating/cooling, geology, heat pump and so on. In addition, there are few practical tools to assess the efficiency of GSHPs considering groundwater flow effects, although the information has been long required in practice.

The purpose of this study is to analyze the effect of groundwater flows on the LCC of a household GSHP through the developed algorithm5). This study assumed the Darcy velocity around the BHE among
10 to 1000 m/y and the heating/cooling loads of a standard residence in seven areas of the country. This study determined required lengths of a single U-tube BHE to minimize the LCC in each area. The groundwater flow effects to reduce the lengths is also discussed. The potentially economic suitability for a household GSHP is shown through a comparison of the target reduction ratio of initial cost for balancing the LCC with another LCC of a competitive ASHP.

2. Material and Methods

2.1 Standard residence for analysis

This study assumed a Japan standard residence of 120 m² in total area for analysis. The residence consisted of a living room, a traditional room, a kitchen on the first floor, and of a bedroom and two kid rooms on the second floor. The residence was the same with that defined in the web site of the national institute. The insulation properties were different among seven areas from north to south in Japan: area 1 in north-west Hokkaido Island; area 2 in south-east Hokkaido; area 3 in north Honshu Island; area 4 in middle and high Honshu Island; area 5 in middle and low Honshu Island; area 6 in South Honshu Island and Shikoku Island; area 7 in Kyushu Island.

Calculated heating/cooling loads were obtained from the website in various conditions including thermal insulation and heating/cooling schedule. The insulation conditions were assumed to satisfy the national target of energy saving after 1999. The heating/cooling schedules were divided as realistic living cases into three types: i) full time heating/cooling operation in the areas 1 and 2, ii) full time heating operation in a living space and interval cooling operation in a living space in the areas 3 and 4 and iii) interval heating/cooling operation in a living space in the areas 5, 6 and 7.

Table 1 summarizes representative cities, their averaged outdoor air temperature $T_a$ and annually total heating/cooling loads in seven comparison areas of Japan. $T_a$ was ranged from 7.29 °C in the area 1 and 18.92 °C in the area 7, reflecting to the heat/cooling loads. The maximum total load $Q$ was 51.5 GJ/y in the northern area 1, and $Q$ consisted mainly of the heating load $Q_h$. The total load decreased toward the south as $Q_c$ decreased. The minimum $Q$ was 19.1 GJ/y in the middle area 5. In the south areas 6 and 7, $Q_c$ increased toward the south because the cooling loads $Q_c$ increased. In the area 6, $Q_c$ was almost the same with $Q_h$, and in the area 7, $Q_c$ was dominant.

2.2 GSHP simulation with groundwater conditions

This study applied the GSHP simulation tool “Ground Club” which was developed by Hokkaido University. The simulation tool was improved to calculate ground temperature changes by the GSHP operation considering groundwater flow effects. The theoretical details were explained in our previous study. This paper briefly described calculation process as below. In the process, a BHE was assumed to a cylindrical model of homogeneous but unsteady heating/cooling rates on the surface. The non-dimensional temperature changes $\Delta T_s^*$ of the ground around the BHE were calculated as a superposition of their hourly temperature response:

$$\Delta T_s^*(t') = \sum_{r} q'(t'-\tau) \frac{\partial \Delta T_r^*(\tau^*) \times C_c(t',U)}{\partial \tau} \tag{1}$$

Here $\Delta T_s^*$ is equal to $2\pi \Delta T_s/q'$, $\lambda$ is effective thermal conductivity of the ground, $q'$ is heat flow per unit depth of the borehole, $q^*$ is non-dimensional $q$, $\tau^*$ is the Fourier number ($=rt^2$, $a$ is the thermal diffusivity of the ground, $r$ is the borehole radius, in non-dimensional ($=1$), $C_c$ is the modification factor in groundwater flow conditions. $C_c$ was calculated from second-order polynomial functions of Darcy velocity $U$. The parameters for $C_c$ were defined in the numerical simulation of groundwater flow:

$$C_c(t',U) = \frac{T_s^*(t')}{T_s^*(U)} \tag{2}$$

The soil temperatures were calculated at each time, and then the temperatures of the heat transfer fluids in the U-tube were calculated based on the heat balance in related to the borehole thermal resistance. The borehole thermal resistance was estimated by the Boundary Element Method. Next, the electric consumptions of the heat pump were calculated from the inlet and outlet temperatures of the fluid. In this study, the heat pump was assumed to be a commercial product with a regular power of 10 kW. The performance type curves were set based on the laboratory test results in the product company. This study configured that a single 25A U-tube was buried in the BHE with a diameter of 120 mm and that the grout material of the silica sand ($\lambda=1.5$ W/(m·K)) was filled. All thermal properties of the

<table>
<thead>
<tr>
<th>Area</th>
<th>City</th>
<th>$T_a$[°C]</th>
<th>Heating $Q_h$[GJ/y]</th>
<th>Cooling $Q_c$[GJ/y]</th>
<th>Total $Q$[GJ/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>7.29</td>
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<td>3.4</td>
<td>51.5</td>
</tr>
<tr>
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<td>Iwanazawa</td>
<td>8.96</td>
<td>41.3</td>
<td>3.5</td>
<td>44.8</td>
</tr>
<tr>
<td>3</td>
<td>Morioka</td>
<td>11.68</td>
<td>30.1</td>
<td>3.5</td>
<td>33.6</td>
</tr>
<tr>
<td>4</td>
<td>Nagano</td>
<td>13.08</td>
<td>32.8</td>
<td>5.6</td>
<td>38.4</td>
</tr>
<tr>
<td>5</td>
<td>Utsunomiya</td>
<td>14.76</td>
<td>13.8</td>
<td>5.3</td>
<td>19.1</td>
</tr>
<tr>
<td>6</td>
<td>Okayama</td>
<td>17.19</td>
<td>10.5</td>
<td>12.7</td>
<td>23.2</td>
</tr>
<tr>
<td>7</td>
<td>Miyazaki</td>
<td>18.92</td>
<td>5.1</td>
<td>15.4</td>
<td>20.5</td>
</tr>
</tbody>
</table>
soil were assumed to be constant: effective thermal conductivity $\lambda$ was 1.5 W/(m·K); a density was 1700 kg/m³; a specific heat was 2.2MJ/(kg·K), for unconsolidated sandy deposits in sedimentary basins of Japan. The initial ground temperatures were calculated with a linear relation with depth. The initial temperature at a depth of 10 m was assumed to be 1.5 K larger than $T_a$ in Table 1. The vertical gradient of temperature was also constant at 0.03 K/m. This study performed the sensitive analysis of the LCC under eight cases of the Darcy velocity $U$ (=1, 10, 20, 50, 100, 200, 500, 1000 m/y).

2.3 Calculation of BHE length and LCC

The required length of the BHE $L_{\text{min}}$ was defined to minimize the 20y LCC in each area. This study calculated the LCC as a sum of an initial cost $IC$ and an operation cost $OC$:

$$LCC = IC + \sum_{\tau=1}^{20} OC(1 - IR)^\tau$$  (3)

$$IC = IC_0 + N \times L \times IC_1$$  (4)

$$OC_2 = \sum_{m} EC_1(t_m) + \sum_{n=1}^{840} EC_2(t_n)E_{\text{HP}}(t_n)$$  (5)

Here $IR$ is inflation rate, $IC_0$ is base cost of $IC$, $N$ is number of BHE, $L$ is length of BHE, $IC_1$ is drilling cost per one meter in depth, $EC_1$ and $EC_2$ are monthly and hourly bulls of electric consumptions, respectively. $E_{\text{HP}}$ is hourly electric consumption of heat pump. This study omitted other components in the LCC, i.e., a maintenance cost, a renovation cost and a disposal cost because the analysis span (20y) was almost the durability lifetime of the heat pump and the maintenance cost was almost zero for the individual residence. This study also assumed that $IC_0$ and $IC_1$ were constant at 2.76 million yen² and 10 thousand yen per unit meter, respectively. The $EC_1$ and $EC_2$ values were used as the public rates at fiscal 2017 year of the electric company in each area, as summarized in Table 2. The annual inflation rate $IR$ was assumed to be a target of the Japan government ($IR = 3\%$). The GSHP simulation was performed with the same cooling/heating loads in three years, and the temperatures were converged for the long-term operation. This study assigned the necessary condition to determine $L_{\text{min}}$ as the temperatures of the circulating fluids were higher than the freezing points, –15 °C of antifreeze (30 % ethylene glycol solution) in the areas 1 to 3 and 0 °C of tap water in the areas 4 to 7.

In general, when $L$ was assumed to be longer, $IC$ became higher, but $OC$ became cheaper. In order to consider the trade-off relationship in the LCC calculation, this study performed the GSHP simulation under different borehole lengths between 20 and 150 m with a 10m interval at each groundwater flow condition. The required length $L_{\text{min}}$ was determined through the interpolation among these lengths to obtain the minimum LCC.

This study also compared LCC of the GSHP with that of the conventional ASHP system, LCC0. This study calculated LCC0 in an assumption that the conventional system composed of 4 units of 4 kW room air-conditioners. The equipment price and the COP of the ASHP were referred from the market research studies⁹⁻¹⁰. The electric consumptions by the ASHP were calculated to divide the same heating/cooling loads of the GSHP by the averaged COP of the ASHP (5.54 in cooling, 3.06 in heating and 1.93 in heating at the low outdoor temperatures; <2 °C). This study compared the LCC of the GSHP with that of the ASHP as a proposed index tRCA; the target ratio of IC for an agreement of LCC between the GSHP and the ASHP with a subvention cost SC:

$$tRCA = \frac{LCC - LCC_0 - SC}{IC} \times 100$$  (6)

In this study, SC was assumed at 0.75 million yen in fiscal 2016 year. When tRCA was negative, the GSHP was economically reasonable relative to the conventional system. On the other hand, when tRCA was positive, the IC of the GSHP should be reduced by the tRCA to compete the ASHP. This study compared the $L_{\text{min}}$, the LCC and the tRCA under different groundwater flow conditions for the standard residence among seven comparison areas.

3. Results and Discussion

3.1 A relation of BHE length and LCC with Darcy velocity

Fig. 2 shows one example of calculation results; $L_{\text{min}}$, annually averaged system COP, LCC, LCC0 and tRCA under different $U$ conditions in the area 4. $L_{\text{min}}$ was ranged between 68 ($U = 1$ m/y) and 36 m ($U = 1000$ m/s); the difference was 28 m despite the change of $U$. $L_{\text{min}}$ appeared when $U$ was over 10 m/y. Moreover, $L_{\text{min}}$ decreased gradually with $U$ log-linearly. Finally, $L_{\text{min}}$ became almost stable when $U$ was over 200 m/y. This relation indicates that groundwater flow effects should be considered between 10 and 200 m/y in the area. The range was similarly seen in other areas (the results were

<table>
<thead>
<tr>
<th>Area</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$EC_1$ [yen/month]</td>
<td>1339</td>
<td>1296</td>
<td>1123</td>
<td>1123</td>
<td>1598</td>
<td>1166</td>
<td></td>
</tr>
<tr>
<td>$EC_2$ [yen/kWh]</td>
<td>23.5</td>
<td>18.2</td>
<td>19.5</td>
<td>20.7</td>
<td>17.8</td>
<td>17.2</td>
<td></td>
</tr>
</tbody>
</table>
Annually averaged system COP of the GSHP was over 4.0 in any U condition. The value was also insensitive to U. The insensitivity of U on COP means that the groundwater flow effect was not distinct to enhance the household system because of limited heating/cooling loads. The range of LCC according to U was about 0.5 million yen (about 10 % of the LCC values). LCC was also converged when U was over 200 m/y. In the area 4, LCC of the GSHP was larger than LCC0 of the ASHP in any case of U. However, if SC was assumed, tRCA became negative in some flow cases and areas: U ≥ 10 m/y in the area 1; U ≥ 1 m/y in the area 2; U ≥ 100 m/y in the area 4. In these cases, the household GSHP becomes economically suitable relative to the conventional ASHP system.

Finally, the comparison of economic suitability of the household GSHP among seven areas is discussed. The areas 1 and 2 in the cold climate were economically suitable for its implementation, because tRCA was negative or almost zero according to any case of U. This was because the COP of the ASHP was assumed to be relatively low in heating, especially at the low temperatures.

In the areas 3, 4 and 5 of moderate climates, LCC was small relatively among the comparison areas. tRCA was not negative except U = 1000 m/y in the

<table>
<thead>
<tr>
<th>U [m/y]</th>
<th>Lmin [m]</th>
<th>COP[]</th>
<th>LCC [M yen]</th>
<th>tRCA [%]</th>
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<tbody>
<tr>
<td>1</td>
<td>2.64</td>
<td>3.73</td>
<td>3.70</td>
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</tr>
<tr>
<td>10</td>
<td>5.4</td>
<td>7.6</td>
<td>3.56</td>
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</tr>
<tr>
<td>100</td>
<td>10</td>
<td>9.2</td>
<td>3.52</td>
<td>-0.76</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
<td>2.64</td>
<td>3.39</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

Figure 2 Sensitivity analysis results of Lmin, annually averaged COP, LCC and tRCA of the GSHP against U in the standard residence of the area 4.
area 4, but was less than 20% in any case of $U$. The areas were potentially suitable for the household GSHP because the current R&D projects have been developing various tools and techniques to reduce the initial costs by 20%\(^3\). In near future when the developments become available in public, the implementation of the household GSHP will be accelerated not only in the cold areas but also in the middle areas with the large population.

In the areas 6 and 7 of the warm climate, although $L_{\text{min}}$ was much smaller than in the areas 1 and 2, $t_{RCA}$ was relatively large, over 20%. When IC of the GSHP will be reduced by 20% as described above, $t_{RCA}$ remains still positive in any case of $U$. In these areas, the cooling loads were relatively high, and the assumed COP of the ASHP in cooling was relatively high. Additional cost reduction of the GSHP, despite current R&D projects, is required to promote the GSHPs in the warm areas 6 and 7.

Commonly in 7 comparison areas, it is interpreted that it resulted that a width of reduction of $LCC$ was limited according to $U$. In other words, the effect of groundwater flows was limited in such a residence as compared with the difference of climate for heating/cooling loads. However, in commercial buildings with relatively large loads, it is expected that an effect of groundwater flow appears more clearly, as shown in a near future subject.

4. Conclusions

<table>
<thead>
<tr>
<th>Area</th>
<th>$LCC_0$ [M yen]</th>
<th>$L_{\text{min}}$ [m]</th>
<th>$LCC$ [M yen]</th>
<th>$t_{RCA}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.90</td>
<td>118</td>
<td>4.67</td>
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</tr>
<tr>
<td>2</td>
<td>3.59</td>
<td>90</td>
<td>4.27</td>
<td>-1.89</td>
</tr>
<tr>
<td>3</td>
<td>2.43</td>
<td>55</td>
<td>3.42</td>
<td>7.38</td>
</tr>
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<td>4</td>
<td>2.64</td>
<td>68</td>
<td>3.73</td>
<td>10.0</td>
</tr>
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<td>40</td>
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<td>19.4</td>
</tr>
<tr>
<td>6</td>
<td>1.87</td>
<td>57</td>
<td>3.50</td>
<td>26.3</td>
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<td>7</td>
<td>1.47</td>
<td>52</td>
<td>3.30</td>
<td>32.7</td>
</tr>
</tbody>
</table>

Figure 3 Comparison plots of $LCC$ and $t_{RCA}$ for $U = 1, 10, 100, 1000$ m/y in seven areas.
This paper conducted the sensitivity analysis of the life cycle cost $\text{LCC}$ of the ground source heat pump system used in a residence of Japan under different groundwater flow conditions. The system simulation determined $L_{\text{min}}$ of the single closed type BHE to minimize the LCC during 20 years in each area. As a result, the advection effect of groundwater flows decreased the LCC as the Darcy velocity increased more than 10 m/y. The increase was not obvious when the velocity was beyond 200 m/y. However, the groundwater flow effect might be limited in the residence of relatively small loads. Alternatively, $L_{\text{min}}$ and LCC were related mainly to the total load in each area. The area comparison indicated that the household GSHP was economically suitable in the northern area 1 and 2 because of relatively large heating loads. The household GSHP was also potentially suitable in the moderately warm areas 3 to 5 when the initial cost will be reduced by about 20 %, probably in near future. As a next study, the simulation study will be performed for other commercial buildings with much larger heating/cooling loads.

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Nomenclature

$C_{\text{c}}$: modification factor
$\text{COP}$: coefficient of performance
$I_{\text{C}}$: initial cost [yen]
$L_{\text{CC}}$: life cycle cost in 20 years [yen]
$L$: borehole heat exchanger length [m]
$Q$: heating/cooling load [GJ/y]
$T$: temperature [°C]
$O_{\text{C}}$: operation cost [yen]
$q$: heat flux on borehole surface [J/(m²·s)]
$r$: borehole radius [m]
$t$: time [s]
$t_{\text{RCA}}$: target reduction ratio of initial cost for an agreement of LCC between GSHP and ASHP [%]
$U$: Darcy velocity [m/y]
$S_{\text{U}}$: subvention cost [yen]
$\alpha$: thermal diffusivity [m²/s]
$k$: effective thermal conductivity [W/(m·K)]

*: non-dimension

Subscripts

0: conventional system
a: outside air
b: circulation fluid
c: cooling
h: heating
s: soil (conduction only)
sw: soil in groundwater (with advection)
min: required minimum value to remain circulation fluid circulation temperatures over freezing points.

References