THERMAL CHARACTERISTICS OF STEEL FOUNDATION PILES AS GROUND HEAT EXCHANGERS

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ABSTRACT

Thermal characteristics are evaluated in the ground thermal energy system with steel foundation piles. Two kinds of field measurements are conducted in different places in cold regions of Japan. In the first one, the use of a double U-tube results in the equivalent heat extraction per unit length of the ground heat exchangers compared to that in a direct circulating heat exchange even in the case with a steel pile of a large diameter of 400 mm. The average effective heat conductivity of the surrounding soil is also estimated to be 1.5 W/m/K. The other measurements using multiple steel piles demonstrate the heating output enough to cover the whole heating demand in the regions.

Key Words: ***ground source heat pump, steel foundation pile, heat extraction test.***

1 INTRODUCTION

Ground heat exchangers using foundation piles have been considered an effective solution for reduction of the initial cost (Takashi 1962) and several types of them have been applied recently. In particular the use of steel foundation piles as ground heat exchangers has been proposed by Morino et al. (Morino et al. 1994). It provides some advantages compared with the conventional methods as follows:

1. Water can be used as a direct or indirect thermal medium with no risk of water leakage from piles due to the waterproof property of steel
2. Steel foundation piles have more staying power and higher heat conductivity than concrete foundation piles have
3. A steel pile of large diameter allows large contact surface area to the surrounding soil

Furthermore, the rotating press-in steel pile foundation method makes possible drastic cost reduction compared with conventional ones. The method has been approved from 1999 in Japan. Total number of buildings and facilities which adopt this method has been achieved more than 300 by the end of 2002. The number will be increased rapidly in the urban area because of its high-speed installation, the quiet construction and no disposal of waste soil.

Here, ground thermal energy systems using certain boreholes are classified as two types of heat exchange. One is a direct circulating heat exchange and the other one is an indirect heat exchange using a typical U-tube or a double U-tube made of HDPE. The former one is available in the warm-temperature region where ground temperature is higher than 15ºC. The latter one becomes useful in order to prevent freezing problems in the cold region where ground temperature is less than 10ºC. This type has the advantage that it’s free from maintenance of water quality and inside wall scale of a heat exchanger in a heat pump although it causes increase of thermal resistance between a thermal medium and the soil, that is, decrease of extracted heat from the soil compared with that in the former at the same temperature (Hamada et al. 1995).

In this paper, thermal characteristics are evaluated in the ground thermal energy system with steel foundation piles. Two kinds of field measurements are conducted in different places in cold regions of Japan in 2003. Objectives of the first one are to clarify thermal characteristics about heat extraction for different cases in the size of a pile, the type of heat exchange, the flow rate of a heating medium and the set temperature. The average effective thermal conductivity of the surrounding soil is also estimated by using the measurement in comparison with the one derived by a theoretical analysis.

Additionally, multiple piles are buried into the ground at the lattice structure in the other place. Typical single U-tubes inserted in the piles are connected with a heat pump of two horsepower. From this measurement, the interference influence on extracted heat is examined between the piles. The seasonal performance of the heat pump and the availability of the system are discussed.

1 HEAT EXTRACTION TESTS WITH STEEL FOUNDATION PILES

1.1 Experimental Apparatus

Figure 1 shows a schematic diagram of the heat extraction test conducted in *Sapporo*, Japan (43ºN, 141ºE). Four steel piles were buried leaving intervals of 10 m at least each other. They have a length of 40 m and different diameters. Two of them and the rest are 400 mm and 165 mm in diameter. Here, we call them SP1 and SP2, respectively. The system can be changed with three different types of ground heat exchangers shown in **Fig. 1**, that is, Type1 of direct circulating, Type2 and Type3 of indirect heat exchange with single and double U-tubes. The U-tube has ISO Standards of 25A and an outside diameter of 32 mm and is made from the PE100 with a wall thickness of 2.9 mm. Heat extraction tests are carried out so that the supply temperature of the antifreezing solution to the ground heat exchangers can be kept constant by control of a three-way valve in the control equipment. Parallel running of two lines is also possible as is shown in **Fig. 1**. The figure also shows measuring points of temperature. Water temperature in the steel piles is measured by T-type thermocouples at 2.5, 5, 10, 20, 30 and 40 m deep for the SP1 and 4, 16, 28 and 40 m deep for the SP2 near the inner wall and in the center of them. Wall temperature on the U-tube is also observed at 20 m and 16 m deep for the SP1 and SP2. PT100 sensors measure the supply and return temperatures for the ground heat exchangers. We call them $T_{f\text{-}in}$ and $T_{f\text{-}out}$ here.

1.2 Geological Features

Figure 2s show results from geological and groundwater surveys. Strata mainly consist of surface soil, peat, volcanic fine sand, volcano and gravel from the upper part. Groundwater level is probably kept at 2.6 m deep. The velocity of groundwater was estimated by the Point Dilution method between 56.8 and 93.7 m per one year around 34 m deep. Ground temperature T_g is measured in an observation well and is 9.3ºC on average.

1.3 Experimental Conditions

Shown in **Table 1** are experimental conditions. SP1 and SP2 are applied in the conditions beginning with Exp.1- and Exp.2- respectively. Each case is conducted for three types of the ground heat exchangers, Type1, Type2 and Type3 shown in **Fig. 1**. Antifreezing solution is circulated at a temperature $T_{f\text{-}in}$ of -5ºC in the conditions with “L” and 2 ºC in the others.

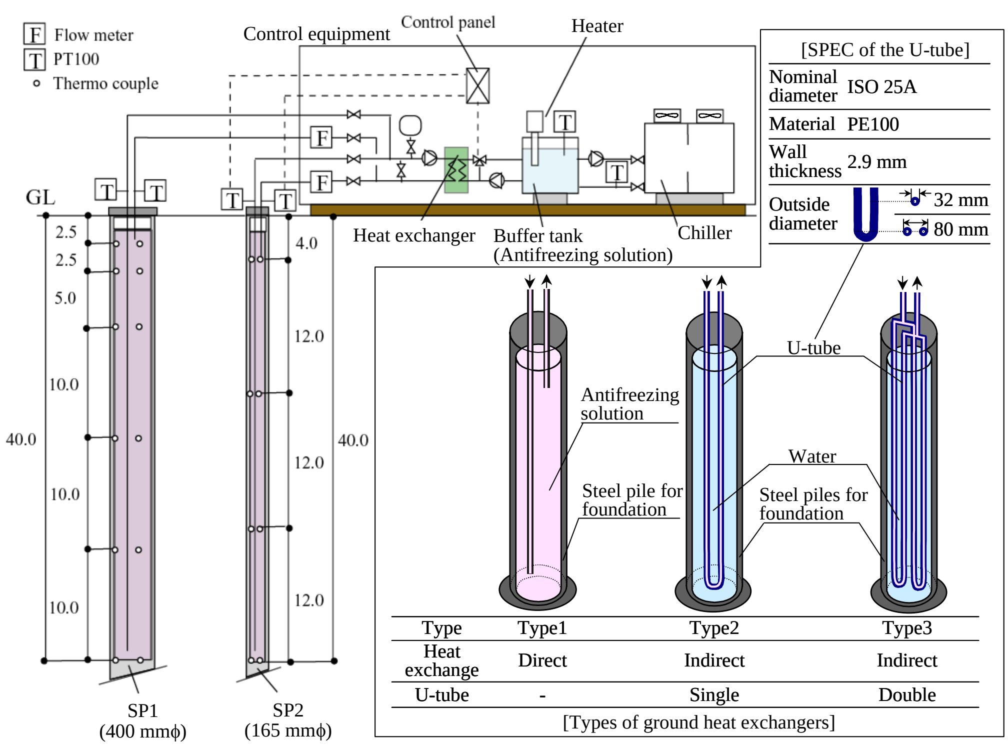
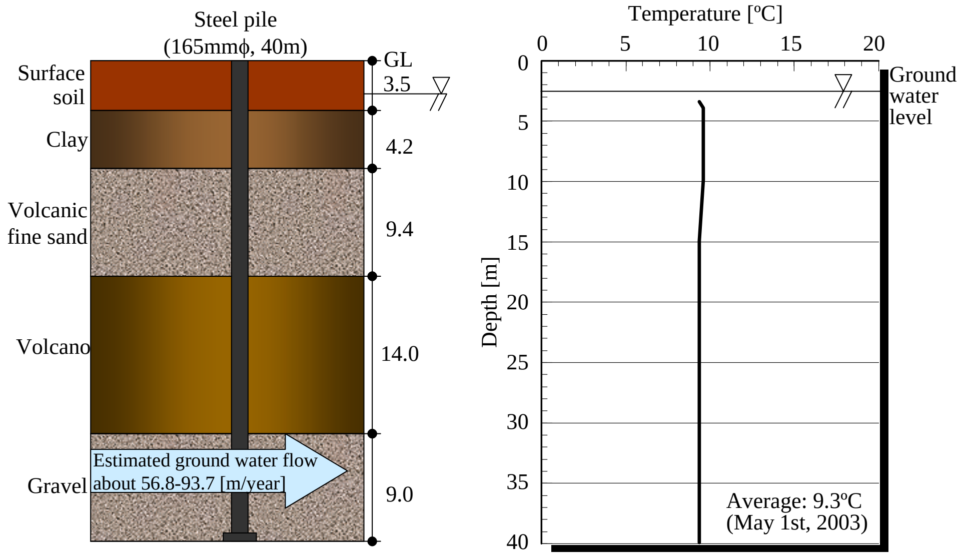


Fig. 1. A schematic diagram of the heat extraction test and description of three types ground heat exchangers



[Strata map] [Vertical temperature profile]

Fig. 2. A strata map and the vertical profile of initial ground temperature

Table 1. Experimental conditions

Exp.No.	Steel pile	Type of the ground heat exchanger	m_f [l/min]	$T_{f\text{-}in}$ [ºC]	Period	
					Start	End
Exp.1-1	SP1	Type 1	5	2	May 30th, 2003	Jan. 13rd, 2003
Exp.1-1L			10 to 30	-5	Aug. 31st, 2003	Oct. 16th, 2003
Exp.1-2		Type 2	10 to 30	2	Apr. 12nd, 2004	Jun. 13rd, 2004
Exp.1-2L			10 to 12	-5	Dec. 1st, 2003	Dec. 18th, 2003
Exp.1-3		Type 3	10 to 30	2	Jal. 29th, 2004	Sep. 30th, 2004
Exp.2-1	SP2	Type 1	10 to 30	2	Jan. 24th, 2004	Mar. 7th, 2004
Exp.2-1L			10 to 30	-5	Aug. 31st, 2003	Oct. 16th, 2003
Exp.2-2		Type 2	10 to 30	2	Apr. 12nd, 2004	Jun. 13rd, 2004
Exp.2-2L			6 to 10	-5	Dec. 1st, 2003	Dec. 18th, 2003
Exp.2-3		Type 3	10 to 30	2	Jal. 29th, 2004	Sep. 30th, 2004

1.4 Experimental Results and Discussion

Figure 3s indicate temperature changes of $T_{f\text{-}in}$ and $T_{f\text{-}out}$ measured in a certain pile in each condition. As seen from the variations of $T_{f\text{-}in}$, it remains almost constant at 2ºC or -5ºC during the measurements in all conditions. $T_{f\text{-}out}$ falls with time at the beginning and remains stable after 240 h (10 days) even in the conditions of Exp.1-1L, Exp.1-2L, Exp.2-1L and Exp.2-2L, which have larger temperature differences than the others.

Extracted heats per unit length of the ground heat exchangers q_{ext} are calculated by Equation(1) and shown in **Figure 4**s. **Table 2** indicates values of $\overline{q_{ext-1}}$ and $\overline{q_{ext-2}}$, which are average q_{ext} from 0 h to 240 h and from 240 h to the end respectively. The table also reveals average temperatures of $\overline{T_f}$ taken between $T_{f\text{-}in}$ and $T_{f\text{-}out}$ in the range from 240 h to the end.

$$q_{ext} = c_{pf}\,\rho_f\, m_f\,(T_{f-in} - T_{f-out})/\,l_{sp} \quad \text{[W/m](1)},$$

where c_{pf}, ρ_f, m_f and T_f are the specific heat, the density, the flow rate and the temperature of the fluid in the steel pile, respectively, and l_{sp} is the length of the steel pile.

The variations of q_{ext} are also in stable situations after 240 h and are considered at quasi-steady state. Extracted heats from Exp.1- conditions, which were conducted with larger diameter steel piles, show the larger changes during the measurement than those in Exp.2- conditions in comparison between the same types of the ground heat exchangers. Here, the ratio of $\overline{q_{ext-2}}$ in the Type1 conditions of direct circulating to that in the Type2 conditions with a single U-tube is 0.83 in Exp.1 and 0.96 in Exp.2. The results mean that the case with a single U-tube can provide nearly equal $\overline{q_{ext-2}}$ to the direct circulating one under the conditions with the SP2 which has a smaller diameter of 165 mm. Similarly the ratio of $\overline{q_{ext-2}}$ in Type1 to that in Type3 is 0.98 and 1.27 in Exp.1 and Exp.2 respectively. This indicates that the use of a double U-tube makes possible to obtain an equivalent heat

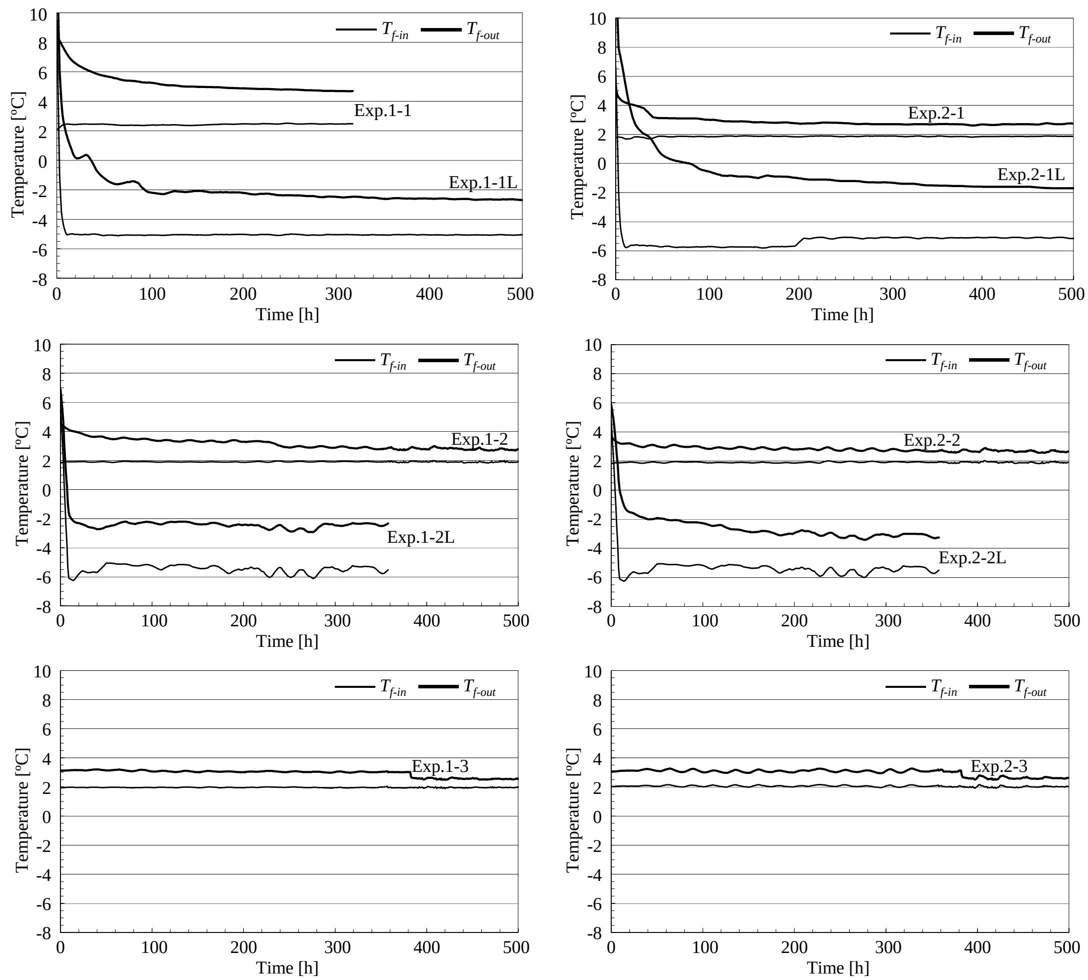


Fig. 3. Temperature changes of $T_{f\text{-}in}$ and $T_{f\text{-}out}$ with time

extraction to direct circulating even in the condition using the SP1 with a larger diameter of 400 mm. In the case of SP2, the rate stands at over 1.0, that is, $\overline{q_{ext-2}}$ in Exp.2-3 exceeds the one in Exp.2-1. This seems to be due to enhancement of heat transfer at turbulent flow in the U-tube in Exp.2-3. The result also reproduces the one calculated by the authors that turbulent flow in a U-tube provides increase of extracted heat. The Reynolds number *Re* can be estimated around 2100 in flow rates of 10 l/min and 5 l/min for the whole system and each U-tube, respectively, and a viscosity of 2 mPa in Exp.2-3. Therefore, the system can probably allow turbulent flow in the pile with *Re* numbers in the transition state or more unless viscosity is much dependent on temperature change.

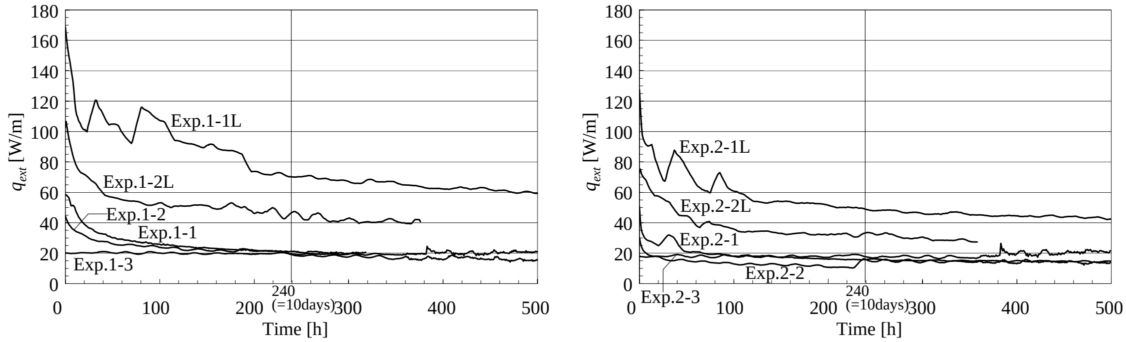


Fig. 4. Variations of extracted heat q_{ext} with time

Table 2. Average values of q_{ext} and T_f in each condition

Exp.No.	$\overline{q_{ext-1}}$ [W/K]	$\overline{q_{ext-2}}$ [W/K]	$\overline{T_f}$ [ºC]	K_{ext} [W/m/K]
Exp.1-1	27.2	20.4	3.6	3.5
Exp.1-1L	94.9	64.6	-3.8	4.9
Exp.1-2	24.3	17.0	2.4	2.4
Exp.1-2L	54.7	41.9	-4.0	3.1
Exp.1-3	19.9	19.9	2.4	2.8
Exp.2-1	19.8	14.9	2.3	2.1
Exp.2-1L	61.6	45.2	-3.3	3.5
Exp.2-2	13.7	14.3	2.3	2.0
Exp.2-2L	38.9	29.9	-4.3	2.2
Exp.2-3	17.9	18.9	2.4	2.7

In this paper, the heat extraction rate K_{ext} is defined as the following equation and also shown in **Table 2**.

$$K_{ext} = \overline{q_{ext-2}} / \Delta T_{g-f} \qquad \text{[W/m/K]} \qquad (2),$$

where ΔT_{g-f} is the temperature difference between the natural ground temperature T_g and $\overline{T_f}$.

Exp.1-1L, Exp.1-2L, Exp.2-1L and Exp.2-2L, which have a lower $T_{f\text{-}in}$ of –5ºC, show higher K_{ext} than Exp.1-1, Exp.1-2, Exp.2-1 and Exp.2-2 in comparison between the same diameters of the ground heat exchangers and types of heat exchange. In particular, Exp.1-1L and Exp.2-1L show 1.4 to 1.7 times higher K_{ext} than Exp.1-1 and Exp.2-1 in the direct circulating heat exchange. This is probably due to an effect of latent heat release through freeze of surrounding soil or filled water in the steel pile at 0ºC. However, it should be noted that excessive freezing might cause damage of a U-tube or a steel pile.

1.5 Calculation of Effective Thermal Conductivity

1.5.1 Evaluation method

Underground effective thermal conductivity λ_e is evaluated by using a cylindrical heat source theory (Carlslaw and Jaeger 1959). Calculation is carried out in a design and performance prediction tool for ground thermal energy systems which the authors have been reported in a previous paper (Nagano et al. 2003). $T_{f\text{-}out}$ is calculated by using measured $T_{f\text{-}in}$ and compared with the measurement. λ_e is finally given when the calculated $T_{f\text{-}out}$ is agreed with the measurement. This time, the measurement of Exp.2-1 is used by following reasons.

* A direct heat exchange condition, where overall thermal resistance is easy to calculate
* Higher flow rate
* $T_{f\text{-}in}$ condition over 0ºC not to freeze

Besides it, T_g of 9.3ºC and the thermal capacity of 3000 kJ/m^3 are given in the calculation.

1.5.2 Results and discussion

In **Fig. 5**, the variations of $T_{f\text{-}out}$ from calculation and measurement are compared. The tendency of calculation fits the experimental result at quasi-steady. Of the three kind of λ_e, the variation with 1.5 W/m/K best matches the measurement. Here, one reason why they have disagreement especially before 50 h may be due to the influence of heat capacity of water in the pile.

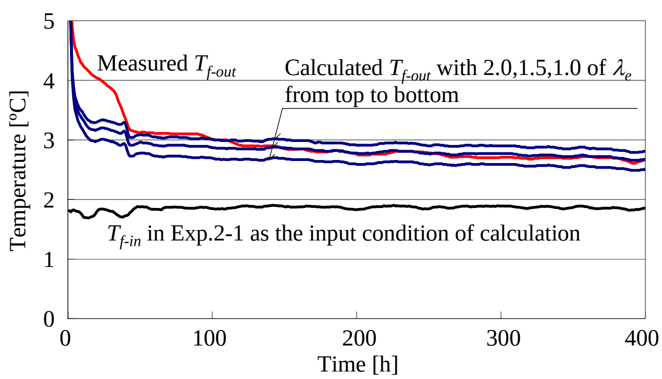


Fig. 5. Comparison of $T_{f\text{-}out}$ between the measurement and calculations

2 FIELD TESTS OF HEAT EXTRACTION WITH MULTIPLE STEEL PILES

2.1 System Description

Another experimental facility with steel foundation piles was constructed in 2003 in *Hanamaki*, Japan (39ºN, 141ºE). **Figure 6** indicates a plan of the system. Twenty five steel piles of 8 m long with a small diameter of 145 mm were installed into the ground with rotating power with the lattice structure at intervals of 1.8 m. Single U-tubes were put in the pile as heat exchangers and connected to a two horsepower heat pump for domestic use. Heat extraction tests were conducted by giving the simulated heating load to the heat pump by a radiator installed in the secondary side. Water temperatures in piles and ground temperatures were measured by T-type thermocouples at points shown in the figure. Pt-100 sensors measure inlet and outlet temperatures of $T_{f1\text{-}in}$ and $T_{f1\text{-}out}$ at the primary side of the heat pump and ones of $T_{f2\text{-}in}$ and $T_{f2\text{-}out}$ at the secondary side of it. The flow rate in each line was controlled around 6 l/min and measured by an electromagnetic flow meter.

2.2 Experimental Results and Discussion

2.2.1 Temperature variations

Figure 7 compares the variations of ground temperatures in different depth vertically at the Point9 of **Fig. 6**. At 4 m deep, the temperature shows the lowest one at the end of the measurement in May 8th, 1.3ºC, by heat extraction in the ground heat exchanger during the test. On the other hand, the temperature at 8 m in depth shows the smallest decrease because of the thermal capacity of the soil downside and is kept at 6.8ºC in May 8th. The tendency of the one at 0.5 m deep is different from the others. The temperature is affected by the temperature change near the ground surface and increased to 8.0ºC by May 8th in spite of the heat extraction test.

Shown in **Fig. 8** are the variations of ground temperatures at all measured points in the horizontal direction at 6 m deep. Temperature changes were, in order of descending prevalence, Points of 8, 1, 5,

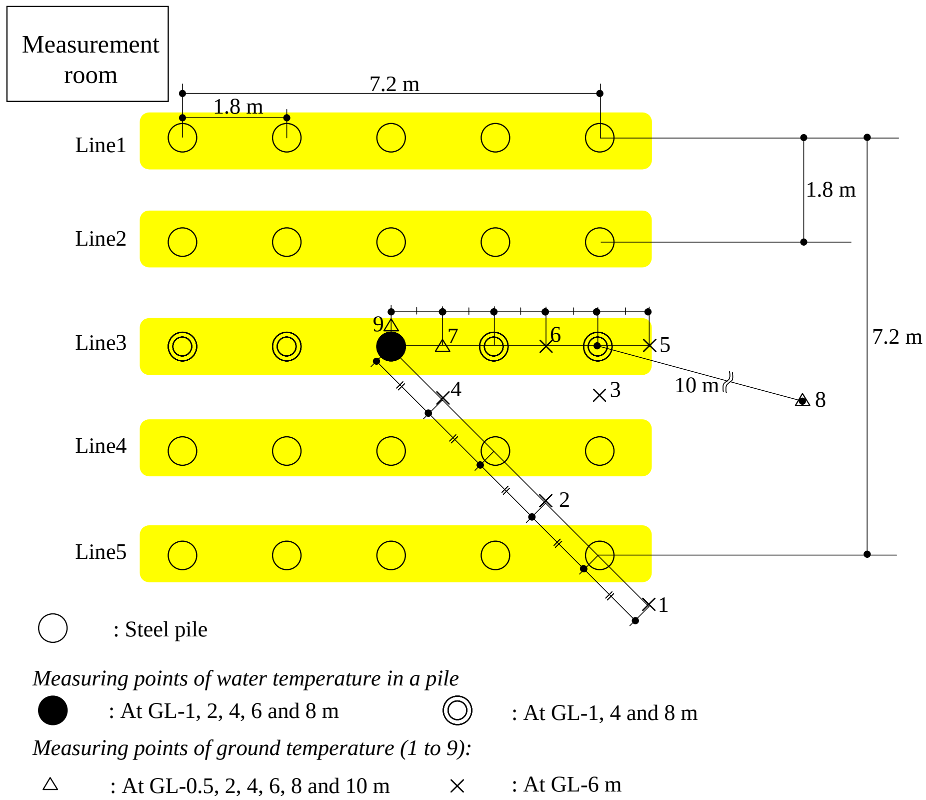


Figure 6. A plan of the experimental equipment with twenty five steel piles in *Hanamaki*

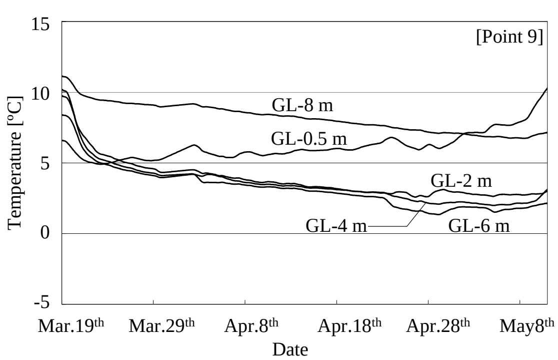


Figure 7. Comparison of ground temperatures in the vertical direction at Point9

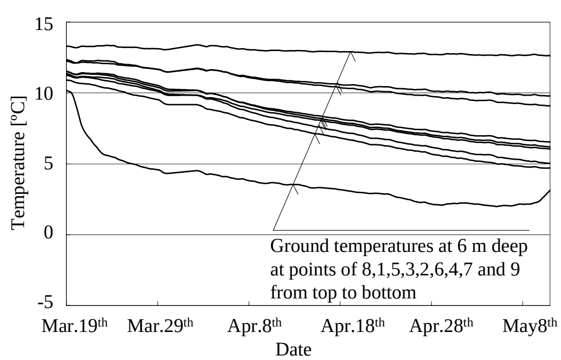


Figure 8. Comparison of ground temperatures at 6 m deep in the horizontal direction

3, 2, 6, 4, 7 and 9. Temperature falls most at Point 9 since the sensor is touched with the external surface of the steel pile. On the other hand, Point 8, which is far from the steel piles, shows almost constant temperature of 13ºC and is little affected by heat extraction. Analysis of these data shows that the influence of heat extraction depends on the number of surrounding piles and the intervals.

Point 5 and Point 7 have different physical relationships between right and left piles. The former is positioned on the right side of a pile and the latter is within two piles. The temperature decrease during the test is 8.3K at Point 7, which is almost double of that at Point 5. This suggests that the superposition principle can be applied for the field of ground temperature.

2.2.2 Comparison of extracted heat

Figure 9 demonstrates the integrating extracted heat Q_{ext} for each Line, which is calculated by Equation (3).

$$Q_{ext} = \sum_{t} q_{ext} l_{sp} \Delta t \qquad [\mathrm{J}] \qquad (3)$$

Higher values of Q_{ext} are obtained at Line 1 and Line 5 since they are less affected by the surroundings than the others are. In comparison with Line2, Line3 provides 0.5 GJ larger Q_{ext} of 3.4 GJ although it should have smaller one considering the position. This seems to be due to the difference of flow course between them. The flow in Line 2 is in parallel and the flow rate in each line is nearly one fifth of the total, 1.1 l/min. In this case, the *Re* number can be calculated as 480 by using a viscosity of 2 mPa, where the flow is considered as laminar flow. On the other hand, the flow in Line 3 can be kept as turbulent one with a *Re* number of 2400, where the line is connected in series. Consequently, it should be emphasized that a flow rate of 5 l/min is necessary at least for each pile in order to keep turbulent flow in the pipe and obtain larger extracted heat in ground thermal energy systems using multiple steel piles.

2.2.3 Possibility for the long term operation

Finally, shown in **Fig. 10** are the variations of heating output from the heat pump and extracted heat from all the piles. The figure also indicates temperatures of $T_{f1\text{-}in}$ and $T_{f2\text{-}out}$ during the measurement. The heating output and the extracted heat both remain stable at 6.5kW and 4.8kW before March 29th and at 6.0 kW and 4.0 kW after that, respectively. The changes around March 29th are because of the one of set temperature $T_{f2\text{-}out}$ from 30ºC to 40ºC. Integrating heating output throughout the first season's operation is finally 26.6 GJ, which is enough to cover the whole heating load in northern cold regions of Japan.

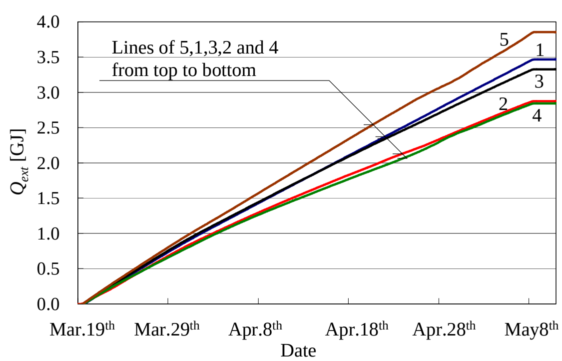


Fig. 9. Integrating extracted heat Q_{ext} for each line

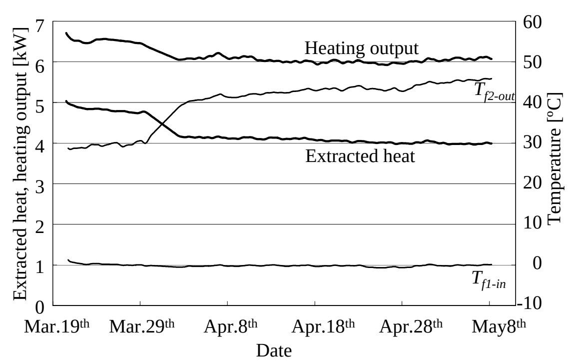


Fig. 10. Extracted heat, heating output and temperatures of $T_{f1\text{-}in}$ and $T_{f2\text{-}out}$ obtained from the first season's operation

3 CONCLUSIONS

1. Heat extraction tests are carried out with steel foundation piles in such a way that the inlet fluid temperature keeps constant. The variations of heat extraction per unit length of the ground heat exchangers q_{ext} are in stable situations after ten days. The use of a double U-tube makes possible to obtain an equivalent heat extraction to direct circulating heat exchange even in the condition using a steel pile with a large diameter of 400 mm in the situation.

2. The effective heat conductivity of the surrounding soil is evaluated as 1.5 W/m/K in comparison calculated temperature variations returned from the ground heat exchanger with a measured one.

3. Another field measurements are conducted with twenty five steel foundation piles of 8 m long. The heating operations with a heat pump throughout the first season indicate the heating output of 26.6 GJ enough to cover the whole heating demand in northern cold regions of Japan.

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