

DEVELOPMENT OF A GROUND SOURCE HEAT PUMP SYSTEM WITH GROUND HEAT EXCHANGER UTILIZING THE CAST-IN-PLACE CONCRETE PILE FOUNDATIONS OF A BUILDING

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Summary

Ground-source (Geothermal) heat pump (GSHP) systems can achieve a higher coefficient of performance than conventional air-source heat pump (ASHP) systems. However, GSHP systems are not widespread in Japan because of their expensive boring costs. The authors have developed a GSHP system that employs the cast-in-place concrete pile foundations of a building as heat exchangers in order to reduce the initial boring cost. In this system, eight U-tubes are arranged around the surface of a cast-in-place concrete pile foundation.

The heat exchange capability of this system, subterranean temperature changes and heat pump performance were investigated in a full-scale experiment. As a result, the average values for heat rejection were 186~201 W/m (per pile, 25 W/m per pair of tubes) while cooling. The average COP of this system was 4.89 while cooling; rendering this system about 1.7 times more effective in energy saving terms than the more typical ASHP systems. The initial cost of construction per unit for heat extraction and rejection is ¥79/W (approx. US\$0.79/W) for this system, whereas it is ¥300/W (US\$3/W) for existing standard borehole systems. Therefore, this system is expected to be commercially viable.

1. Introduction

Ground-source heat pump (GSHP) systems can achieve a higher coefficient of performance than conventional air-source heat pump (ASHP) systems because the ground, which functions as the heat source or sink, is at a higher temperature in winter and lower in summer than the air temperature. In addition, there will likely be some mitigation against the effects of the heat island phenomena, as this system does not emit exhaust heat into the atmosphere during air conditioning. However, GSHP systems are not popular except as experimental versions in Japan. This is primarily due to the high cost of boring to run piping underground. For example, such boring costs average about ¥3,000/m (approx. US\$30/m) in the USA, whereas the same work is about ¥10,000/m (US\$100/m) in Japan.

Thus, even if the heat pump performance in GSHP systems is more effective than that of the more common ASHP systems, the GSHP systems are unable to recoup the initial piping costs within their lifecycles. The authors have developed a GSHP system that employs the foundation piles of buildings as the heat exchangers in order to reduce the initial boring cost. In this research, a full-scale experiment was conducted. The heat exchange capability of this system, the subterranean temperature changes and performance of the heat pump were investigated. Furthermore, the construction costs of this system were also examined.

2. System Outline

In this system, some U-tubes are arranged around the surface of cast-in-place concrete pile foundations as shown in Fig. 1. The U-tubes are normally made of high-grade polyethylene or crosslinked polyethylene. These U-tubes are usually 3/4 or 1 inch (27 or 34 mm) in diameter. The usual diameters of cast-in-place concrete pile foundations are from 1500 to 4000 mm. Thus, this arrangement is expected to offer superior heat exchange performance. The U-tubes are installed against the reinforcing bars used in the cast-in-place concrete pile foundations, so the strength of the foundation pile is ensured.

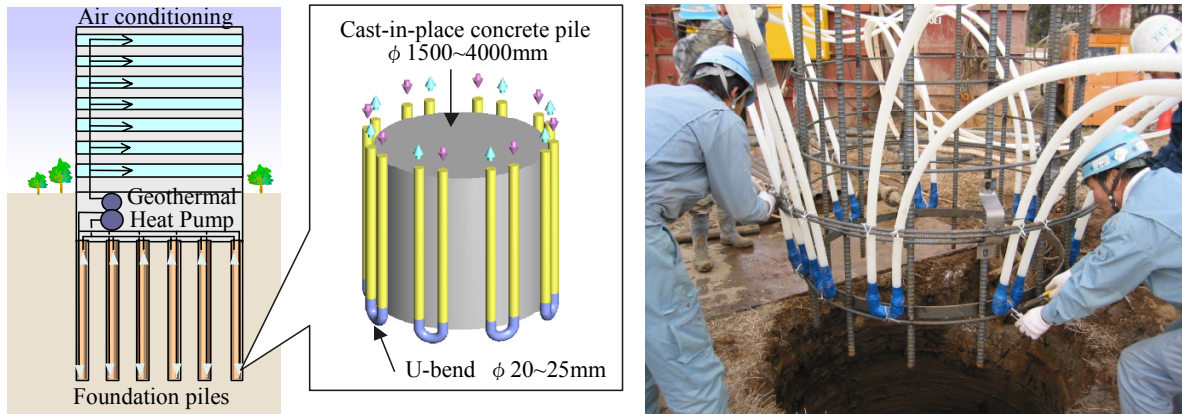


Figure 1 Outline of the heat exchange system using cast-in-place concrete piles

3. Full-Scale Experiment

3.1 Experimental Equipment Outline

3.1.1 Underground heat exchanger

An experimental institution was built on-site at the University of Tokyo in Chiba. Chiba is east of Tokyo, and the average annual air temperature is about 15.4°C, with the average air temperature in August being about 26.4°C and in January about 5.4°C. Accordingly, both heating and cooling functions are necessary. A plan of the experimental institution and the system configuration is shown in Fig. 2.

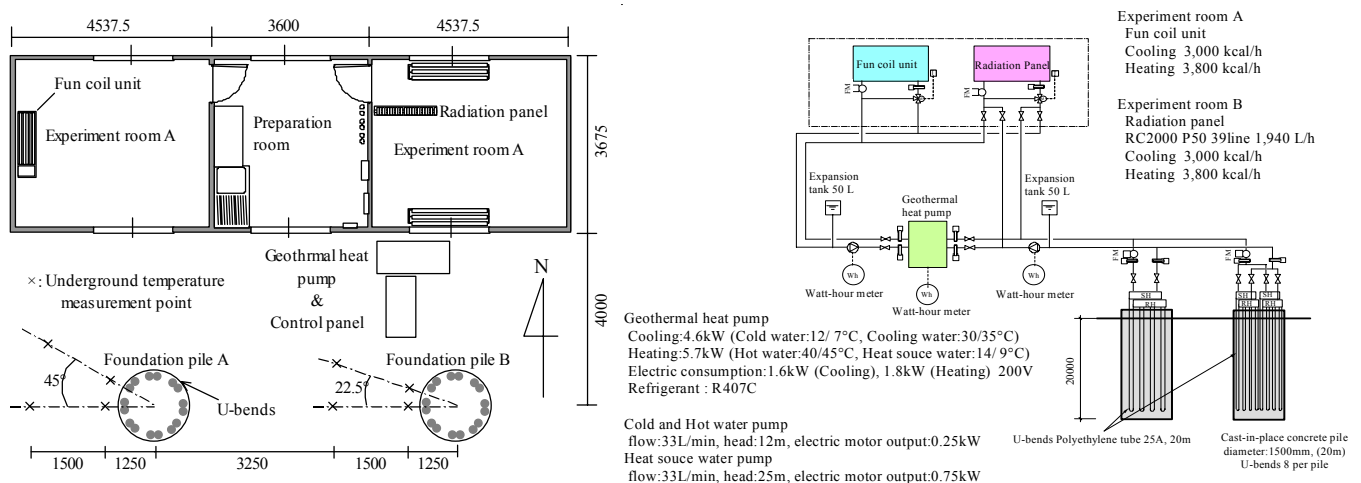


Figure 2 Plan of the experimental institution and system configuration

There were two cast-in-place concrete piles (both 1,500 mm in diameter, 20 m tall) around which 8 U-tubes (External diameter: 34.0 mm; internal diameter: 28.8 mm) were installed. It is possible to control the number of U-tubes in operation by opening and closing their valves.

3.1.2 Heat pump

The system employed in this experimental equipment consists of a water-to-water heat pump with a reciprocating compressor (4.6 kW cooling, 5.7 kW heating). Cold and hot water circulates through a fan coil unit and a radiation panel in two examination rooms respectively, as shown in Figure 2. The flow of cold and hot water is 27 l/min (0.00045 m³/s). The flow of the heat source (sink) water is 33 l/min (0.00055 m³/s).

3.1.3 Indoor air-conditioning system

This system has two rooms. One has a fan coil unit installed. The other has a radiation air conditioner. Thermostat and electrical valves control the amount of water supplied to the fan coil unit.

3.2 Experiment Outline

The heat pump in this system was operated from 9:00 to 18:00, Monday to Friday as in typical office buildings. It was not operated on Saturday or Sunday. In summer (from June to September), heat was discharged (sunk) into the ground. Conversely, in winter (from December to March), heat was extracted (sourced) from the ground. A list of the measurement items is shown in Table 1.

Table 1 The Measurement Items

Measured Item	Measuring equipment	Measurement point
Subterranean temperature	T-type thermo couples	Depth: 1m, 10m, 19m
U-bend surface temperature	T-type thermo couples	Depth: 1m, 10m, 19m
Heat source/sink water temperature	Platinum measurement resistor	In the pipe
Cold and hot water temperature	Platinum measurement resistor	In the pipe
Water flow	Flow meter	In the pipe
Electrical power used	Electric power meter	Power panel
Outside temperature, relative humidity, wind velocity, wind direction, quantity of solar radiation, rainfall		

4. Cooling and Heating Results in 2003

4.1 Underground Temperature

Fig. 3 shows the variations in the underground temperature at measuring points A and B and air temperature in 2003. The subterranean temperature was about 20°C one meter below ground level (G.L. -1m), about 19°C at G.L. -10m and about 17°C at G.L. -19m in both measuring points A and B as shown in Fig. 6 at the start of the air-conditioning operation (7/16). The subterranean temperature at each point gradually rose thereafter. The subterranean temperature at G.L. -1m had reached about 25°C by the time the air-conditioning operation ended. The subterranean temperature at G.L. -1m was significantly influenced by the ambient air temperature. However, subterranean temperatures only changed a few degrees at G.L. -10m and G.L. -19m throughout the year. At the start of the heating operation (12/25), the subterranean temperature at G.L. -10m was about 19°C, while that at G.L. -19m was about 17°C. The subterranean temperatures at each point fell gradually after the start of this operation. The subterranean temperatures at G.L. -10m and G.L. -19m stabilized at about 15°C during the heating operation in February and remained nearly constant until the operation ended (3/28).

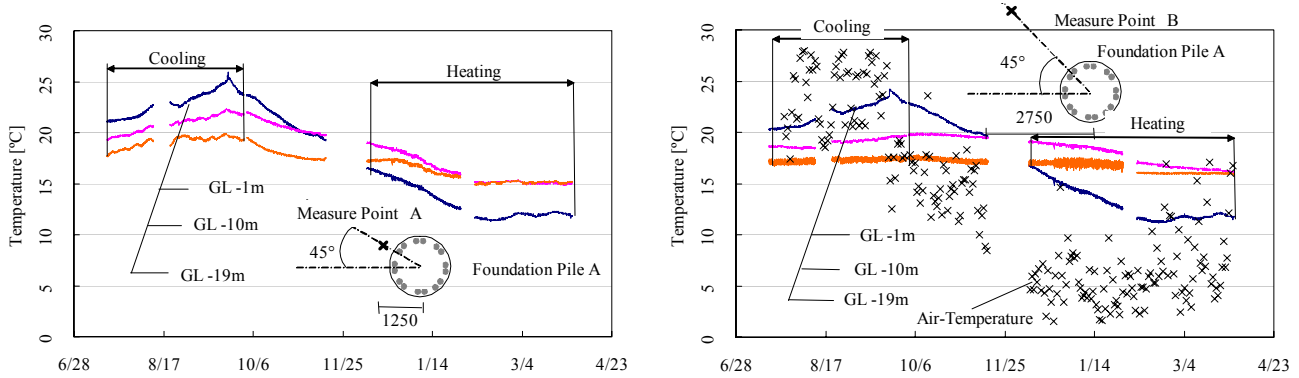


Figure 3 Underground and air temperature variations (left: point A, right: point B)

4.2 Heat Source/Sink Water Temperature

The air temperature and heat source/sink water temperatures for cooling and heating are shown in Fig. 4. The heat sink water temperature at the start of the cooling operation was about 20°C, rose gradually after that and reached about 29°C just before the end of the cooling period. The average temperature of the heat sink water and air during the cooling period were about 24.5°C and 29.2°C respectively. The heat sink water temperature was about 4.7°C on average – and about 12.3°C at the maximum – lower than the air-temperature. On the other hand, the heat source water temperature at the beginning of heating was about 17°C and fell gradually after the start of the operation and remained at about 13°C from early January until the end of March. The average air temperature during the heating period was about 9.9°C, while the minimum was about 1.1°C. The average temperature for the heat source water was about 3.1°C, while the maximum was about 11.9°C, higher than the air temperature. Thus, using the ground water as a heat source or sink was more effective than using ambient air. Accordingly, GSHP is expected to be more effective than ASHP both in terms of cooling and heating.

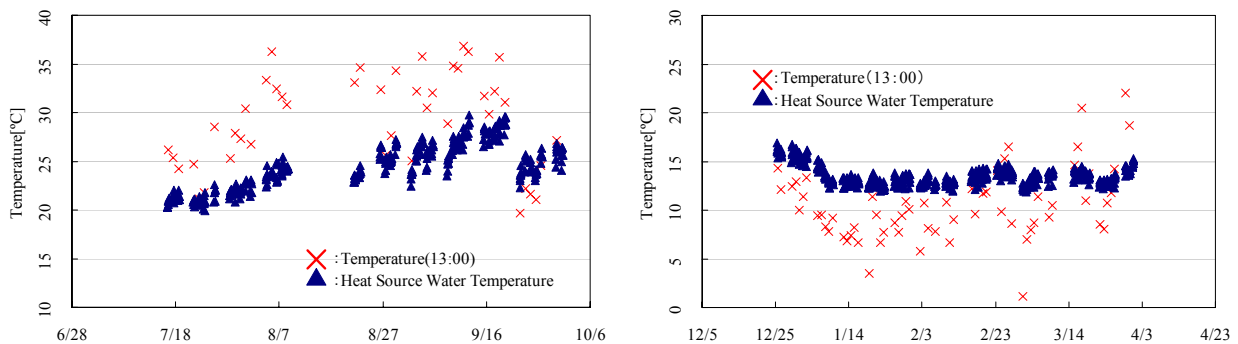


Figure 4 Heat sink/source water temperatures (left: cooling (sink), right: heating (source))

4.3 Heat Extraction/Rejection From/Into The Ground

The averages for the heat extraction and rejection either from or into the ground of the foundation piles A and B at the outset of the cooling and heating periods is shown in Fig. 5. The maximum values for heat rejection were 158 W/m (pile A) and 164 W/m (pile B) respectively, while the average values for heat rejection were 100 W/m (pile A) and 120 W/m (pile B) respectively while cooling. The heat rejection per paired U-tube was about 12.5~15 W/m during the cooling period. The maximum values for heat extraction were 119 W/m (pile A) and 124 W/m (pile B) respectively, while the average values were 44 W/m (pile A) and 52 W/m (pile B) respectively while heating. Heat extraction per paired U-tube was about 6~7 W/m during the heating period.

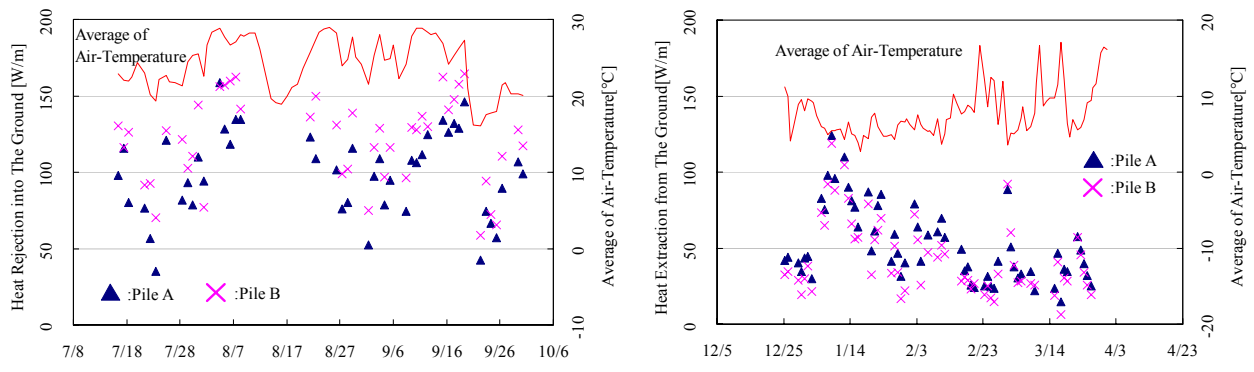


Figure 5 Heat extraction/rejection from/into the ground (left: cooling (sink), right: heating (source))

4.4 Coefficient Of Performance

The coefficient of performance (COP) for this system, the heat sink/source water temperature and air-conditioning load while cooling and heating are shown in Fig. 6. The maximum COP was 6.4, while the average was 3.7 while cooling. When the air-conditioning load was high or the heat sink water temperature was low in August, the COP recorded high values. The maximum COP was 5.0 while the average was 3.2 while heating. When the air-conditioning load was high or the heat source water temperature was high in January, the COP recorded high values.

Although, the authors had expected that the average heat extraction/rejection values would reach 160 W/m per pile (i.e. 20 W/m per U-tube), the actual value was much less than expected. It is thought that this was due to the low air-conditioning load on this system; therefore an additional load was installed, and the cooling experiment was repeated in 2004. These results will be described in Section 4.

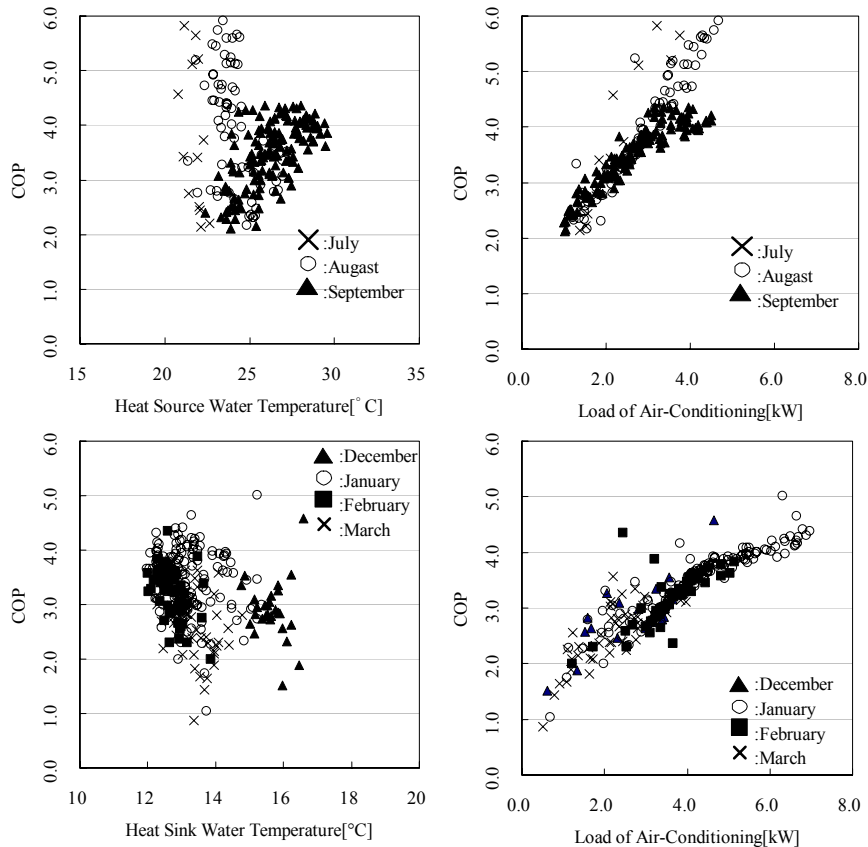


Figure 6 Coefficient of performance (top: cooling, bottom: heating)

5. Cooling Results in 2004

The cooling results in 2004 are shown in Figs. 7~9. The maximum values for heat rejection were 259 W/m (pile A) and 278 W/m (pile B) respectively, while the average values were 204 W/m (pile A) and 220 W/m (pile B) respectively from 6/16 to 8/21. The average values for heat rejection were 186 W/m (pile A) and 201 W/m (pile B) while cooling. This attained the author's expectations (160 W/m per pile). Here, the COP for ASHP was calculated from the air temperature measured at the experimental site and the performance curve of a typical ASHP. The COPs for this system (GSHP) and ASHP are shown in Fig. 10. The average COPs for this system and ASHPs were 4.89 and 2.90 while cooling respectively. Thus, this system is about 1.7 times more efficient than the more common ASHP systems.

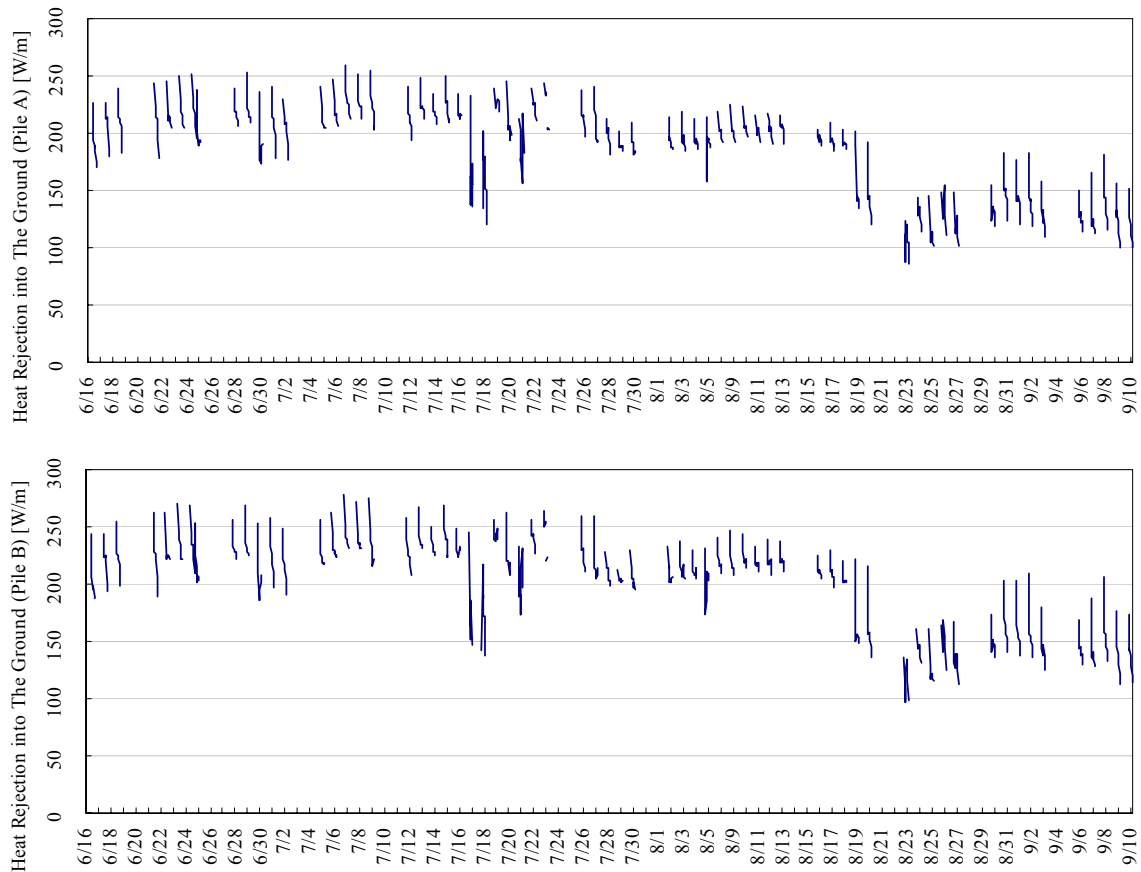


Figure 7 Heat rejection into the ground in 2004

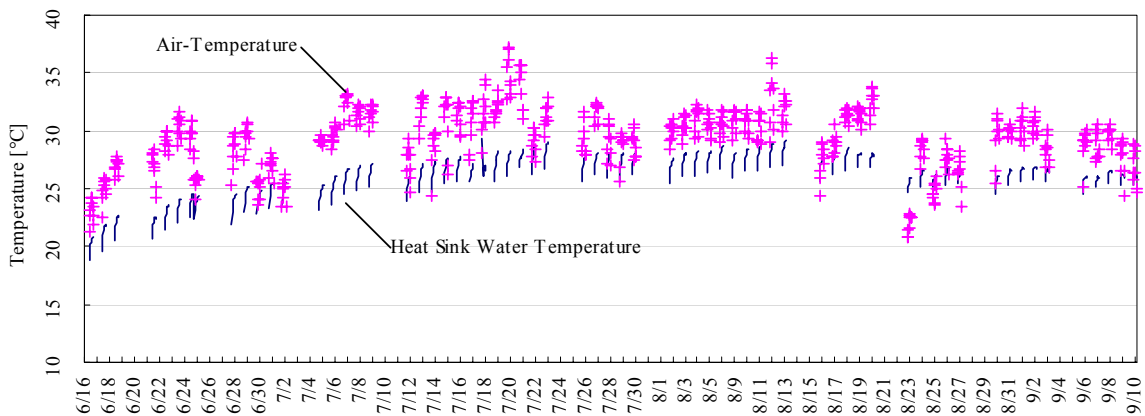


Figure 8 Air temperature and heat sink water temperature in 2004

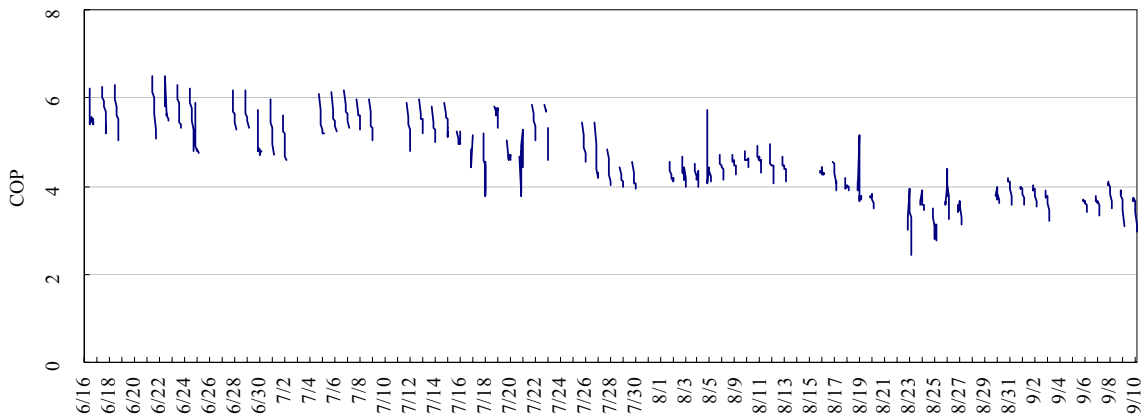


Figure 9 COP change for cooling in 2004

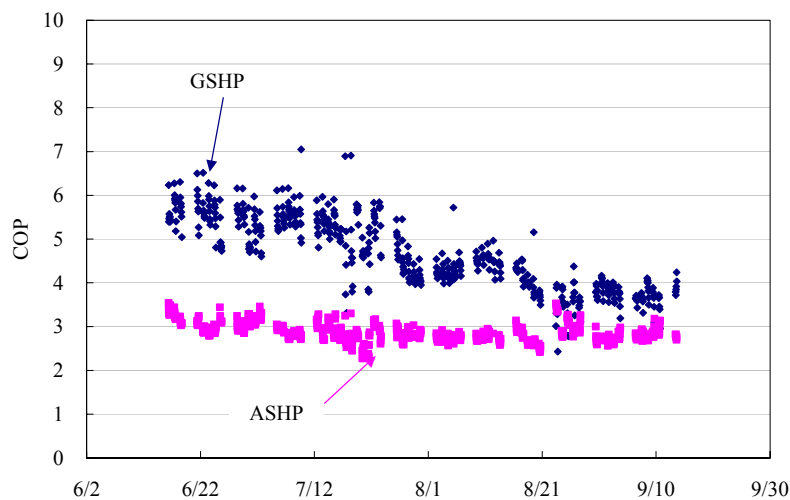


Figure10 Units COP

6. Examination of Construction Cost

A comparison of the construction cost between the usual borehole system and our proposed system is shown in Table 2. Here, a single U-tube is assumed to be used in the usual borehole system. The heat extraction and rejection per unit length of a single U-tube is assumed to be 40 W/m. The boring cost is ordinarily ¥10,000/m (approx. US\$100/m) in Japan. The heat extraction and rejection capabilities of the proposed system are based on the cooling experiment performed in 2004. The construction cost for the proposed system is based on an example introduced in an actual building. The cost of construction per heat extraction and rejection unit of the proposed system is 75 percent cheaper than that of a borehole system. Accordingly, the proposed system is expected to pay for itself within ten years.

Table 2 Comparison of Cost

Form of heat exchange	Borehole type	Proposed system (Cast-in-place concrete pile type)
	(Single U-tube)	(8 pairs of U-tubes)
Heat extraction and rejection per unit of heat exchange [W/m]	40	200
Boring costs [¥/m]	10,000	-
Piping costs [¥/m]	2,000	7,100
Additional labor costs for foundation & piling work [¥/m]	-	8,700
Total cost [¥/m]	12,000	15,800
Total cost per extraction and rejection heat unit [¥/W]	300	79

7. Conclusions

- (1) The authors have developed a GSHP system using the cast-in-place concrete pile foundations of a building as heat exchangers in order to reduce the initial boring cost.
- (2) In this system, eight U-tubes are arranged around the outer surface of cast-in-place concrete pile foundations.
- (3) The heat exchange capability of this system, the subterranean temperature change and performance of the heat pump were investigated in a full-scale experiment.
- (4) The average values for heat rejection were 186~201 W/m (per pile, 25 W/m per pair of tubes) while cooling.
- (5) The average COP for this system was 4.89 while cooling, so this system is about 1.7 times more efficient than the more common ASHP system.
- (6) The initial cost of construction per heat extraction and rejection unit is ¥79/W (approx. US\$0.79/W) for this system, whereas it is ¥300/W (US\$3/W) for the standard borehole system.
- (7) This system is expected to be commercially viable.

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