DEVELOPMENT AND ANALYSIS OF SEASONAL UNDERGROUND THERMAL-STORAGE HVAC SYSTEM USING NATURAL ENERGY AND PILE FOUNDATION

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Abstract: The system described in this paper stores natural energy collected at low temperatures during winter in the ground under a building, and it uses this energy for air-conditioning in summer. This is an innovative seasonal thermal-storage system that is cost-effective because the necessity for additional piping work for the heat exchange is avoided by embedding the pipes in the structural pile foundations. An HVAC system simulation tool was developed to analyze the performance of the system, and the results were verified using the measured data. Then, the conditions of optimal operation were investigated and applied to the real system every year. As a result, the system coefficient of performance (COP) was improved, reaching 7.14 in the third year of operation, as compared to 3.61 at the beginning.

Key Words: Natural energy, Underground thermal storage, Using pile foundation, Optimization, Performance verification

1 INTRODUCTION

The "soil thermal-storage natural-energy air-conditioning system using the pile foundation" is a new air-conditioning system that uses the soil under the building as a thermal-storage medium. It saves the energy from the cold of winter, and uses it in cold water for air-conditioning in summer. Because this is a technology that uses the climate peculiar to Japan (i.e., a climate with four clear seasons), it seems that it could contribute greatly as a new thermal-storage technology in the future, although examples of practical domestic use are still scarce.

Moreover, this technology has an advantage over other technologies: its effect can be observed in the daytime in summer, when energy conservation is most required and technologies using natural energy sources are most desirable.

2 FEATURES OF SYSTEM

2.1 Natural energy use

This system uses natural energy (Figure 1); it takes cold energy from the low-temperature air in winter, stores it in the soil, and uses this cold energy in summer for air-conditioning. The cooling systems using air from outside and the natural ventilation are natural-energy technologies. Their effect is demonstrated by using the energy from the cold winter to reduce the daily peak energy consumption for air-conditioning in summer.

2.2 Soil thermal-storage technique

This soil thermal-storage system uses about 10,000 m^3 of soil. The moisture transport occurs within the cut-off wall; this was necessary in the underground construction of the heat-storage tank for the time between seasons. With the circulation of water in the piping laid underground in the building pile and the adoption of an exchange system, it was unnecessary to dig a new foundation for a heat-exchanger installation.

2.3 Architectural outline

Architectural name: YONDEN building

Address	:	KAGAWA Pref., JAPAN
Lot area	:	8074.78 m^2
Building area	:	2438.07 m^2
Total floor area	:	13,922.72 m^2
Structure	:	Steel frame
Number of stories	:	7 floors(above the ground)
		1 floor (underground)
Height of building	:	Ground level (GL)+32.15m
Typical application	:	Office



Graphic 1: YONDEN building

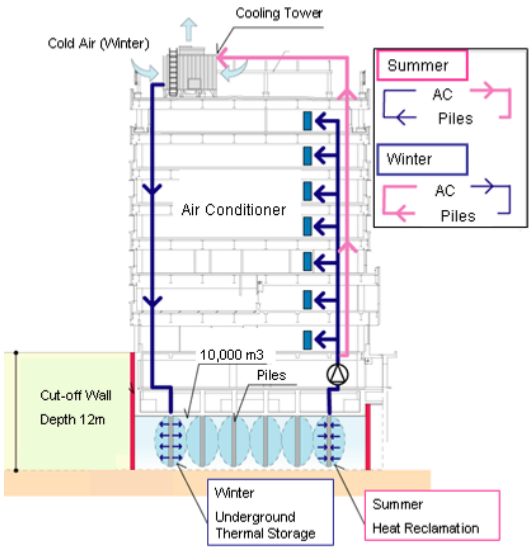


Figure 1: Soil thermal-storage system

3 OUTLINE OF SOIL THERMAL-STORAGE AIR-CONDITIONING SYSTEM

3.1 Air-conditioning facilities

The outline of the air-conditioning equipment of the YONDEN Building is used here to introduce the system. For air-conditioning, the equipment uses the heat-source equipment of the cool- temperature water supplied by district heating and cooling (DHC) facilities both adjacent and not adjacent to this building. Two coils are set up in 53 air-conditioning machines; heat from the DHC and the soil is supplied in the cold-water coil in the former steps, and heat from the DHC and the cool- temperature water thermal-storage tank is supplied to the cool- temperature water coil of the latter part.

3.2 Outline of soil thermal-storage air-conditioning system

The soil thermal-storage air-conditioning system conserves cold energy in the soil by cooling water in the cooling tower at nighttime in winter, when the air has a low temperature, and circulating it through the piping set up in the building pile. In summer, using the piping in the soil, the cold energy can be used for the air-conditioning system. The polyethylene piping is arranged in 64 foundation piles such that it resembles a spiral, and heat exchange is facilitated between the vadose water and the soil. The layout of the air-conditioning heat-source system and the foundation pile is shown in Figures 2 and 3, respectively. The route from the piping in the foundation pile to the set header does not include the lower side of the cool- temperature thermal-storage water tank; it includes the underground route in other areas (Graphic 2). Air and heat exchange are facilitated by operating a sealing-up-type cooling tower (CT1) and pump (PC1), and cold energy in the soil is saved during the night in winter. The saved cold energy is extracted using pumps PC2 and PC3 in the daytime in summer. However, the flow quantity on the DHC side of heat exchanger HEX4 is controlled, so that the amount of cool water may be fixed to ensure that the return temperature of the water is 23 ℃, and the temperature of the sending header is 19 ℃. When the temperature of the sending header is 19 ℃ or less, cold water from the DHC does not flow in HEX4. The operation of the soil thermal-storage system is controlled, and the return temperatures of cold water fluctuate in relation to the average outside temperature, the soil temperature, and the soil temperature in the winter thermal-storage system. When heat is radiated in summer, it is controlled by the relation between the average temperature and a set value of the soil temperature.

Table 1: Outline of air-conditioning system

Heat Source	District Heating and Cooling Systems Thermal Energy-storage Unit (1000 m3)
Air Conditioner	Air Handling Unit(Four-tube unit) 4600CMH × 53 Units,VAV Control, FCU
Ventilation System	Total Heat Exchanger (CO_2 Control)



Graphic 2: Piping under the building

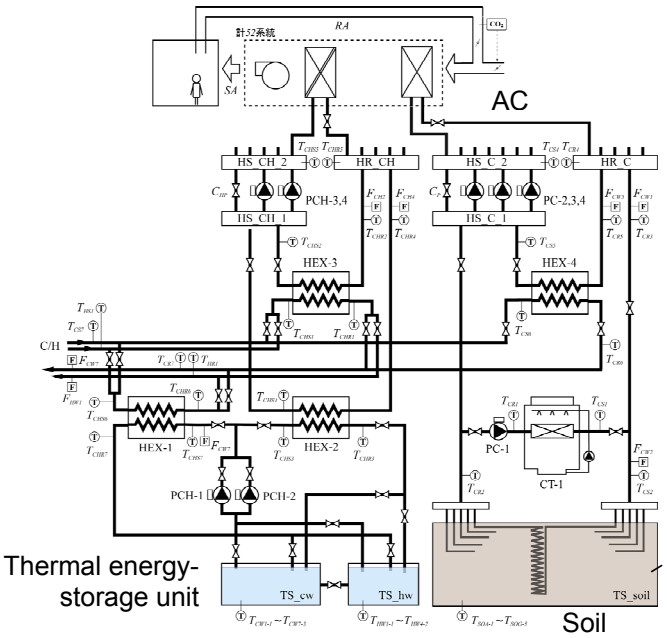


Figure 2: Heat-source system chart

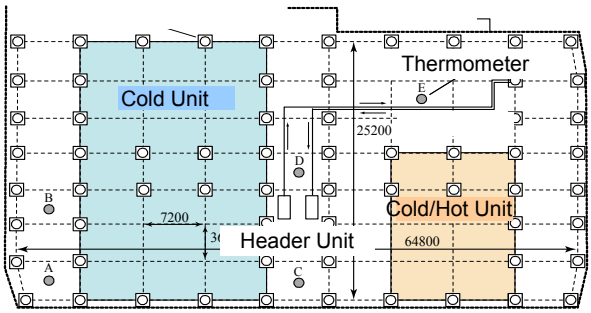


Figure 3: The foundation pile

4 CONSTRUCTION TECHNIQUE

4.1 Soil condition

For the soil of the site, underground refers to the GL from the topsoil layer. Because the loose sandy ground continued up to about 12 m below GL and the groundwater level was high, the breasting and the cut-off wall were installed as stability measures and spring-water measures when digging the foundations. It was inferred that the area containing sandy ground that had been enclosed with the impermeable layer (viscous soil layer) in the cut-off wall and underground (about 10,000 m^3) could be used as a thermal-storage medium for the soil thermal-storage system.

4.2 Method of constructing piling base and piping

64 site making concrete enhancing piles (axis diameter Φ1.3 m and bottom diameter Φ1.5–2.1 m), which exhibited a high bearing capacity through a decrease in the amount of exhaust soil and the use of an efficient pile section, were used in the base of the multistory part. In addition, to ensure that the basic structure would remain sound during an earthquake, the pile head was made from steel-pipe rolling concrete. Therefore, the bar arrangement for the structure of the steel-pipe rolling part became unnecessary, and it was possible to set up the pipe for the soil thermal-storage system. The pile could be used as an effective heat-exchange material (Figure 4). It was constructed while carrying out the pressurized filling with water that exerted pressure, coagulation heat, and buoyancy measure for the concrete in the piping.

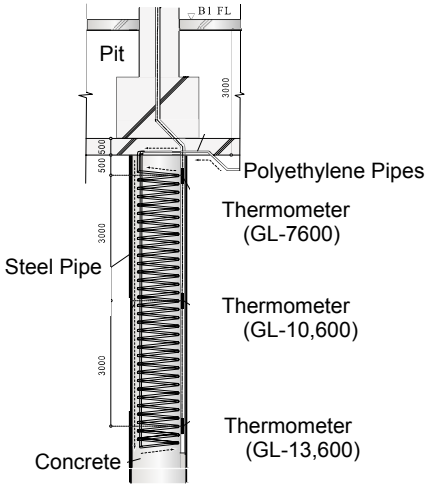


Figure 4: Piling base and piping



Graphic 3: Piling base and piping



Graphic 4: Polyethylene pipes

4.3 Piping material

Because the corrosion of piping and heat exchangers was forecast for a high salinity of the underground water, the underground heat-exchange method was adopted. For the material to be used in the soil and for the heat exchange, cross-linked polyethylene pipes were chosen for their good corrosion resistance; about 14,000 m of 20A(6/8 inch) piping was used (Graphics 3 and 4).

4.4 Measurement plan

Temperature sensors were installed on the pile and in the soil for the control and measurement of temperature in the soil thermal storage. Temperature sensors were installed at points A to F (Figure 3) in the soil, and the temperatures at depths of 500 mm, 3500 mm, and 6500 mm from the pile head were measured. The temperatures of the ten piles were measured at equal heights. The temperature sensors used a thermocouple system.

5 RATING PRACTICE

5.1 Rating practice in first year

The volume of cold water in the thermal storage in the first year was 50 m^3/h. When the heat was captured, it was controlled with a two-way valve so that the exit temperature of the air-conditioning machine was 23 ℃. Moreover, the inverter also controlled the flow quantity. The rating in the first year first is detailed below.

5.1.1 Effect of DHC heat supply load leveling

The comparative efficacy was estimated by comparing the energy usage of this system and that of the DHC. As a result, the load reduction rate (peak-cutting rate) when the soil thermal-storage system was used for the cooling load at the peak time on Monday, August 15, was 8.7%, and it was confirmed that this system was effective in load leveling.

5.1.1.1 Peak shift rate (year)

The rate of soil thermal-storage use in the energy used for air-conditioning (load shift rate) was 5.5% per year (Table 2).

5.1.2 Energy efficiency

5.1.2.1 Amount of soil thermal storage (in winter)

It was confirmed that an energy of 213.4 GJ could be transmitted to the soil from the energy of 218.8 GJ that had been acquired in the cooling tower when the soil thermal storage was driven; about 2.5% had been lost as heat through the piping, etc.

The energy stored by thermal storage in the soil is consumed by the fan, the watering pump, and the cold-water circulation pump of the cooling tower. The breakdown is as follows: 55% is used by the cooling tower fan, 31% is used by the cold-water circulation pump, and 14% is used by the watering pump. Twenty-seven gigajoules is consumed by the entire thermal-storage operation, and the coefficient of performance (COP) is 7.9 for the thermal storage, as calculated from the ratio of the amount of energy consumed to the energy provided.

5.1.2.2 Amount of soil thermal storage (in summer)

As a result of the heat-collection operation, 145.1 GJ of thermal energy was used as energy for air-conditioning in summer. This is 68% of the amount (213.4 GJ) of energy when thermal storage is carried out. Thermal diffusivity to the upper part of the soil is the main factor in the use of the remaining 32%. The energy necessary for heat recovery from the soil accounts for all the energy consumed by the pump. The amount of energy when heat is collected in summer amounts to 145.1 GJ, and because the amount of energy consumed is 13.2 GJ, the COP when heat is collected is 11.0. It was confirmed that this system was contributing to the decrease in energy consumption in summer through thermal storage between seasons.

5.1.2.3 COP during the year in which soil thermal storage was carried out

The COP of the thermal-storage air-conditioning system during the whole year is evaluated from the results of the thermal-storage operation and the heat-collection operation. Because the amount of thermal energy is 145.1 GJ and the amount of the energy consumed is 40.2 GJ, the COP of the soil thermal-storage air-conditioning system is 3.61 over the year. As for the consumption energy, the case of thermal storage became 67% and the case of heat radiation became 33%.

5.1.3 Operating improvement for the second year of operation

In order to improve the system COP compared with the results of the first year, it was thought that energy reductions should be achieved in the pump power, the thermal-storage operation, the cooling-tower power, and the heat-collection operation. Even though the case study carried out by detailed operational simulation ended during the first year, and the flow quantity of cold water was changed from 50 m^3/h to 30 m^3/h in the thermal storage, the storage of heat barely changed. However, it was only after the driving of thermal storage in the second year started that the simulation results appeared, and the second year was driven by a flow quantity of 45 m^3/h of cold water.

Moreover, when we examined the simulation ending during the first year concerning the temperature setting of the cold water of the coil return, it was found that if the temperature setting of the return cold water value was raised, an increase in recovered energy was obtained in the heat-collection operation. The value set for the second year was changed to 25 ℃ on the basis of this result. Moreover, operating of overtime was prohibited in year second though the heat collection operating of overtime was done in year first.

5.2 Rating practice in second year

The amount of thermal storage energy was 374.1 GJ, because the thermal-storage driving period was extended in the second year, which led to an energy increase of 75% compared to the first year. Therefore, the amount of energy collected also increased by about 41% compared with 145.1 GJ in the first year. The efficiency of the thermal storage was about 55%, which was a large decrease compared with the efficiency of 68% for the thermal storage in the first year.

5.2.1 Effect of DHC heat supply load leveling

5.2.1.1 Peak-cutting rate (peak day in summer)

The peak-cutting rate was 7.55% at eight o'clock on August 22, 2006, which was the maximum load day, the decrease in the rate was more than that in the first year. However, for the whole day, the reduction in the peak rate for the whole day improved by 8.9%.

5.2.1.2 Peak shift rate (year)

The peak shift rate improved during the year, compared with 8.6% in the first year. The amount of energy (373.6 GJ) at the soil thermal storage was effectively transmitted to the soil from the 394.3 GJ of energy acquired in the cooling tower. About 5.2% was lost through piping, etc. Moreover, the COP decreased more than 6.3 and years first at thermal storage. It seems that this is because the thermal-storage driving period was long, so the temperature fluctuation of the vadose water was small and the power consumption increased.

5.2.2 Energy efficiency

5.2.2.1 Amount of soil thermal storage (in winter)

The amount of energy collected from the soil as of November 10, 2006, was 54% (201.4 GJ plus the storage of heat). As for the power consumption required for energy to be

extracted from the soil, the COP was 22.9, which is two or more times better than that in the previous year by 13.0 GJ. The soil use when operating of overtime last year is discontinued, and the COP was improved greatly by raising the return temperature from 23 to 25 ℃.

5.2.2.2 COP of the soil thermal storage during the year

The energy consumption was 68.5 GJ, and the COP was 2.97, which was lower than that during the first year of operation of the soil thermal-storage air-conditioning system (204.1 GJ of collection energy). As for the consumption energy, it was 13.0 GJ (19%) for a collection energy of 55.5 GJ (81%) for the thermal storage, with great losses from the thermal storage.

5.2.3 Operating improvement for driving in the third year

Since the problem of efficiency improvement in the thermal-storage system had become clear, it was assumed that an inverter was installed in the fan of the cooling tower as the ratio that occupied into the consumption energy was large. The flow quantity of cold water was assumed to be 30 m^3/h. The cooling-tower fan inverter value was assumed to be 50%. Moreover, the heat-collection operation was implemented, along with a constant flow quantity at a pumping rate of 15 m^3/h. As a result, because a high performance could be confirmed, the heat collection operation in the third year was calculated by assuming a pumping rate of 15 m^3/h.

5.3 Rating practice in third year

5.3.1 Effect of DHC heat supply load leveling

5.3.1.1 Peak-cutting rate (peak day in summer)

The peak-cutting rate was 6.4% at eight o'clock on August 20, 2007, which was the maximum daytime load; this decreased more than in the second year. The peak-cutting rate over the whole day was 8.9%, and it was steady during the second year. It seems that this is because the soil heat discharge could not be increased at the maximum peak load as a constant flow quantity was assumed in the pump operation.

5.3.1.2 Peak shift rate (year)

The peak shift rate decreased a little during the year, compared with 7.9% in the second year. It seems that it is assumed the decrease of the volume of water in the thermal storage and the inverter 50% operating of the fan of the cooling tower for system COP improvement, and the thermal storage calorie decreased.

5.3.2 Energy efficiency

5.3.2.1 Amount of soil thermal storage (in winter)

The storage of heat until March 31, 2007, was 280.3 GJ. The energy consumption required was 24.04 GJ (pump: 5.05 kW, cooling-tower fan: 10.82 kW, cooling-tower pump: 8.17 kW), and the efficiency of the thermal storage was 11.66, which was a great improvement compared with the efficiency of the thermal storage (COP: 6.74) in the second year. The efficiency of the thermal storage calculated by the simulation is 11.20, so it is understood that the simulation provides accurate estimates.

5.3.2.2 Amount of soil heat collection (in summer)

The amount of energy collected was 189.9 GJ. The efficiency of the thermal storage reached 68%, with a COP of 50.6 when energy was heat radiation COP 12.3 at thermal storage and systems COP 7.14 (Table 2).

Table 2: Effect of underground thermal storage on load leveling

		First year	Second year	Third year
Thermal storage operation	Period	2/3/2005- 14/4/2005	4/12/2005- 26/4/2006	12/23/2006- 3/31/2007
	Soil thermal storage energy [GJ]	213.4	374.1	280.3
Heat reclaim operation	Period	25/6/2005-4/7/2005 25/7/2005-12/11/2005	29/6/2006- 10/11/2006	1/7/2007- 22/10/2007
	Soil thermal storage energy [GJ]	145.1	205.1	189.9
Peak cutting rate maximum air-conditioning hourly load		8:00 15/8/2005 0.344 (GJ/h) / 3.964 (GJ/h) =8.7%	8:00 22/8/2006 0.280 (GJ/h)/ 3.43 (GJ/h) =7.5%	8:00 20/8/2006 0.220 (GJ/h)/ 3.43 (GJ/h) =6.4%
Peak cutting rate maximum air-conditioning daily load		8:00 15/8/2005 2.2 (GJ/day) / 29.0 (GJ/day) =7.7%	8:00 22/8/2006 2.9 (GJ/day) / 32.4 (GJ/day)=8.9%	8:00 20/8/2006 3.0 (GJ/day)/ 33.3 (GJ/day) =8.9%
Peak shift rate cooling load in August		47.8 (GJ/month) / 710.3(GJ/month) =6.7%	58.9 (GJ/month) / 710.3 (GJ/month) =8.3%	56.8 (GJ/month)/ 710.9(GJ/month) =8.0%
Peak shift rate cooling load during year		145.1 (GJ/year) / 2643.5 (GJ/year) =5.5%	204.1 (GJ/year) / 2373.1 (GJ/year) =8.6%	189.9 (GJ/year) / 2412.7 (GJ/year) =5.5%

6 SUMMARY

A "soil thermal-storage natural-energy air-conditioning system using the pile foundation" has been developed, and it has been adopted in the YONDEN Building. Simulation technology was used in the design stage and the operation phase in order to understand the temperature behavior of complex underground soil. As a result, DHC heat-supply load leveling could be achieved while achieving a high system COP during the year through the optimization of the system.

7 REFERENCES

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