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Research on Ground Temperature Restoration Characteristics of Large-Scale Ground Source Heat Pump System

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Abstract

Ground temperature restoration characteristics are the crucial factors to evaluate whether a ground source heat pump system can keep long time steady operation. They are mainly dependent on soil thermal properties, layout of pile group, operation/shutoff ratio, cooling/heating load, thermal imbalance ratio and so on. On the one hand, several types of vertical pile foundation heat exchangers are intercompared to determine the most efficient one by performance test and numerical method. On the other hand, according to the layout of pile group of a practical engineering and running conditions of a GSHP system in Shanghai, the temperature distribution during a period of five years is numerically studied. The numerical results are analyzed and are used to provide some guidance for the design of large-scale GSHP system.

Key words: ground source heat pump, pile foundation heat exchanger, ground temperature restoration, thermal imbalance ratio

1. Introduction

Sustainable geothermal energy technologies for heating and air-conditioning in buildings have been very attractive since significant development of ground source heat pump (GSHP) system was achieved in these years [1-6]. Recently, utilization of the pile foundations of buildings as ground heat exchangers have attracted much attention for it reduces the cost and enhances the heat transfer [7-10]. It is often regarded as an energy pile or heat exchanger pile system in the literature and several types can be found in practical applications. Large amount of research on the ground heat exchangers and the heat pump systems can be found. However, there are few practical examples concerning the evaluation of pile foundation heat exchangers and the underground field performance. Lately, numerical methods in the GSHP system, combined with the experiment in situ, have been widely applied and significantly developed [5,11-15]. In the cases when longtime ground temperatures variation and the potential of geothermal energy in operation require to be investigated, they appear to be good alternatives to the experiments on the premise of being well verified and validated.

In this paper, a case study is presented to assess ground temperature restoration characteristics for a district heating and cooling system in Shanghai, China. First, three-dimensional numerical simulations, coupling heat convection and conduction through water in pipe, reinforced concrete(RC) pile and soil, are performed to determine the most efficient type of pile foundation heat exchangers. Experimental data are used to validate the numerical results. Second, numerical method is further applied to investigate five-year variations of the ground temperatures. The potential of geothermal energy and the operating performance of ground heat exchanger selected are analyzed using the modified energy output based on the practical ground temperatures in operation. Results of the present study are to be used to a district heating and cooling system in Shanghai, China, based on which river water will be used as a supplementary source for an hybrid GSHP system.

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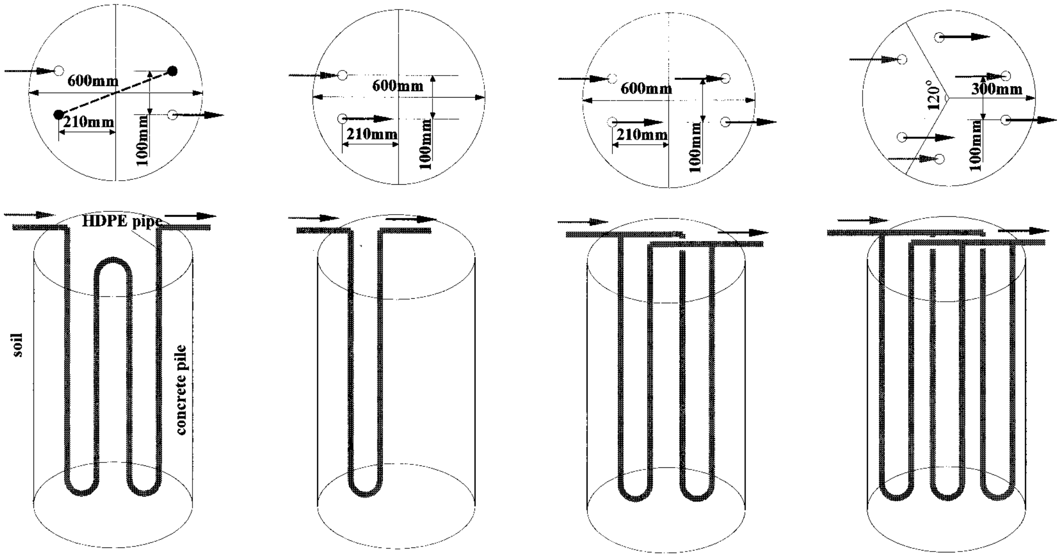


W-shaped type Single U-shaped type Double U-shaped type Triple U-shaped type

Fig. 1. Four types of underground heat exchangers investigated (pipe inner diameter, d=2cm).

2. Selection on ground heat exchangers

2.1 Project Introduction and Pile foundation Heat Exchangers

An energy scheme for the district heating and cooling system and a report of geological survey for the GSHP system were completed in 2006, based on which a group of 5500 pile foundations in a land parcel of 1000mx100m, cast-in-situ and made of RC, were used as energy piles. These energy piles will be operated in a GSHP system and are designed to take about 30% thermal load of the district heating and cooling system. The potential of geothermal energy are to be discussed and supplementary source is to be provided by river water, which has been adequately calculated and tested last year. According to the climate data of Shanghai, space cooling season is from May to September and space heating season from December to next February.

Depth of frozen earth in Shanghai is about 8cm and soil temperature under 5m depth stays almost constant. The pile foundation heat exchangers, length 25 m, are then vertically laid at the depth of 10.4m. Cast-in-situ RC bearing piles are used and heat exchange is performed by taking advantage of the inner portion of piles. Outer meter of the piles is 600mm. The thermal medium is water, which flows in the high-density polyethylene (HDPE) pipes casted in the piles. Four types of underground heat exchangers investigated and their sizes are shown in Fig. 1. Properties of RC, HDPE and soil are listed in Table 1.

Table 1. Physical properties of materials.

Material	Thermal conductivity (W/m K)	Density (kg/m^3)	Heat capacity (J/kg K)
Soil (sandy silt)	1.3	1847	1200
RC	1.628	2500	837
HDPE	0.42	1100	1465

2.2 Experimental Data

Performance experiment of four types of ground heat exchangers have been conducted in situ. The view of the pile foundation heat exchangers and experimental system are shown in Figs. 2 and 3, respectively. Water was supplied into the PE pipes and its temperature was stabilized at about 35℃ by a water tank of constant temperature and two electric heaters (See Fig. 3). Supply temperature and return temperature were measured by platinum resistance thermometers. Volumetric flow rate was measured by a turbine flowmeter. To observe the heat transfer performance of the four types of ground heat exchangers, dynamic measurements were carried out and results were obtained when all parameters came to be stable.

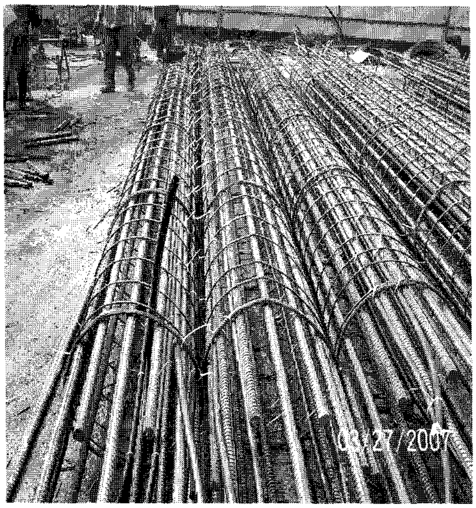


Fig. 2. View of pile foundations before casted and buried.

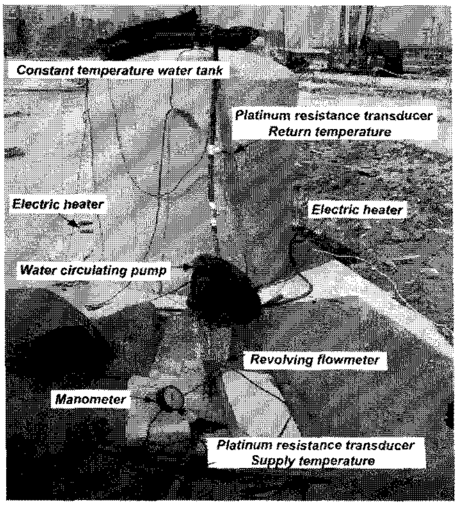


Fig. 3. Experimental system.

Fig. 4 provides the stable results of water temperature and the performance of the four ground heat exchangers investigated. Water supply temperature is approximately 35℃ and the flow rate is controlled at three levels: 0.342m^3/h, and its double, tripe. Energy output from the ground heat exchanger is calculated by the flow rate and temperature difference, and the heat transfer coefficient is derived by the energy output and the average temperature difference between water and soil. Soil temperature under 5m depth stays almost constant and it is 18.2℃ according to the measurements.

Experimental data provide the maximum value of energy output, and some percentages will be adopted as the design load. The results in Fig. 4 will be discussed in the latter numerical study. The most efficient type of pile foundation heat exchanger is to be decided based on the experimental data and numerical results.

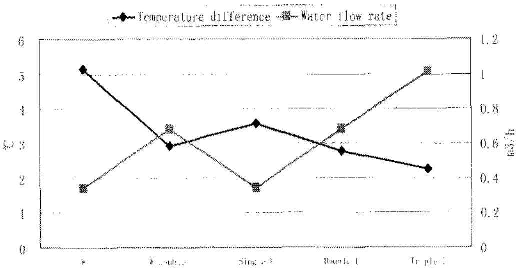
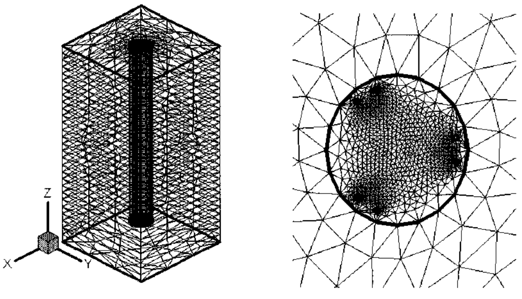


Fig. 4. Performance of underground heat exchangers from experimental data.

2.3 Numerical Method

As for numerical study on the solid-fluid coupled heat transfer encountered in the ground pile foundation heat exchangers, the mass, momentum, turbulence and energy conservation of water flow, and the energy conservation of soil and RC piles are considered. The standard κ–ε model together with the standard wall functions [16] are employed for the water flow and heat transfer through the pipes. Conductive differential equation is used to model the heat transfer through the piles and soil. The pressure-velocity coupling in the flow region is achieved by using the SIMPLEC algorithm [17]. The second-order upwind differencing scheme is used to evaluate the advection terms for the Navier-Stokes equations, the energy equation and the turbulent transport equations. In Shanghai, groundwater velocity in the soil is ranged from 3.65m to 10.95m/yr, so the effect of groundwater advection is neglected. The finite volume method is applied to discretize the equations in the space. Sizes of a 3D soil zone used to study the heat transfer performance of different ground heat exchangers are 4mx4mx27m (depth).

Boundary conditions of inflow of the HDPE pipes are $u_{in}=4L/\pi d^2$, t_{in}, and turbulent intensity 1%, hydraulic diameter 0.02m(where, L is the flow rate, d is the inside diameter, t_{in} is the inlet water temperature). Outflow of the pipes are set as single direction outflow. Vertical surfaces and top surface of the soil zone are assumed adiabatic. Bottom surface is 18.2℃. Initial temperature of the soil is 18.2℃. Physical properties are provided in Table 1.



(a) (b)

Fig. 5. Meshes used for the numerical simulation (88000 nodes for the triple U-shaped).

a) view of the total mesh and b) top view of the mesh in and around the pile

Grid-independent solution is tested using three levels of non-structured grid sizes and the eventual grids are described in Fig. 5 (take the triple U-shaped type as an example). Meshes are gradually refined from the outer soil to pile and intraductal flow. First grid size near the inner wall of pipe is so adjusted that the standard wall functions can be applicable, i.e., non-dimensional first grid size locates at 11.225~60.

2.4 Numerical Results and Type Selection

Unsteady simulation is performed to achieve the final stable temperature variation along the water flow and the return temperature. Numerical results are compared with the experimental data and are used to evaluate to heat transfer performance of pile foundation heat exchangers investigated. As shown in Fig. 6, good agreement of energy output and heat transfer coefficient between the numerical and experimental results is achieved. To investigate the effect of water flow rate on the heat transfer, an extra case, W-shaped type with half flow rate 0.342m^3/hx0.5, is also calculated. From the numerical results and experimental data, absolute energy output of the triple U-shaped type is the largest among all heat exchangers, followed by W-shaped with double flow rate, double U-shaped, W-shaped with reference flow rate, U-shaped and W-shaped with half flow rate. Based on the reference of 0.342m^3/h, the double and triple U-shaped type have double and triple flow rate, respectively. However, their absolute energy output is only 28% and 56% larger than that of the W-shaped type with the reference flow rate, respectively. Absolute energy output of the W-shaped type with double flow rate is only 10% larger than with reference flow rate, while, as for the W-shaped type with the reference flow rate, energy output is 43% larger than that of the half flow rate. Comparatively, it is decided that the W-shaped with the reference flow rate is regarded as the most efficient type and is employed by the project. In addition, the W-shaped type is preferred because it is easier to adjust the energy output to larger extent than the U-shaped type.

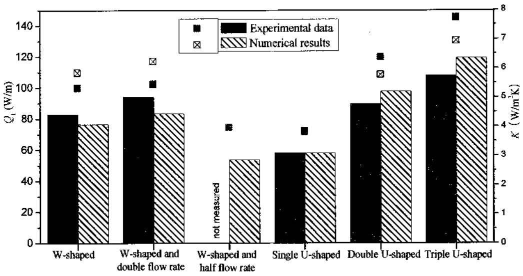
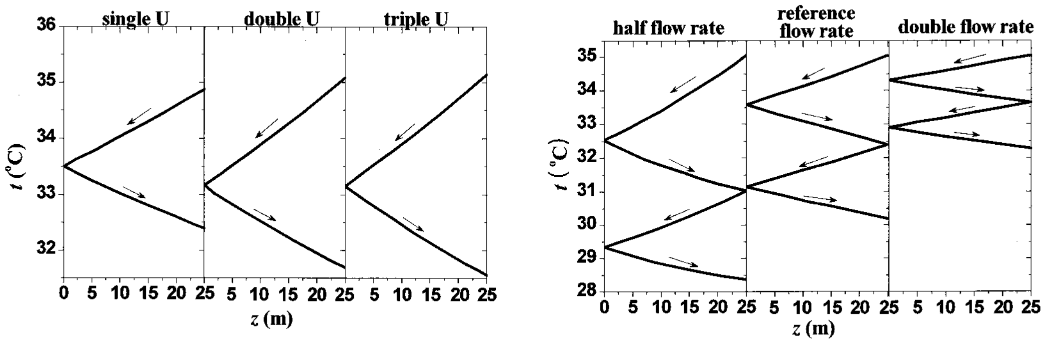


Fig. 6. Numerical results of heat transfer performance and the comparisons with experiments.

As shown in Fig. 7, water temperature declines along the flow direction. It seems that the change of



(a) W-shaped type (b) U-shaped type

Fig. 7. Axial temperature variation along water flow in pipes.

water temperature is linear along the pipe. However, slight changes of the slope observed indicate that the temperature does not decline uniformly. The reason is that water temperature descending will reduce the heat transfer potential from water in pipe to the soil and thus lead to slower descending of water temperature. Therefore, water temperature descending is slightly decreased along the flow direction. It is also seen from Fig. 7 that water return temperature simulated agrees well with the experimental data in Fig. 4.

3. Simulation of ground temperatures

3.1 Geometry and Boundary Conditions

A geometrically periodic unit of the pile group discussed in Sec.2.1 is presented in Fig. 8, which consists of 8 engineering piles (W-shaped with the reference flow rate) and 4 lattice piles. In the total area of 1000mx100m for the pile group, a corner of 10 unitx10 unit is used to figure out the ground temperature distribution and variation. It is implemented through using the simplified symmetrical boundary conditions for two interior faces of the corner and using soil's initial temperature as the boundary conditions for two exterior faces. To incorporate the effect of surrounding soil, this corner, 55mx55m, is enlarged to an area of 75mx75m and the two exterior faces are therefore moved outward 20m (See Fig. 8). As for the long-time simulation of ground temperatures by the group of pile foundation heat exchangers, a two-dimensional volume-control method is used. Therefore, the vertical heat transfer is neglected. In addition to the boundary conditions discussed above, specified heat flux is fed to the exterior surface of the water pipes without interior water flow. The values of heat flux are determined by experimental data of energy output in Fig. 6 which are regarded as the maximum energy output. The running time is from 9am to 9pm in both cooling season and heating season. Design load is decided by a percentage of the maximum value. Table 2 presents the two studied cases.

Table. 2. The two studied cases.

	Design load	Thermal imbalance ratio
Case 1	65% of experimental data	10%
Case2	55% of experimental data	3%

3.2 Results and Analysis

Simulations for the two cases of different thermal imbalance ratio are carried out under the design loads and conditions above. Based on the initial value of 18.2℃, five-year ground temperature distributions are solved numerically. Mean ground temperature of every month and its variations in the first year for the two cases are shown in Fig. 9. It is observed that mean temperature rise due to the pile foundation heat exchanger is mainly determined by the thermal imbalance ratio and the highest temperature in the year by the design load of cooling season.

Using the design load for the two cases, total elevated mean temperature before cooling season is

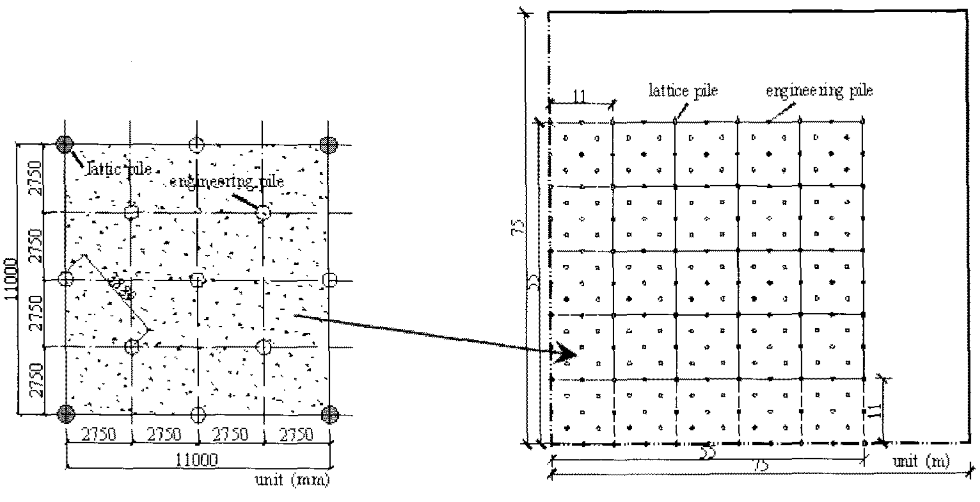
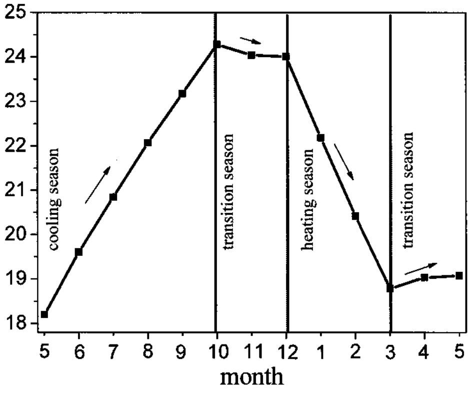
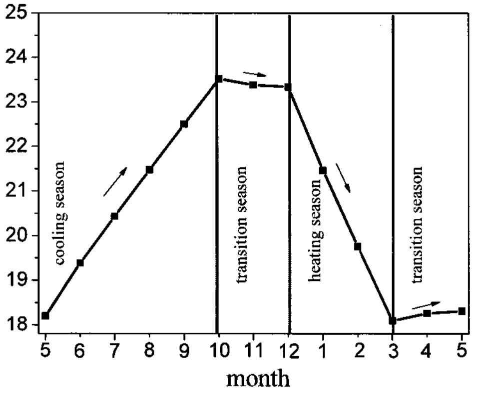


Fig. 8. View of a periodic unit of pile group and a corner of 10x10 units used.



(a) Case1



(b) Case2

Fig. 9. Variations of mean ground temperature in the first year of running.

2.77℃ and 0.81℃ for the two cases, respectively, and total elevated mean temperature after cooling season is 8.39℃ and 6.02℃, respectively. Fig. 10 presents the annual mean ground temperature before and after the cooling season, from which the potential of geothermal energy is very encouraging. Furthermore, the highest temperature in the field for both cases is found much less than 32℃, so the so-called thermal screen does not occur after five years and the GSHP system can proceed with its stable running. Due to the ground temperature rise, the design energy output of heat exchangers may be reduced. It is difficult to precisely derive the real energy output from the soil. However, the mean temperatures throughout the whole cooling or heating season can be used to evaluate the potential of geothermal energy.

Fig. 11 shows the ratio of modified load to the design load according to the averaged mean temperatures which are obtained by averaging the mean ground temperature in cooling and heating season, respectively. The modified load is defined using the averaged mean ground temperature, mean water temperature (7.5℃ in heating season) and heat transfer coefficient (*K* assumed not varied). From Fig. 11, it is observed that the real energy output from the soil is significantly influenced by the ground temperature variation. Owing to the thermal imbalance, averaged ground temperature of cooling, transition and heating seasons keeps increasing during the five years. Therefore, the modified load in cooling season tends to decrease, while that in heating season tends to increase. The GSHP system related to present ground heat exchangers can apparently disregard the potential of geothermal energy in heating season. As for the potential of geothermal energy in cooling season, larger thermal imbalance leads to faster decreasing in

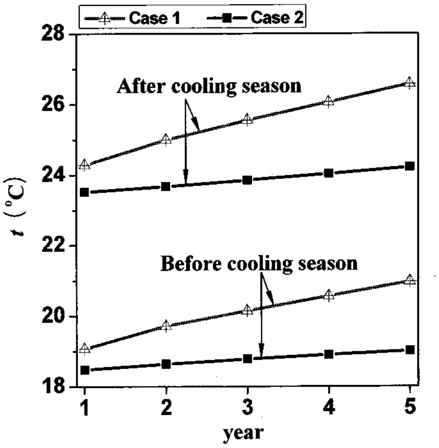


Fig. 10. Annual mean ground temperature.

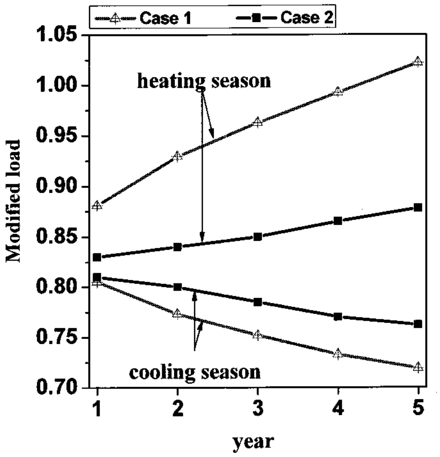


Fig.11. Modified load using the averaged temperatures.

the energy output from the soil. In the present case study, design load is really reduced by 20% to 30% in the five years. However, as a conservative parameter, the modified load is not to directly indicate a sharp drop of the potential of geothermal energy in cooling season. The reason is that the ground temperature is derived based on the design load and it is then higher than under the modified load. Therefore, the current modified load is a conservative parameter and the real potential of geothermal energy is certainly higher than that indicated in Fig. 11.

4. Conclusions

In this paper, pile foundation ground heat exchangers are investigated and its most efficient type is decided based on the 3D fluid-solid coupled numerical simulations and corresponding experimental data. Five-year simulations of the ground temperatures for the practical pile group are performed to evaluate ground temperature restoration characteristics and the potential of geothermal energy in the present application. Some concluding remarks are extracted from this study as follows:

Both experimental data and numerical results of heat transfer performance demonstrate that the W-shaped type of pile foundation ground heat exchanger with moderate medium flow rate appears to be most efficient and is finally adopted.

Water temperature descending in the pipe reduces the heat transfer potential from water in pipe to the soil and it tends to slightly decreased with the flow direction.

Under thermal imbalance ratio of 10% and 3%, total elevated mean ground temperature of five-year running is 2.77℃ and 0.81℃, respectively. Design load employed, 65% and 55% of the maximum energy output from experiment, will not produce thermal screen. It confirms that the GSHP system can proceed with its stable running.

According to the averaged mean ground temperature in cooling and heating season, modified load is defined to investigate the impact of ground temperature variation on the energy output of ground heat exchangers. As a conservative parameter, the reduced load, 70%-80% of the design load, is proved to underestimate the real potential of geothermal energy. Therefore, higher energy output of the pile foundation heat exchangers can be expected for the practical engineering.

Moderate cooling/heating load and small thermal imbalance ratio are beneficial to ground temperature restoration.

References

[1] S. Kavanaugh, Ground source heat pumps, simple, efficient, reliable, ASHRAE J. 40 (1998) 31-36.

[2] R.G. Bloomquist, Geothermal space heating, Geothermics. 32 (2003) 513-526.

[3] L. Ozgener, A. Hepbasli, and I. Dincer, Performance investigation of two geothermal district heating systems for building applications: energy analysis, Energy Build. 38 (2005) 286-292.

[4] J. Spitler, Ground-source heat pump system research — past, present and future, HVAC&R Res. 11 (2005) 165-167.

[5] W.B. Yang, M.H. Shi and H. Dong, Numerical simulation of the performance of a solar –earth source heat pump system, Appl. Thermal Engineering. 26 (2006) 2367-2376.

[6] L. Ozgener, A. Hepbasli, and I. Dincer, A key review on performance improvement aspects of geothermal district heating systems and applications, Renew Sustainable Energy Rev. 11 (2007) 1675-1697.

[7] K. Morino, T. Oka, Study on heat exchanged in soil by circulating water in a steel pile, Energy Build. 21 (1994) 65-78.

[8] L. Laloui, M. Moreni and L. Vulliet, Behavior of a dual-purpose pile as foundation and heat exchangers, Canadian Geotech. J. 40 (2003) 388-402.

[9] L. Laloui, M Nuth and L. Vulliet, Experimental and numerical investigations of the behavior of a heat exchanger pile, Int. J. for Numer. and Analyt. Methods in Geomech. 30 (2006) 763-781.

[10] Y. Hamada, H. Saitoh, M. Nakamura, *et al.*, Field performance of an energy pile system for space heating, Energy Build. 39 (2007) 517-524.

[11] K. Den Braven, E. Nilson, Performance prediction of a sub-slab heat exchanger for geothermal heat pumps, ASME Tans. J. Sol. Engng. 120 (1998) 282-288.

[12] C. Gauthier, M. Lacroix and H. Bernier, Numerical simulation of soil exchanger-storage systems for greenhouses, Sol. Energy. 60 (1997) 333-346.

[13] X. Li, Y. Chen, Z. Chen, *et al.*, Thermal performances of different types of underground heat exchangers, Energy Build. 38 (2006) 543-547.

[14] O. Ozgener, A. Hepbasli, Modeling and performance evaluation of ground source (geothermal) heat

pump systems, Energy Build. 39 (2007) 66-75.

[15] H. Esen, M. Inalli and M Esen, Numerical and experimental analysis of a horizontal ground-coupled heat pump system, Build Environ. 42 (2007) 1126-1134.

[16] B.E. Launder, D.B. Spalding, The numerical com putation of turbulent flows, Comput. Methods Appl. Mech. Eng. 3(1974) 269-289.

[17] J.P. Van Doormaal, G.D. Raithby, Enhancement of the SIMPLE method for predicting incompressible fluid flows. Numer. Heat Transfer. 7(1984) 147-163.