ESTIMATION OF SHALLOW GEOTHERMAL POTENTIAL TO MEET HEATING DEMAND IN A BUILDING SCALE

by

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The heat exchanger can use shallow geothermal energy to provide regional heating and cooling demand in winter and summer. In this paper, a large-scale public building is taken as the example, and the energy system in the building is taken as the research object. Firstly, through the collection of geothermal drilling geographic information and geothermal data, the geothermal reserves and geothermal recoverable resources are evaluated. Secondly, the cooling and heating demand of the building is calculated by using HVAC simulation software. Then, the heat transfer capacity of a single pile is evaluated and the lay-out scheme of the underground heat exchange pile foundation of the building is given. The actual heating effect of the heat exchange pile foundation system is explored, and the heat transfer characteristics of heat exchange pile foundation under different working conditions are compared and analyzed. Finally, reasonable suggestions for the arrangement of heat exchange pile foundation are given.

Key words: *shallow geothermal energy, building energy efficiency, building energy demand, heat exchange pile, renewable energy*

Introduction

With the improvement of people's living standards, heating and air conditioning systems in public buildings and residences have become a common demand, and the energy consumption of this part can account for 25-30% of the total energy consumption of society. Geothermal energy has been recognized as an alternative resource to traditional fuel energy due to attractive advantages such as renewability, cleanliness and cost effectiveness [1]. Most of China's energy consumption is mainly from coal energy, coal is a non-renewable resource and the mining process is prone to engineering disasters [2]. Therefore, the engineering community needs to explore a new building energy-saving technology that can be combined with engineering characteristics, both to obtain energy, but does not produce environmental problems.

Ground source heat pump is a well-established technology that has been widely used for space heating/cooling of buildings. Several recent research advances have led to improvements in the energy efficiency of these systems, making them an attractive alternative for heating buildings [3]. At this time, energy pile technology, which is derived from ground source heat pump technology, began to emerge in the engineering world. The core idea of energy pile is to use the buried pile foundation as a heat exchange component and obtain the shallow geothermal energy from strata.

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In recent years, many studies have explored the feasibility of geothermal use in urban areas through various methods [4-7]. Zhang *et al.* [8, 9] developed a GIS-based simulation model to establish an evaluation system for the feasibility of city-scale ground-source heat pump installations. To date, most studies have evaluated regional-scale geothermal energy potential [10, 11].

In this paper, we intend to take a large-scale public building as an engineering case study, through the geothermal potential estimation, building demand simulation and pile foundation heat transfer efficiency of a variety of factors analysis to achieve the feasibility of pile foundation heat transfer system.

Material and methods

Study area

Engineering Project is a large-scale public building. The total heating demand area of the building is 16886 m^2, the height of the building is 4 m, and the length and width of the building are 137.8 m × 96.2 m. According to geological survey report, the strata are:

- *3 m vegetative fill layer*: mainly yellowish brown, locally grayish brown and brown, mainly powdered clay and powdered soil,
- *7.5 m powdered clay layer*: mainly, yellowish brown locally brownish yellow, grayish brown, uneven soil quality,
- *6.5 m powder soil layer*: brownish yellow, uneven soil quality,
- *2.70 m powder sand layer*: brownish yellow, powdered soil, powdered clay interlayer, locally containing clay mass,
- *4.40 m powder clay layer*: brownish yellow, locally yellowish brown, grayish yellow, uneven soil quality, containing powder clay and powder fine sand interlayer,
- *4.20 m powder soil layer*: brownish-yellow, uneven soil quality, containing powder clay interlayer,
- *5.2 m powder fine sand layer*: brownish yellow, powder soil, powder clay,
- *6.8 m powder clay layer*: brownish yellow, containing powder soil and powder fine sand interlayer,
- *3.8 m powder clay layer*: brownish yellow, containing powder clay interlayer,
- *4 m powder fine sand layer*: brownish yellow, powder clay,
- *9.8 m powder clay layer*: brownish yellow,
- *9.3 m powder clay layer*: brownish yellow, containing powder, fine sand and clay interlayer, and
- *9.8 m pulverized clay layer*: brownish yellow, with pulverized clay interlayer.

Thermal balance calculation

The calculation of regional geothermal energy reserves is based on the thermal storage method, which evaluates the amount of geothermal resources beneath the building and the amount of recoverable geothermal resources, and the amount of resources calculated by the volume method cannot be fully extracted. The equations of the shallow geothermal deposit in this area are given:

$$\sum_{i=1}^{n} C_1 A D_1 \Delta t \tag{1}$$

$$C = \rho_r C_r (1 - \varPhi) + \rho_w C_w \varPhi \tag{2}$$

$$R = \frac{Q_k}{Q_r} \tag{3}$$

where Q_r is the geothermal potential, A – the area of calculation area, D – the thermal storage thickness, Δt – the temperature difference between thermal storage temperature and annual average temperature, C – the average specific heat capacity of heat storage rock and water, ρ_r – the density of heat storage rock, C_r – the specific heat of heat storage rock, ρ_w – the density of geothermal water, C_w – the specific heat of water, Φ – the porosity of heat storage rock, R – the geothermal resource recovery rate, Q_k – the heat that can be extracted from the well, and Q_r – the geothermal resources buried in underground thermal strata.

Building heating demand simulation and calculation

The total heating demand area of the enclosure structure is 16886 m^2. The dominant wind direction throughout the year is CSW. In summer, the indoor air pressure is 1002.9 hPa, the indoor air dry bulb temperature is 34.8 °C, the outdoor is 26.6 °C, the ventilation outdoor is 30.4 °C, and the ventilation outdoor humidity is 61%. Atmospheric pressure is 1025.1 hPa. In winter, air conditioning outdoor calculated temperature value is –9.5 °C, air conditioning outdoor calculated temperature value is 55%, outdoor calculated temperature is –3.2 °C, outdoor calculated temperature of heating –7.0 °C, the extreme minimum temperature is –19.6 °C, the maximum depth of frozen soil is 0.58 m. The calculation parameters of building are shown in tab. 1.

Table 1. Calculation parameters of building

Room name	Summer temperature [°C] humidity [%]		Winter temperature [°C] humidity [%]		Fresh air requirement [m^{3}h^{-1}]	Noise standard [dB]
Office	26	55	20	≥35	30	45
Chamber	26	55	20	≥35	14	45
Exhibition hall	26	55	20	≥35	30	45
Check room hall	26	55	18	≥35	10	45
Ecological room hall	30	–	18	–	4 times	50
Container room hall	30	–	18	–	2 times	50

Basic heat consumption of buildings

The basic heat consumption of the retaining structure reads:

$$q' = KF\left(t_n - t'_w\right)\alpha \tag{4}$$

where K is the heat transfer coefficient of building, F – the area, t_n – is the indoor calculating temperature in winter, t_w – the outdoor calculating temperature in winter, and α – the temperature difference correction coefficient of building.

Calculation of basic heat consumption of buildings

The temperature difference heat transfer of the enclosure structure is suggested:

$$Q_1' = KF\left(t_n - t_W'\right)\alpha \tag{5}$$

where Q_1' is the heat sink transfer capability.

Orientation correction heat consumption of buildings

Design specifications specify that different orientations are selected according to the following correction rates: North, Northeast, Northwest-3%, East, West-5%, South-9%, the design specification stipulates that in general, wind additional is not considered.

Cold air infiltration heat consumption of buildings

The heat consumption of cold air infiltration is described:

$$Q_2' = 0.278 n_k V_n \rho_w c_p \left(t_n - t_W'\right) \tag{6}$$

where V_n is the room volume, n_k – the room ventilation rate, ρ_w – the air density at outdoor calculated temperature, and c_p – the specific heat of air at constant pressure.

Cold air intrusion heat consumption of buildings

Under the action of wind pressure and hot pressure in winter, cold air invades the room from the open outer door. The heat consumed by heating this part of air to the indoor air temperature is called cold air intrusion heat consumption. The cold air invasion heat consumption is written:

$$Q_3' = 0.278 V_w \rho_w c_p \left(t_n - t_W'\right) \tag{7}$$

where V_w is the amount of cold air inflow.

Single pile heat exchange capacity

According to the *Ground source heat pump system engineering technical specifications* (GB50366-2009), for winter and summer conditions, single pile heat transfer capacity Q_H and Q_C can be calculated:

$$Q_H = \frac{L\left(t_{\max} - t_\infty\right)}{R_f + R_{pe} + R_b + R_S \times F_H + R_{SP}\left(1 - F_H\right)} \tag{8}$$

and

$$Q_C = \frac{L\left(t_\infty - t_{\min}\right)}{R_f + R_{pe} + R_b + R_S \times F_C + R_{SP}\left(1 - F_C\right)} \tag{9}$$

where F_H and F_C are the heating (cooling) operation quota, which is the unit in a heating (cooling) season operation hours and a heating (cooling) hours ratio. The thermal resistance R_f is calculated:

$$R_f = \frac{1}{\pi d_1 K} \tag{10}$$

where d_1 is the inner diameter of U-tube. The thermal resistance R_{pe} of the inner wall of the R_{pe} U-tube is represented:

$$R_{pe} = \frac{1}{2\pi\lambda_p}\ln\left[\frac{d_e}{d_e-(d_2-d_1)}\right] \tag{11}$$

where d_2 is the outer diameter of *U*-tube, $d_e = (n)^{1/2}d_2$ – the equivalent diameter of tube, n – the number of tubes, and λ_p – the average thermal conductivity of *U*-pipe. The thermal resistance R_b of pile reads:

$$R_b = \frac{1}{2\pi\lambda_b}\ln\left(\frac{d_b}{d_e}\right) \tag{12}$$

where λ_b is the average thermal conductivity of pile concrete and d_b – the pile diameter. Let us denote:

$$I(u) = \frac{1}{2}\int_u^\infty \frac{\mathrm{e}^{-s}}{s}\mathrm{d}s$$

The thermal resistance R_S of strata and are given:

$$R_S = \frac{1}{2\lambda_S} I\left(\frac{r_b}{2\sqrt{a\tau}}\right) \tag{13}$$

where λ_S is the average thermal conductivity of soil, r_b – the pile radius, a – the soil thermal diffusivity, and τ – the running time. The additional thermal resistance R_{SP} – the caused by short-term continuous pulse load is suggested:

$$R_{SP} = \frac{1}{2\pi\lambda_s} I\left(\frac{r_b}{2\sqrt{a\tau}}\right) \tag{14}$$

Results

Geothermal potential calculation of the building-scale

According to the calculation, the geothermal potential in this area is $2.61 \cdot 10^{11}$ kJ. When there are few data, the recoverable amount can be calculated by the method rate when the recoverable geothermal fluid cannot be accurately calculated. The recovery rate of recoverable geothermal resources should be reasonably determined according to the rock types of different thermal reservoirs, the temperature of thermal reservoirs and the exploration and development of resource. When the degree of local thermal survey is low and the geothermal data information is less, the coefficient can be taken as the empirical value. The geothermal recovery rate in this paper is 15%. The specific calculation is based on the eqs. (1)-(3) of the thermal reservoir volume method. The amount of recoverable geothermal resources in this area is $3.92 \cdot 10^{10}$ kJ, equivalent to 1350 tons of standard coal.

Building heating demand simulation and calculation

The numerical simulation software of HVAC is used to calculate the hourly cooling and heating load of the building. The annual cooling and heating demand is shown in fig. 1. The maximum cooling demand of the project is 1286.31 kW, and the maximum cooling demand time occurs at 14 p. m. on July 21. The maximum heating demand of the project is 883.18 kW, and the maximum heating demand occurs at 16 p. m. on January 21. The design demand is based on the maximum cooling and maximum heat demand and cannot guarantee the maximum cooling within five working days. The total cooling demand is 1286.31 kW and the total heating demand is 883.18 kW. The design heating index is 52.30 W/m^2, the design

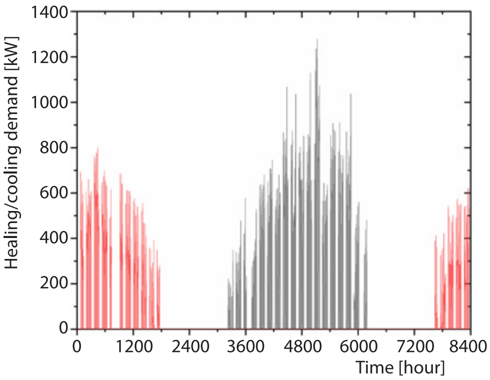

Figure 1. Hourly cooling and heating load of building

cooling index is 76.17 W/m^2, the total cooling capacity during the cooling period is 458799.17 kWh, and the total heat capacity during the heating period is 343448.94 kWh.

Heat exchange calculation and lay-out scheme of Pile foundation

Here we consider the project design using pile ground source heat pump system, summer air conditioning refrigeration, and winter heating. The construction depth of pile pipe is 16 m. The cooling demand of the building is 1286.31 kW, and the total heat demand of the building is 883.18 kW. The heating demand is much smaller than the cooling load, so the system is selected according to the cooling demand.

The center distance of the pile foundation is selected to be 3 m, and up to 1290 piles can be buried under the building. According to the heat exchange capacity of the single pile and the demand required for the project, the lay-out scheme of the heat exchange pile foundation is designed and the application scheme of the heat exchange pile foundation under the two working conditions of the pile length of 16 m and 43 m are discussed. The number of pile foundations required to meet the building heating demand are given:

$$n_H = \frac{Q_{RE}}{Q_H} \tag{15}$$

and

$$n_C = \frac{Q_L}{Q_C} \tag{16}$$

The condition under the pile length of 16 m and 43 m are shown in fig. 2. When the thermal conductivity of pile concrete material is taken as 1.95 W/mK, the heat exchange capacityof single pile in winter is about 1110.24 W, and the heat exchange efficiency of single pile in winter is 69.39 W/m, which is calculated according to the eq. (15) to meet the winter heat demand of 796 piles. The heat transfer capacity of single pile in summer is about 934.4 W, and the heat transfer efficiency of single pile in summer is 58.4 W/m, 1377 heat transfer piles are needed to meet the cooling demand, taking the maximum number of piles 1377, the underground situation of this project cannot meet the load demand. Since the heat transfer capacity of the pile is not sufficient to meet the load required by the upper building according to the actual project length of 16 m, the pile optimization scheme is proposed to increase the pile depth to 43 m to assess the feasibility of its regional heat transfer pile application. Similarly, the heat exchange capacity of single pile in winter is about 2983.77 W. It is calculated that 296 heat transfer piles are needed to meet the heat demand. The heat exchange capacity of single pile in summer is about 2511.2 W, 513 heat exchange piles are needed to meet the cooling demand of the building.

The heat transfer capacity and the number of piles under different working conditions are compared and analyzed. When the pile length increases, the heat transfer of a single pile increases by 1.68 times and the number of pile is significantly reduced, which provides great convenience for the project construction.

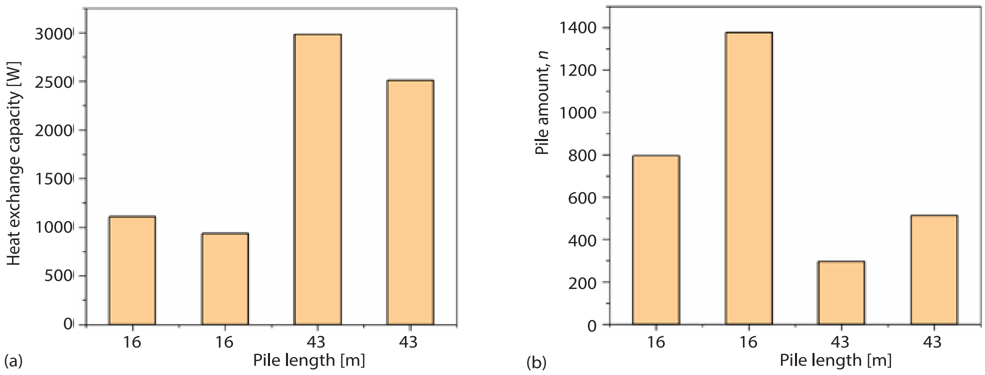

Figure 2. Heat transfer efficiency; (a) comparison of the heat transfer capacity and (b) comparison of the heat transfer pile amount

Conclusion

Taking heat exchange pile foundation as the research object, the feasibility evaluation of the engineering application of heat exchange system for large-scale public building is carried out to seek a suitable utilization of shallow geothermal energy. According to the geological test report, the geothermal reserves of the area are calculated to be $2.61 \cdot 10^{11}$ kJ, with heat equivalent to 9000.08 tonns of standard coal, and the recoverable geothermal resource of the thermal storage of the area is $3.92 \cdot 10^{10}$ kJ, equivalent to 1350 tonns of standard coal. The HVAC numerical simulation software is used to simulate the cooling and heating loads of the enclosure results to calculate the building's hourly cooling and heating demand, and the cooling demand 1286.31 kWh. The calculation method of heat exchange pile and the pile arrangement scheme are given, and the heat exchange effect of pile foundation under different heat exchange pile length conditions is discussed.

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Nomenclature

A – area of calculation, [m^2]
C_r, C_w – specific heat, [kJkg^{-1}°C^{-1}]
c_p – specific heat capacity, [kJkg^{-1}°C^{-1}]
D – thermal storage thickness, [m]
d_b – pile diameter, [m]
K – heat transfer coefficient, [Wm^{-2}°C^{-1}]
n – number of tubes, [–]
Q_k – heat, [kJ]
Q_r – geothermal resources buried, [kJ]
Q'_1 – heatsink transfer capability, [W]
r_b – pile radius, [m]
Δt – temperature difference, [°C]
t_n – indoor calculating temperature, [°C]
t'_w – outdoor calculating temperature, [°C]
V_n – room volume, [m^3]
V_w – amount of cold air inflow, [m^{3}h^{-1}]

Greek symbols

λ_b, λ_p, λ_s – average thermal conductivity, [Wm^{-1}K^{-1}]
ρ_r, ρ_w – density, [kgm^{-3}]
Φ – the porosity, [%]

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