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A performance case study of energy pile foundation at Rosborg Gymnasium (Denmark)

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Abstract

The Rosborg Gymnasium building in Vejle (Denmark) is partially founded on 200 foundation pile heat exchangers (energy piles). The thermo-active foundation has supplemented the heating and free cooling needs of the building since 2011 (4,000 m^2 living area). Operational data from the ground source heat pump installation has been compiled since the beginning of 2015. The heating requirement of the building supplied by the ground source heat pump exceeds the free cooling covered by ground heat exchange. The asymmetric utilisation of the soil should in principle, imply a decrease in the long-term ground temperatures. However, operational data show that the temperatures of the heat-carrier fluid do not fall below +4.2ºC during the heating season (winter) and that the soil recovers to undisturbed conditions during the summer when heat demand is low. In addressing the consequences of an imbalanced ground heat extraction/injection activity, this paper provides a performance study of the energy pile-based ground source heat pump installation utilising operational data. The study demonstrates that the measured seasonal performance factors so far are lower than expected: 2.7 in heating mode and 4.2 in cooling mode. Nevertheless, there is room for improvement if novel energy management strategies are applied. This highlights the relevance of considering the daily heating/cooling requirements of the building during the design phase of the heating and cooling system. Moreover, this study demonstrates the feasibility of ground source heat pump systems based on energy foundations in heating-dominant buildings.

Keywords - Shallow geothermal energy, GSHP, energy foundation, energy pile, case study, performance factors, performance.

1. Introduction

The Danish government has set two main environmental targets: to reduce a 40 % the greenhouse gas emissions by the year 2020 relative to 1990 and to cover the total domestic energy consumption by renewable energy sources by 2050 [1]. In combination with other renewable energies, shallow geothermal energy storage and abstraction has a great potential for realizing these two objectives.

As a new alternative to borehole heat exchangers (BHE) the construction industry developed the foundation pile heat exchanger (energy pile) in the 1980s [2]. Energy piles are thermally active building foundation elements with embedded geothermal pipes fixed to the steel reinforcement in which a circulating fluid exchanges heat with the pile and the surrounding soil. As such, the foundation of the building both serves as a structural component and a heating/cooling supply.

Extensive research has been reported by [3, 4, 5, 6] on the performance of ground source heat pump (GSHP) systems based on traditional BHE. [7] demonstrate that the thermal performance of the system is maintained over five years due to the applied energy management strategies. Typically, GSHP systems require a run-in period of one to two years before a satisfactory system performance is obtained.

Energy foundations are usually associated with high initial costs, but the literature give indications to the economic feasibility relative to traditional heating and cooling systems reported in case studies [8-10], experimental investigations [11, 12] and numerical models [13]. Current knowledge about energy management obtained from existing BHE installations can be applied to thermo-active geostructures which potentially improves both user acceptance and the cost-effectiveness of the system. However, the scarcity of actual published operational data hampers the dissemination of GSHP systems which mainly relates to uncertainty about long-term structural performance under different thermal loading regimes.

In Denmark, there are currently three energy pile foundations that utilise relatively small precast rectangular pile heat exchangers produced by Centrum Pæle A/S. This study is limited to the energy pile foundation at Rosborg Gymnasium (high-school) in Vejle, Denmark. Previous research indicates that the foundation is over-dimensioned in terms of thermal performance [14]. The system is fully operational yet there is a need to better understand its performance and to consider the operation of the GSHP system.

This paper aims to provide a performance study of the energy pile based GSHP system at Rosborg Gymnasium utilising measured, operational data. The paper is organized as follows. Firstly, the test site is described. Secondly, the methods section describes the analysis applied to the operational data. Thirdly, the operational data are analysed, and the performance study is presented and discussed before conclusions are drawn.

2. Description of the Site

An extension of Rosborg Gymnasium is founded on 200 energy piles that have supplied the heating of a 3,949 m^2 living area since 2011. The study area consists of two storeys and a large open canteen area which is situated in the south-west part of the building complex.

The pile foundation was dimensioned taking into account only the mechanical load from the building. That is, the thermal load from the geothermal use of the piles was neglected, as were the thermo-mechanical implications hereof.

The quadratic cross section (0.30 x 0.30 m^2) 15 meter long energy pile has a W-shape PE-X pipe arrangement heat exchanger fixed to the steel reinforcement [14]. The minimum distance between the piles is 1.5 m.

The GSHP system supplies heating in winter while in the summer, the heating circuit is closed. This permits the heat-carrier fluid to flow through the refrigeration circuit, thereby bypassing the heat pump, thus supplementing "free cooling" of the southern rooms in the building. In this way, the heat from the building is utilised for recharging the ground. The actual cooling demand of the building exceeds that which can be supplied by the GSHP system. Figure 1 shows a conceptual diagram of the GSHP system operating in heating mode. It is important to note that the ground-coupled system does not supply the domestic hot water.

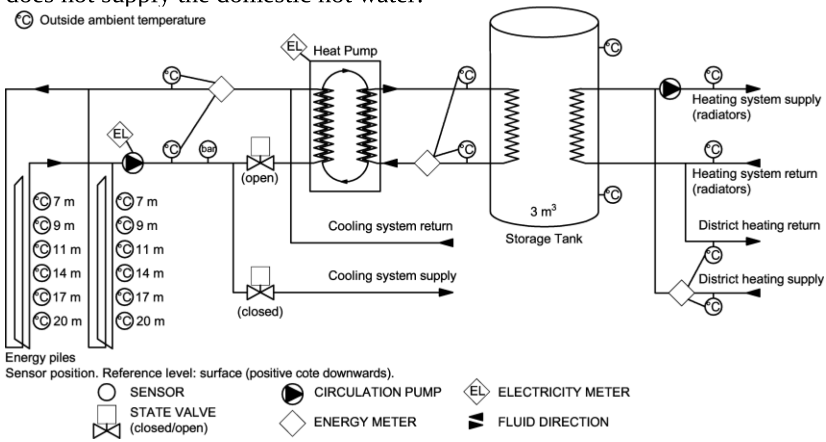

Fig. 1 Schematic of the GSHP systems with energy piles in heating mode and the sensor network.

The 200 pile heat exchangers are divided in 16 groups and within each group, the energy piles are connected in parallel. 2 of the 200 energy piles are instrumented with Pt100 temperature sensors positioned as shown on the left side in Fig. 1. The ground loop utilises a 20 % ethylene glycol based water solution as heat-carrier fluid.

The heat pump consists of a water-to-water unit with a nominal heating capacity of 200 kW and two compressors. The heat pump heats/charges a water accumulation tank from which a traditional radiator-based heating system is supplied. The district heating network serves as an auxiliary heating system. Free cooling utilises ventilation fan-coils coupled to the pile system.

Figure 1 illustrates the control and monitoring system and the relevant parameters for the GSHP system including: inlet and outlet temperatures and flow rates in different loops, local temperature measurements, electricity consumptions and heat pump status (on/off).

The foundation is situated 70 cm below terrain, below the primary groundwater table (any future vertical reference pertains to terrain elevation) with energy piles founded in glacial sand and gravel situated at 5 to 6 meters depth. The glacial sediments are topped by postglacial organic mud. Groundwater is artificially drained from the area. Groundwater flow is expected but it has not been investigated further. Prior soil investigations yield an estimated bulk soil thermal conductivity, λ_s, of 2.4 W/m/K and a volumetric heat capacity, S_{vc}, of 2.4 MJ/m^3/K [14].

All measurements were recorded for a period of 345 days starting on January 18th 2015 in an interval of 60 minutes for the temperatures in the energy piles, the temperatures in the top and bottom of the tank and the on/off state of the heat pump, while the rest of the readings were recorded in 1-minute interval. The district heating data was only available from March the 27th and just two of the Pt100 sensors placed in the instrumented energy piles have worked, malfunctioning from October 2015.

3. Methods

GSHP system performance evaluation consists of data collection and analysis. The methodology applied to the observed data includes an estimation of the heating and free cooling consumptions of the building and an analysis of the energy efficiency of the GSHP system.

3.1. Heating and Free Cooling Consumptions of the Building

The radiator loop was not monitored. Therefore, the heating consumption of the building has been quantified by adding the following two contributions: the energy extracted from the tank and the energy added from the district heating network. The sum of the two contributions yields the thermal energy supplied by the radiators to the living area (Fig. 1). The energy extracted from the tank has been determined by calculating the energy balance from charge and discharge cycles with the top and bottom (tank) temperature records (Fig. 1). The thermal losses of the tank have been considered in accordance with ASHRAE [15].

The free cooling delivered has been established from the temperature and flow readings from the ground loop.

3.2. Efficiency of the GSHP System

The analysis of the energy efficiency of the GSHP installation is based on thermal energy production. The records of inlet, T_{in} [°C], and outlet, T_{out} [°C], temperatures and flows, f [m^3/s], facilitate computation of the instantaneous thermal power outputs, Q [kW], for heating or cooling, using (1):

$$Q = \rho c_p \cdot f \cdot (T_{in} - T_{out}) \qquad (1)$$

where ρc_p is the volumetric heat capacity of the heat-carried fluid.

Three main thermal power outputs are determined and analysed on the basis of the compiled, operational data. The following data, pertaining the closed circuits depicted in (Fig. 1), is collected :

- The energy extracted/rejected from/to the soil by the energy piles.
- The energy delivered to the storage tank by the heat pump.
- Energy supply from the district heating network, i.e., the energy added to the energy which is extracted from the storage tank.

Equation (1) is integrated with respect to time to obtain the accumulated energy during a specified time interval. The electricity consumption of the system, W_{SYS}, is also quantified by integrating the sum of the electricity consumptions of the compressors, W_{HP}, and the circulation pumps, W_{CP}, over time.

The energy efficiency of the system in heating mode is characterized by the coefficient of performance (COP) which is defined as the ratio between the heat output of the heat pump [kW] and the electricity consumption of the compressors and the circulation pumps [kW].

In heating mode, the total thermal energy delivered to the tank is the sum of the thermal energy abstracted from the ground and the measured electricity consumption of the compressors. The same expression is used to determine the energy efficiency ratio (EER) in free cooling mode. In this case, the electricity power consumption corresponds only to the usage of the circulation pumps, while the heat output is the thermal load rejected/injected from/to the ground. The aggregated COP for the entire heating season is defined as the seasonal performance factor (SPF) which includes total power consumption in the system operation over the heating season.

4. Results and Discussion

In the following, the performance of the GSHP system is analysed for the 345-days period.

4.1. Heating and Free Cooling Consumptions of the Building

The total heating consumption for the studied period is 106.57 MWh and the free cooling supplied is 4.44 MWh, which is very low compared to the heating requirements. The GSHP heating system was active for 3400 hours (6072 hours of heating period) while free cooling was utilised for 800 hours during the summer (2208 hours). The asymmetric utilisation of the soil where the net heat flow into the ground between discharge and charge fluxes is not balanced, should in principle, imply a decrease in the long-term ground temperature.

The heating delivered by the heat pump during the period of study is 100.79 MWh, which corresponds to 95% of the total heating requirement (see monthly breakdown in Fig. 2). The district heating contribution was 5.78 MWh, corresponding to 5 % of the total heating consumption. That is, the additional heat required from the district heating was insignificant.

4.2. Efficiency of the GSHP System

Figure 2 shows the monthly energy extracted from the ground compared to the heat delivered by the heat pump. The energy supplied in August is due to the accumulation tank being charged and not actual heating consumption by the building.

Figure 3 shows the monthly performance factors of the GSHP installation. The average of the instantaneous COP values is around 3.0, which is acceptable considering the heat pump manufacturer's estimated COP of 3.49 for fluid temperatures between +7 ^{o}C and +12 ^{o}C. The COP provided by the manufacturer is based on experimental data obtained in steady state heat pump characterization tests.

The SPF for heating is relatively low following the summer despite an increase from 2.0 to 2.7 from spring/summer to autumn. The circulation pumps were continuously working until August 2015, which substantially increased the corresponding electricity consumption, adversely affecting the overall performance of the installation. In September 2015, the external circulation pumps were programed to activate only at every compressor cycle. Subsequently, the electricity consumption has decreased (see Fig. 3). The cooling SPF is 4.2 with a standard deviation of 2.1, which indicates that the monthly average EERs are highly unstable. Hence, the system operation needs to be adjusted.

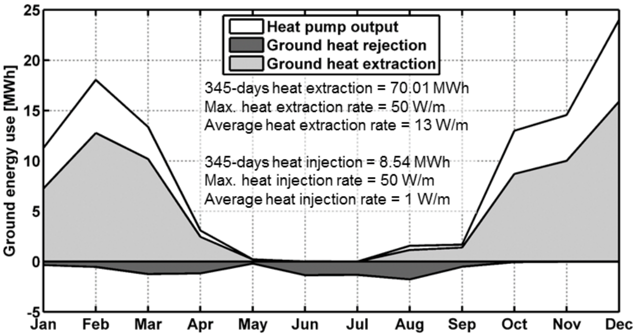

Fig. 2 Key figures for the thermal use of the energy piles in 2015.

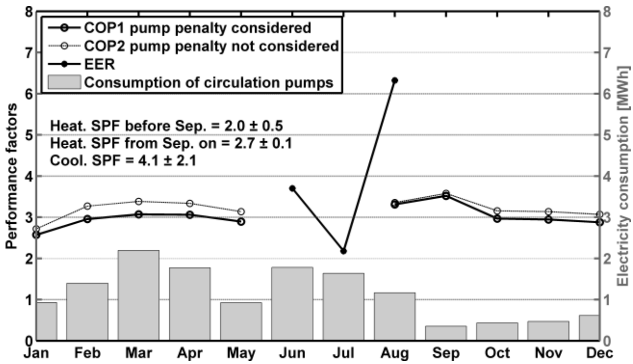

Fig. 3 Monthly performance factor for the GSHP system in heating and free cooling mode, respectively. SPFs: the electricity consumption of the secondary elements is considered also over the periods where the heat pump is not running, as it affects the overall performance.

Figure 4 illustrates measurements during a single day in January 2015 (A) and in December 2015 (B), respectively, of fluid inlet- and outlet temperatures to the heat pump, outdoor air temperatures, fluid supply temperatures to the storage tank and electricity consumption of the compressor.

The temperature of the return fluid to the energy piles does not decrease below 6 ^{o}C. When the compressor activates (spikes to 60 kW in January and to 30 kW in December in Fig. 4) the temperature difference between inlet and outlet is around 3 ^{o}C. The water supplementing the accumulation tank peaks at 55 ^{o}C. Notice that the power consumed by the circulation pumps in January is continuously 3 kW while it approaches 0 kW in December. From the 22nd of December (B in Fig. 4) just one compressor is active and the ground loop flow rate has been halved, which implies longer heat pump cycles, in the order of hours instead of minutes, to supply identical heating with lower heat pump capacity and flow rates.

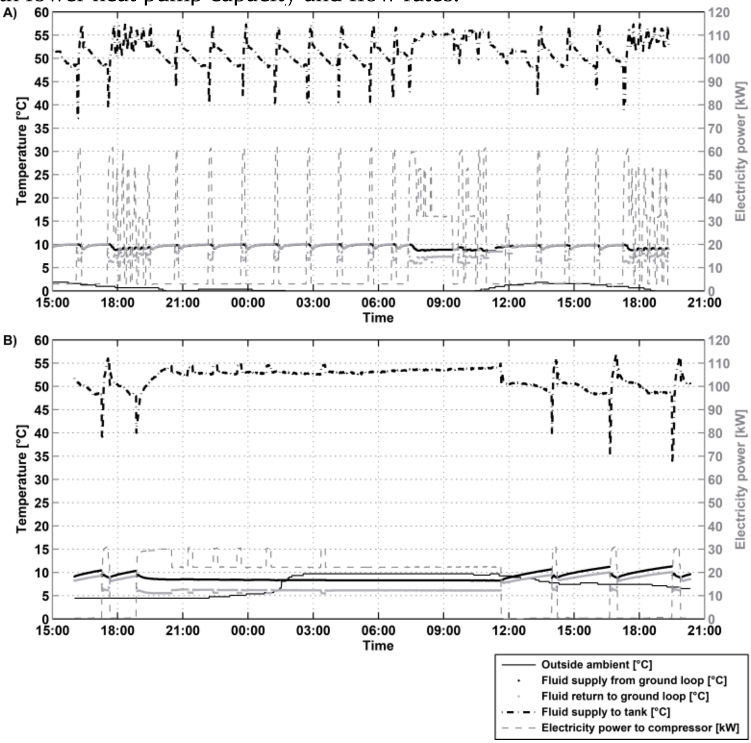

Fig. 4 30-hour performance A) on the 20/01/2015 and B) on the 27/12/2015.

4.3. Ground Energy Balance

Figure 2 shows the monthly extracted and injected thermal energy from and to the ground. The injected energy corresponds to the free cooling production which amounts to 8.54 MWh, corresponding to 12% of the 70.01 MWh extracted by the heat pump. The disagreement with the 4.44 MWh of free cooling consumption mentioned earlier is due to the involuntary free cooling registered from January to May 2015 which recharges the ground as the circulation pumps transfer heat from the building to the ground during heat pump standby. Figure 2 also provides the heat extraction rates per meter length of energy pile, during heating and cooling (50 W/m in both cases) which agree well with reported literature values for “normal underground and water-saturated sediments” given by BS-EN-15450-2007 [16].

4.4. Ground Loop Temperatures and Flow

Lower entering fluid temperature entails lower performance of the system. Figure 5 shows the daily average of the supply and return glycol temperatures for the ground loop. The unusual temperature increase in May and June is potentially due to the change in operation from heating to free cooling.

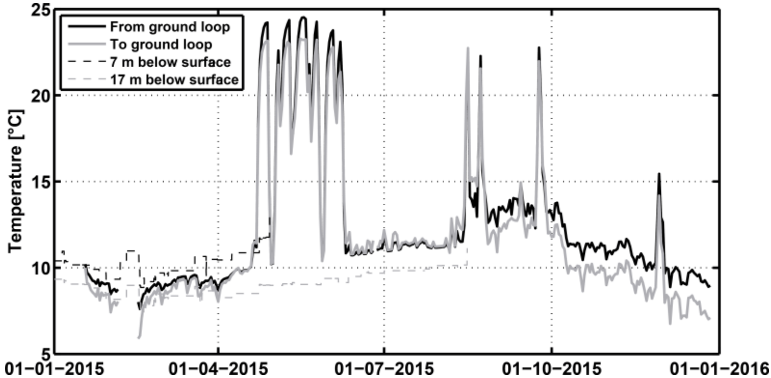

Fig. 5 Ground loop and energy pile temperatures.

In heating mode, the entering fluid temperature is greater than the leaving fluid temperature. While in cooling mode, the heat absorbed from the building increases the leaving fluid temperature, which can be seen to occur from and following June. Due to the decrease in the heating consumption in April and May and ground thermal recharge due to free cooling during summer, the initial ground temperature is recovered and surpassed prior to October according to the brine temperatures in the ground loop.

The expected groundwater flow in the area could bring a continuous load of heat, regardless of the heat injection by free cooling, which may disturb the temperature of the ground, affecting the energy budget of the thermal reservoir. This will be quantified in future research.

The lack of continuous circulation and the associated involuntary recharge of the ground cause the temperature difference between the inlet and outlet of the ground loop to increase following summer (Fig. 5).

Long-term space heating operation measurements indicate that the minimum temperature of the brine entering the heat pump is approximately 6.5 ^{o}C whereas the minimum leaving fluid temperature is 4.2^{o}C. The measured brine temperatures are significantly higher than the +2 ^{o}C limitation recommended by [17].

The two pumps circulating the brine in the ground loop operate in parallel at 15 m^3/h each. The heat pump, however, operates at either 10 m^3/h or 20 m^3/h depending on whether one or two compressors are active. The resulting flow per energy pile yields a Reynolds number of 1400, which is not sufficient for ensuring turbulent flow conditions. Therefore, the total thermal resistance of the energy pile is higher which negatively affects the heat transport to and from the pile. To ensure turbulence the flow rate must be increased by at least 45 % although its implications on the running costs could be counter-productive.

The energy pile temperatures were monitored approximately 7 m and 17 m below terrain (Fig. 5). The pile temperature measurements reflect the variation in the ground loop temperatures. Pile temperatures are relatively high throughout the year, implying that heat extraction from the ground can be further increased. Moreover, this indicates that the energy foundation is over-dimensioned in terms of thermal capacity.

4.5. New Strategies

Optimizing the energy performance of GSHP system can be achieved by managing its operation. The following proposals potentially improve the GSHP performance:

- Reduce the electricity consumption of the circulation pumps by synchronising properly their cycles and the compressors.
- Increase the ground loop flow in order to decrease the pile thermal resistance.
- Adapt the thermal energy generated by the system with the thermal load, increasing heat extraction from the ground. To this end, the ventilation can be supplied with the GSHP system instead of with the district heating network.
- Adjust the activation indoor temperature and flow conditions for the circulation pumps to improve the free cooling performance and increase its use by ventilation of additional rooms during the summer.

5. Conclusions

The Rosborg Gymnasium building in Vejle (Denmark) is partially founded on 200 energy piles. The thermo-active foundation has supplemented the heating and cooling of the gymnasium since 2011 (4,000 m^2 living area). This paper provides a performance study of the energy pile-based ground source heat pump installation utilising operational data compiled since the beginning of 2015.

The results indicate that the GSHP system is a viable option. However, an overall heating seasonal performance factor (SPF) of 2.7 and a mean coefficient of performance (COP) value of 2.9 in December 2015 indicate that the electricity consumption of the circulation pumps is relatively high and that it can be further reduced. Future investigation will encompass a comparison with traditional energy sources in terms of economy and CO2 emissions.

Ground loop temperatures are high during all seasons, implying that the GSHP system is over-sized in terms of thermal performance and capacity. As such higher heat extraction rates (from the ground) can be applied. Free cooling significantly improves the thermal recovery of the soil during the summer.

If the heating and cooling demands of the building are known, an optimal sizing of the heat pump and a more accurate estimation of the required number of energy piles are possible. To that end, the dimensioning needs to be based on ground thermal response test analysis and thermal dynamic simulations of the building and of the energy pile system.

Further research on Rosborg Gymnasium case study will include longer operational data periods, groundwater flow implications in the energy recharge and withdrawal processes of the ground and thermal influences between activated and non-activated piles in irregular foundation patterns.

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