NUMERICAL STUDY OF THE THERMAL PERFORMANCE OF ENERGY MICROPILES IN NORDIC REGION

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KEYWORDS

Energy micropiles, energy geostructure, thermal performance, retrofitting

ABSTRACT

The idea of using underground structures for heating and cooling was first concretized in the 1980s with energy slabs, followed by piles, retaining walls and tunnels [1]. These structures, which play an energy role in addition to their conventional structural role, are referred to as “energy geostructures”. Pile foundations are currently among the most used energy geostructures. They are particularly suitable for utilizing the ground thermal energy, as they extend to depths where soil temperature is quite constant and independent from daily or seasonal variations [2,3]. However, for structural retrofitting, underpinning of existing foundations, and in areas with space, vibration, and noise constraints, micropiles are the most suitable solution. Moreover, micropiles are suited for difficult ground and drilling conditions as is the case in many Nordic countries.

Due to its very cold climate, the Nordic region needs more heating than cooling. This study investigates the thermal performance of an energy micropile in the Nordic region. The results show that the energy micropile provided a thermal power of about 31 W/m after a 30 day-simulation period, which demonstrates the potential of energy micropiles for heating buildings in the Nordic region during winter. However, a drop in heat output was observed over time, which later stabilized. Therefore, for long-term use, a hybrid/integrated solution of energy micropiles with district heating system, solar pannels and other energy sources can be utilized to compensate for the unbalanced thermal load and increase the performance of the system. In addition, the group effect of

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energy micropiles and the thermal effects of the presence of grout in the system should be further investigated.

1. INTRODUCTION

In the early 1950s, in response to the demand for innovative techniques to underpin historic buildings and monuments, the “palo radice” or “root pile” was developed by an Italian construction company, Fondedile [4]. The technology was later introduced in several other countries, and “root pile” was replaced by “micropiles”. Micropiles are smaller piles with a diameter of less than 30 cm and a length of usually less than 30 m [4]. Despite their small size, large loads of up to 5000 kN can be sustained thanks to the high-capacity steel elements utilized. They are particularly suitable when soil and drilling conditions are difficult. The equipment used to install micropiles is not as large and heavy as that required for conventional piles. Therefore, they can easily be used in swampy areas and in areas with wet or soft surficial soils [4], as is the case of the Nordic region, with minimal impact on the environment. The most populated areas of the Nordic region are covered with very soft soils, such as marine, glacial, and post-glacial clays, and silts [5]. There exist several study cases on the use of micropiles in soft soils [6,7].Today, micropiles are mostly used as foundation support elements, underpinning of existing foundations, structural retrofitting and in situ reinforcement. Depending on the ground properties and the required bearing capacity among many factors, micropiles made of steel, grouted, driven, or drilled may be used. Figure 1 shows a case study of the installation of a grouted micropile in an existing building for seismic strengthening.

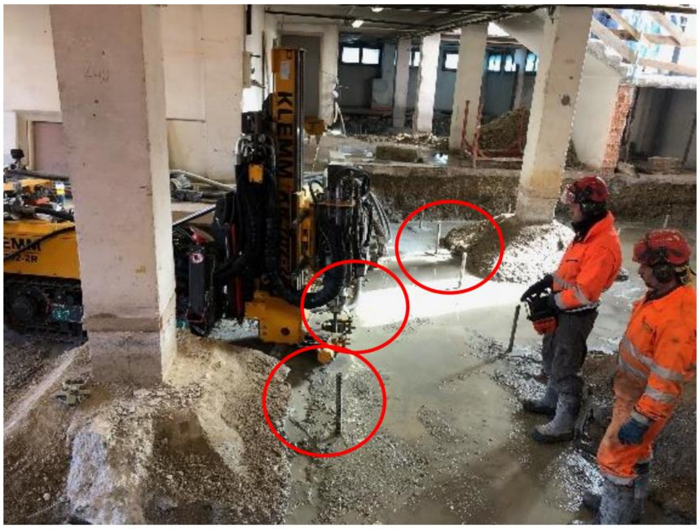


Figure 1 Installation of TITAN micropiles for seismic retrofitting (the red circles enclose the top of some micropiles).

The use of micropiles could be extended to the heating and cooling of buildings, by using plastic pipes in which a heat exchanger fluid circulates, exchanging heat between the ground and the building (Figure 2).

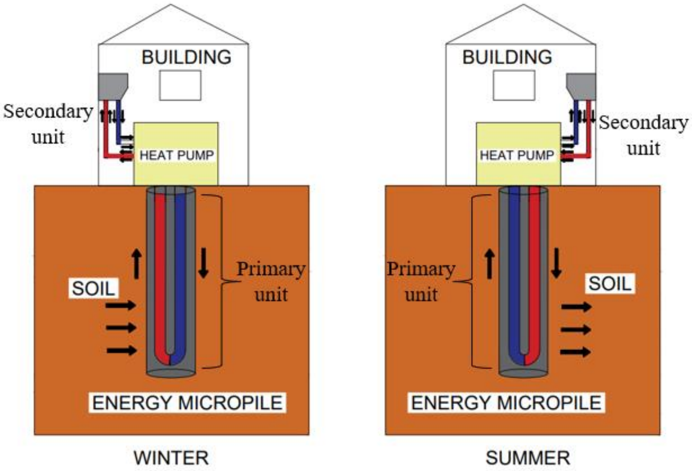


Figure 2 Scheme of energy micropile systems in a building.

In this way, micropiles can provide both structural and energy rehabilitation [8] and are then referred to as energy micropiles. In fact, energy micropiles have proven their efficiency in cooling of buildings in summer, with a thermal performance of about 30W/m [9], comparable to that of energy piles. In the Nordic countries, which are known for their very cold climate, more heating is required than cooling. This numerical study investigates the thermal performance of an energy micropile in the Nordic region. The software COMSOL Multiphysics has been used for the analysis. The model was created and validated with TRT test data available in literature and further used to simulate an energy micropile over a period of 30 days under winter conditions.

2. NUMERICAL SIMULATION

The software COMSOL Multiphysics version 6.1 (COMSOL, 2018) was used in this study to conduct the thermal analysis. The 3D model comprises three main elements: pipes, the structural body (composed of grout and/or steel), and the ground. The micropile was 12 m long and 20 cm wide with a 103/72 steel pipe reinforcement in which a 32 mm pipe was introduced. The model was validated using the thermal response test data in Jalaluddin et al. [10].

Mathematical formulation

The equation governing incompressible flow is derived from the fundamental principles of conservation of mass and momentum. Specifically, the conservation of mass principle for a stationary and incompressible flow is mathematically expressed by the continuity equation as:

$$\nabla \cdot \rho \boldsymbol{u} = 0$$

The Navier-Stokes equation for incompressible flow, accounting for transient effects, is expressed as [11]:

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u}\right) = -\nabla p + \rho \boldsymbol{g} + \mu \nabla^2 \boldsymbol{u}$$

where ρ represents the fluid density [kg/m^3], $\boldsymbol{u}$ denotes the velocity field of the fluid [m/s], p signifies the pressure field [Pa] and μ denotes dynamic viscosity. The heat transfer in solids and liquids interface of Comsol Multiphysics solves for the following equations [12]:

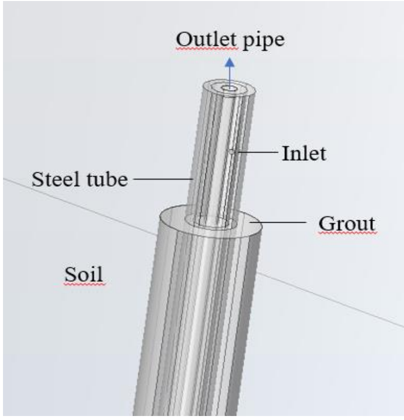
$$C_p(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T) + \nabla \cdot (\boldsymbol{q} + \boldsymbol{q_r}) = Q_{ted} + Q$$

$$C_p(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T) + \nabla \cdot (\boldsymbol{q} + \boldsymbol{q_r}) = Q + Q_p + Q_{vd}$$

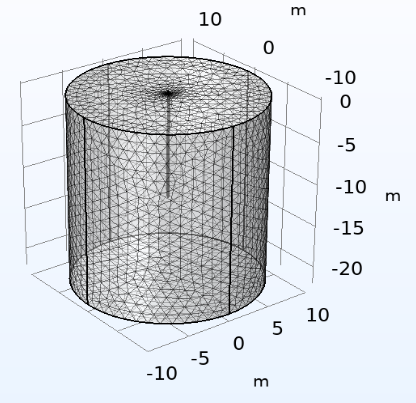
Where $\boldsymbol{q}$ is the heat flux by conduction [W/m^2], $\boldsymbol{q_r}$ is the heat flux by radiation [W/m^2], Q_{ted} is the thermoelastic damping and accounts for thermoelastic effects in solids and Q_p represents the work done by pressure changes and Q_{vd} represents viscous dissipation in the fluid.

Initial and boundary conditions

The soil and micropile domains were assumed to be isotropic and homogenous and at an initial temperature of 10°C. A thermal insulation boundary condition was assumed at the top surface of the soil domain, while a temperature of 10°C was fixed at both the bottom and perimeter boundaries. A coaxial pipe configuration was adopted in the grouted micropiles wherein the steel tube served as the inlet pipe and a centre HDPE pipe as the outlet pipe. A fine mesh distribution was adopted in the model as illustrated in Figure 3.



(a)



(b)

Figure 3 3D FEM model:(a) geometry and (b) mesh distribution.

The flow rate and inlet temperature of the fluid were 10^{-4} m^3/s and 4°C respectively. A nonlocal integration coupling over the boundary surface was defined to evaluate the outflow temperature at the outlet point of the pipes. The thermal power was calculated using the following thermal energy equation as:

$$H = \frac{Q_{in}\,\rho_{hcf}\,C_p\,\Delta T}{L}$$

The properties of the materials used in the simulation are given in table 1.

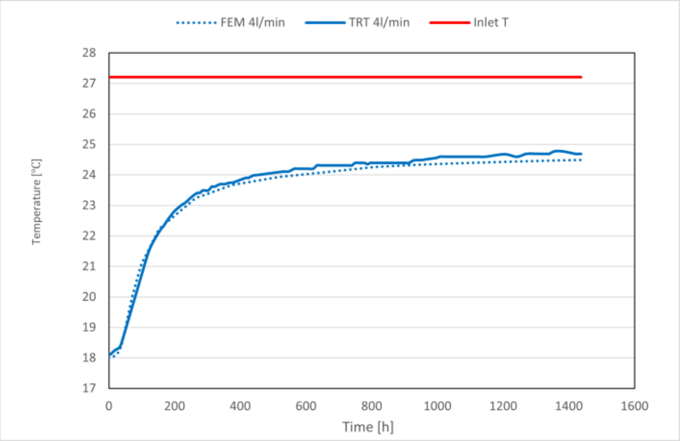
Table 1. Main properties of materials used in the simulation

Properties	Fluid (water)	Pipes (HDPE)	Steel (S355J2H)	Grout	Soil (Clay)
Thermal conductivity [W/(m K)]	0.6	0.6	45	1.6	1.2
Specific heat capacity [J/(kg K)]	4186	2000	420	880	1800
Density [kg/m^3]	1000	950	7850	2300	1700

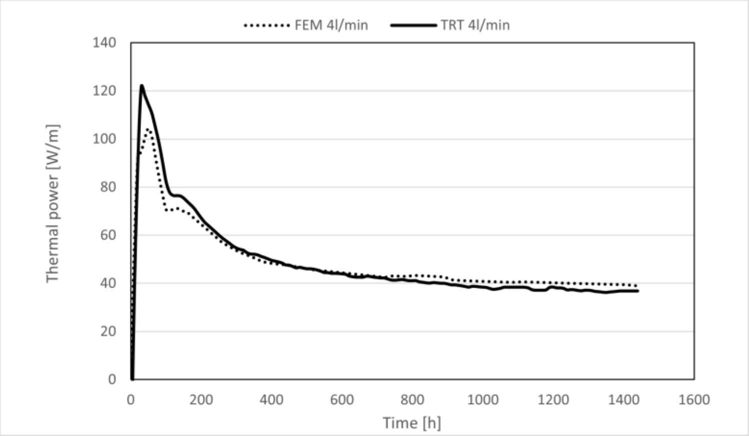
3. RESULTS AND DISCUSSION

Model validation

As previously indicated, the thermal response test data of Jalaluddin et al. [10] was used to validate the model. A perfect agreement of the outlet temperature and the thermal power can be observed between the tests results and the simulation results (Figure 4).



(a)



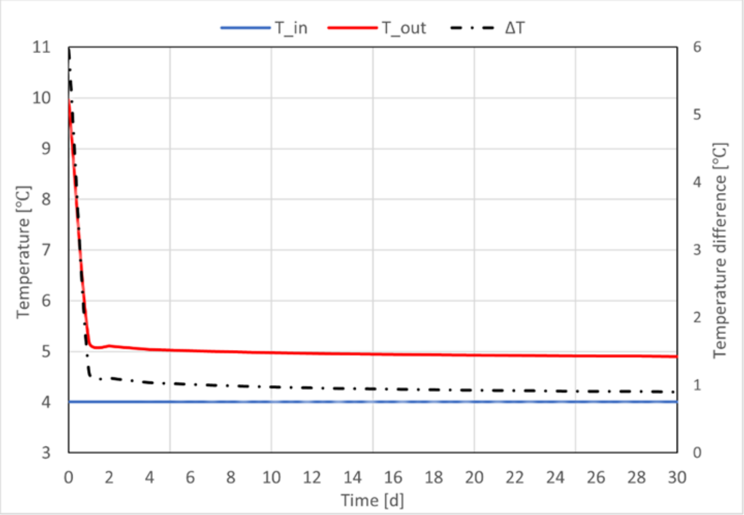
(b)

Figure 4 Comparison between thermal response test data and FEM results: temperature (a) and thermal power (b).

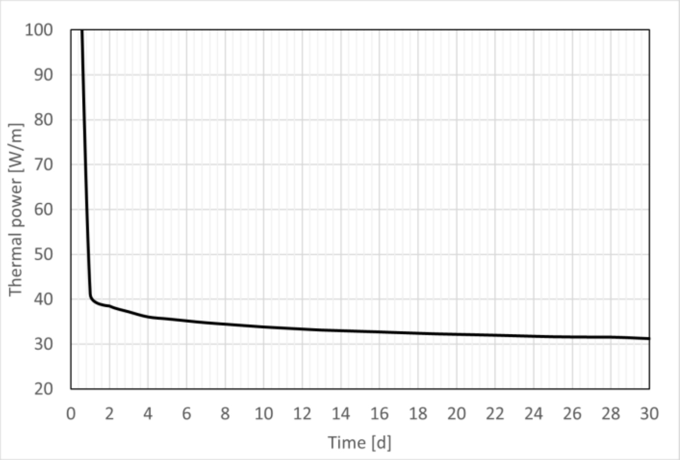
The largest difference is observed at the peak of the thermal power plot, representing an approximate difference of 15%. This validation confirms the reliability of the numerical model, affirming its suitability for further analysis.

Simulation results

The validated model was then used for the simulation. Figure 5 shows the fluid outlet temperature with time.



(a)



(b)

Figure 5 Simulation results in terms of: temperature (a) and thermal power (b).

An outlet fluid temperature approximately equal to its initial temperature is observed at the beginning of the simulation when t < 1 day. However, after 1 day, the temperature considerably drops to 5°C thereby decreasing ΔT. As time progresses, ΔT decreases more slowly and the outlet temperature eventually stabilizes at a value of 4.9°C. The same pattern is observed with thermal power, where the thermal power at t = 1 day is 41.13 W/m which then reduces to about 31.17 W/m after 30 days.

The performance of the system is highest at the beginning when the temperature difference between the soil domain and the pile domain is largest. As the exchange fluid circulates in the system, it extracts heat from the ground and therefore leaves at a higher temperature. With more heat extraction, the difference in temperature between the two domains decreases thereby reducing the performance of the system. Furthermore, as micropiles are usually installed in a group, although a large number increases the total heat extraction from the ground, this may lead to a faster thermal equilibrium in the system. Moreover, due to thermal interference, the average thermal performance of a single micropile may decrease over time. In addition, although the reinforcement tube is usually flushed before the exchange fluid is circulated, some grout may still be present in the annular space, which may lead to grout intrusion in the heat pump and thus disrupt the thermal performance of the system.

4. CONCLUSIONS

In this paper the thermal performance of a grouted coaxial energy micropile installed in clay during winter was analysed for the Nordic region. The 30-day study shows that the energy micropile can provide about 31.17 W/m which illustrates its potential for heating buildings in the Nordic region. However, since the thermal performance of the system was observed to decrease over time, it is recommended to use a hybrid/integrated system of energy micropiles with district heating system, solar pannels and other energy sources to balance the unbalanced thermal load and improve performance. In addition, the effect of a larger number of micropiles in a group and the presence of grout in the annular space may reduce the thermal performance of the system and should therefore be further investigated.

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