Numerical modeling and analysis of the effect of different parameters on the efficiency and thermal performance of energy piles

Mohammad Hossein Sobhdam[1], Mohammad Mehdi Ahmadi[1*]

[1]Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT

In recent years, with the growth of industrial societies, the amount of energy consumption in the world has been increasing. On the other hand, the most consumed energy sources in the world are non-renewable energy sources. For this reason, governments and industries have invested in facilitating and make renewable energy sources cheaper. One of these renewable energies is geothermal energy, which is one of the most economical ways to use this energy, using heat exchange systems in piles and foundations. Various construction methods have been used to implement energy piles and many parameters are involved in their design. In this research, the effect of each of these parameters on the thermal performance of the energy pile is investigated using 3D numerical modeling and using the finite element method with COMSOL. Flow rate, pile length, pipe diameter and thickness and center-to-center distance of pipes are the parameters that have been investigated in this research. Also, by using the Taguchi method, the effect of important parameters on the output power of the energy pile, in the short and long term, were compared and ranked. The obtained results have shown that reducing the flow rate, increasing the length of the pile, reducing the diameter and thickness of the pipe improves the thermal performance of the energy pile. In addition, pipe configuration, pile length and the distance from the center to the center of the pipes compared to other parameters, are the most important parameters affecting the output power of the energy pile.

KEYWORDS

Geothermal energy - Energy pile - Thermal performance - Numerical modeling – Taguchi method

[*] Corresponding Author: Email: mmahmadi@sharif.edu

1. Introduction

The growing global focus on renewable energy has elevated interest in energy piles. According to the IPCC, the Earth's surface temperature has risen by about 1.5°C since pre-industrial times, largely due to excessive greenhouse gas emissions [1]. Building heating systems are significant contributors, emitting over 2250 megatons of CO_2 annually, as reported by the IEA [2]. Heating and cooling systems based on renewable sources can play a pivotal role in reducing these emissions. Ground Source Heat Pumps (GSHPs) are a promising solution in this context. Energy piles, a type of GSHP, offer a dual function: structural support and thermal energy exchange with the ground. Their dual functionality makes them particularly attractive [3]. While promising, energy pile design lacks a comprehensive standard for integrating thermal and mechanical behavior, leading to reliance on empirical models [4].

Several experimental and numerical studies have been conducted. Research shows that heating induces compressive stress and thermal expansion in piles. The radial nature of heat transfer, rapid thermal stabilization, and thermal resistance are key performance aspects. Studies further reveal that soil thermal conductivity and flow regime significantly affect performance, while pile material conductivity is less impactful. 3D numerical models emphasize the importance of pipe surface area, pile length, and pipe arrangement (e.g., U-shape, W-shape, helical and so on) [5, 6].

Groundwater flow plays a crucial role, with even small flows enhancing heat exchange, especially in colder seasons. Pipe configuration also affects thermal efficiency. While helical pipes show lower total heat transfer, they offer higher efficiency per unit flow [7, 8].

This research uses 3D finite element modeling in COMSOL to analyze the effects of pile length, pipe diameter, material, flow rate, and spacing between pipes across various pipe configurations. Using the Taguchi method, the study ranks the influence of each parameter on thermal performance, providing practical insights for optimal energy pile design and real-world implementation.

2. Methodology

In this study, a numerical model was developed using COMSOL Multiphysics to investigate the thermal performance of a concrete energy pile embedded in a soil domain measuring 25 m × 4 m × 4 m. A 20 m long, 0.8 m diameter pile was placed at the center of the domain. The chosen dimensions enable practical implementation using conventional drilling equipment with reduced costs and technical constraints.

The heat exchange system consists of high-density polyethylene (HDPE) U-shaped pipes, each 16 m in length, arranged in series with 200 mm center-to-center spacing. The pipes have an internal diameter of 16 mm and wall thickness of 4 mm, surrounded by a 70 mm concrete cover. The top 4 m of the pile contains no pipe to minimize surface temperature fluctuation effects. Water, used as the heat transfer fluid, enters the system at 34 °C with a constant flow velocity of 0.4 m/s.

Boundary conditions include fixed temperatures on the lateral and bottom surfaces of the soil domain, while the top surface is thermally insulated. The initial temperature of the soil is assumed to be 14 °C.

Mesh generation was carefully optimized to ensure computational efficiency and accuracy. A combination of tetrahedral elements (for soil and pile) and prismatic elements (for pipes) was used. The prismatic mesh was generated using a 2D triangular surface mesh on the pipe cross-section, then extruded using the Swept mesh technique [9]. This approach significantly reduced the degree of freedom and computational cost. The final mesh for a single U-pipe configuration comprised 560,640 elements and 836,950 degrees of freedom.

3. Results and Discussion

An increase in the fluid flow velocity within an energy pile leads to a rise in the outlet fluid temperature. However, the relationship between flow velocity and outlet temperature is nonlinear. As the velocity increases, the rate of temperature rise diminishes, and at high velocities, the change in outlet temperature becomes negligible. Furthermore, at lower flow velocities, increasing the number of U-loops in series within the energy pile pipe results in a noticeable decrease in outlet fluid temperature. Conversely, this effect becomes insignificant at higher velocities. It was observed that by increasing the flow velocity from 0.1 m/s to 1.5 m/s, the outlet temperature increased by 30% in the U-pipe, 43% in the W-pipe, and 52% in the 3U-pipe. Similarly, the heat exchanged between the fluid and the surrounding environment increased by 38% for the U-pipe, 54% for the W-pipe, and 66% for the 3U-pipe under the same change in flow velocity.

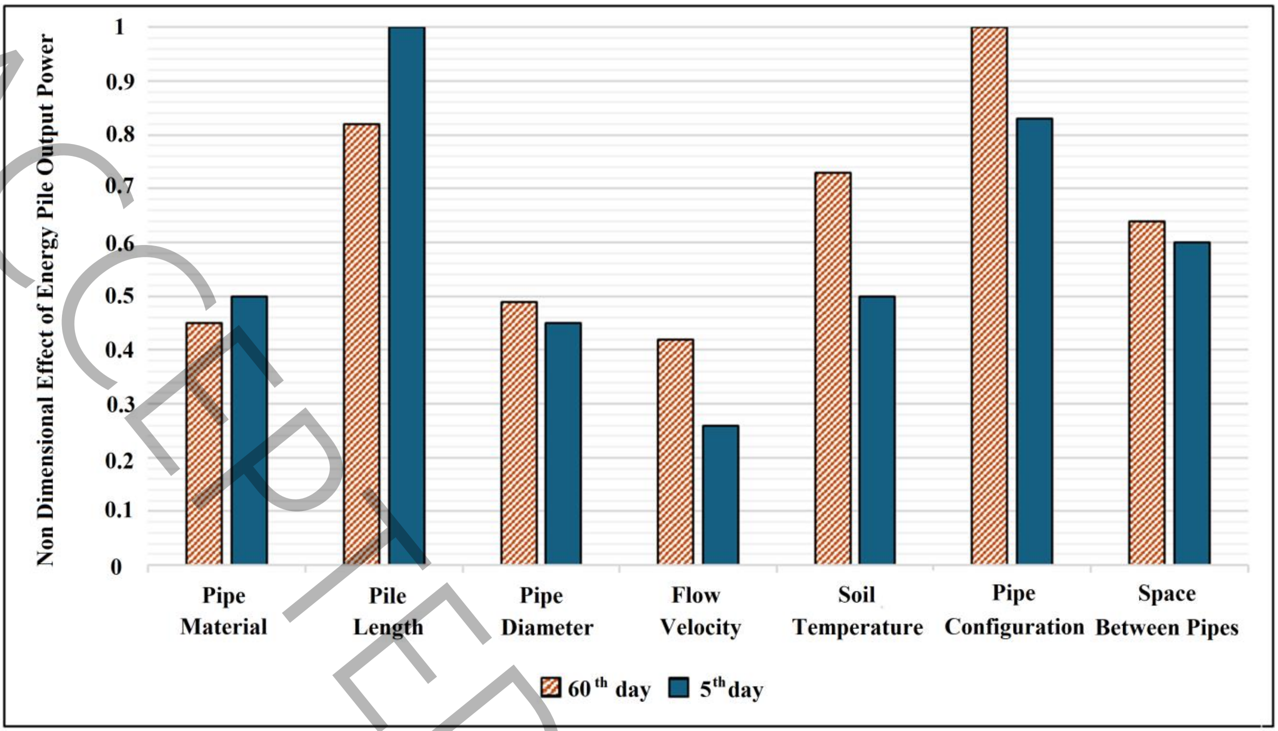

Figure 1. Non dimensional effect of different parameters on energy output of energy pile

The length of the energy pile significantly affects the outlet fluid temperature. When the pile length increased from 10 m to 70 m, the outlet temperature decreased by 20% for the U-pipe, 27% for the W-pipe, and 31% for the 3U-pipe. Notably, the majority of this temperature drop occurs at shorter pile lengths. In addition, the heat exchanged per unit length of the pile decreases substantially with increasing pile length. For instance, in the 3U-pipe configuration, this reduction exceeds 45%, while in the U-pipe it is around 20%.

Increasing the wall thickness of the polyethylene pipe enhances the outlet fluid temperature. For instance, in a U-pipe configuration, increasing the pipe thickness from 2 mm to 10 mm results in a 2% rise in outlet fluid temperature. Although a thicker pipe wall reduces the energy pile's thermal efficiency, it must not be so thin that it fails to withstand the pressures exerted by fresh concrete during installation.

With a constant flow velocity, increasing the pipe diameter results in a higher outlet fluid temperature. At very small and very large diameters, the thermal performance of the energy pile becomes independent of the pipe length. However, for larger diameters, the amount of heat exchanged increases with pipe length. For example, at a pipe diameter of 42 mm, although the outlet temperature in the U-pipe is only 1.6% higher than that of the 3U-pipe, the amount of heat exchanged in the 3U-pipe is 88% greater than in the U-pipe.

The center-to-center spacing of the pipes plays a crucial role in mitigating thermal interference and improving the energy pile’s performance. Increasing this spacing from 100 mm to 300 mm in the 3U-pipe configuration leads to a 3.2% reduction in outlet temperature. In configurations such as the 10U and 9U-pipes, where the outlet pipe carrying cooled fluid is located too close to the inlet pipe containing hot fluid, thermal interference occurs. This significantly affects the thermal efficiency of the energy pile, resulting in reduced overall performance.

Among various experimental design approaches, the Taguchi method stands out for its simplicity, efficiency, robustness, and adaptability in engineering problems. Its implementation begins with the construction of an appropriate orthogonal array, a two-dimensional matrix that defines the parameter levels for each simulation (modeling) scenario. Each row corresponds to a specific experimental run, while each column represents a particular parameter, ensuring statistical independence and mutual orthogonality between parameters. This structure allows equal representation of all parameter levels across simulations, enabling reliable identification of the most influential factors on the output. In this study, seven parameters were selected for evaluation: pipe spacing, pipe arrangement, soil domain temperature, fluid velocity, pipe diameter, pile length, and pipe material. These were chosen based on technical literature, experimental studies, and practical implementation standards. For example, pipe diameters were selected according to DIN 8074 and ISO 4427 standards for HDPE pipes with a nominal pressure rating of 16 bar. Pipe material was considered from low

(HDPE) to high (steel) thermal conductivity values. Simulations were conducted over a 60-day period, with thermal performance evaluated on day 5 and day 60 as representatives of short-term and long-term behavior. Statistical analysis, particularly the mean-level calculation method, was used to determine each parameter's effect on the system's thermal output (i.e., exchanged heat). This analysis involved averaging the output for each level, calculating the difference between levels, and ranking the parameters based on their influence.

Figure 1 illustrates the dimensionless impact of various parameters on the energy pile's output power. In the short term, soil ambient temperature and pipe material each have about half the influence of pile length, while pipe diameter has slightly less impact. In the long term, the effects of pipe diameter, pipe material, pipe spacing, and soil temperature converge, showing similar influence levels. Notably, the impact of soil ambient temperature increases by over 50% in the long term, likely due to the system approaching thermal equilibrium, making soil conditions more significant for sustained energy output performance.

4. Conclusions

In this study, the impact of various parameters—including flow velocity, pile length, pipe diameter, pipe wall thickness, and others—on the thermal performance of energy piles was investigated using three-dimensional finite element numerical modeling. U-shaped heat exchange pipes, arranged in series, were employed within the energy pile system. The developed numerical model was validated against previous experimental and numerical studies, ensuring its accuracy and reliability for further analysis. Additionally, the Taguchi statistical method was applied to evaluate and compare the influence of each parameter on the output thermal power of the energy pile system.

Increasing fluid flow velocity raises the outlet temperature, but the relationship is nonlinear, with diminishing temperature gains at higher velocities. At low velocities, increasing the number of U-shaped pipes in series significantly lowers outlet temperature, while this effect is minimal at high velocities. Changing flow velocity from 0.1 to 1.5 m/s increased outlet temperature by 30% (U-pipe), 43% (W-pipe), and 52% (3U-pipe), with corresponding heat exchange increases of 38%, 54%, and 66%. Longer pile lengths reduce outlet temperature and heat exchange per unit length, especially for shorter piles. Larger pipe diameters increase outlet temperature but show length-independent performance at extreme sizes. Increasing polyethylene pipe thickness raises outlet temperature slightly but may reduce system efficiency. Larger center-to-center pipe spacing reduces thermal interference, improving performance. Taguchi analysis identified pile length, pipe arrangement, and pipe spacing as the most influential parameters on output power, with flow velocity having a comparatively minor effect.

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