学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Design and performance evaluation methodology of thermal piles with large diameter and heat capacity
(熱容量を持つ大口径基礎杭利用地中熱交換器の設計・性能評価手法に関する研究)

In today's world, the demand for energy is immense, leading to substantial annual energy consumption. The foremost environmental challenge facing humanity is global warming, largely attributed to the greenhouse effect caused by carbon dioxide (CO2) emissions. These significant CO2 emissions mainly stem from the extensive use of fossil fuels to meet diverse energy needs. Notably, building energy consumption represents about 40% of global energy usage, with heating and cooling in buildings accounting for 50%-60% of this figure. To substantially reduce greenhouse gas emissions, energy supplies for space cooling and heating must be shifted from fossil fuels to renewable energy sources.
Ground Source Heat Pump (GSHP) systems are increasingly being adopted in residential and commercial buildings worldwide. However, their widespread application is hindered by the need for large land areas for boreholes when installing multiple Ground Heat Exchangers (GHEs). Thermal piles, a novel type of vertical GHE, exhibit superior heat exchange capabilities because of their large diameter and high thermal capacity. Their primary advantage is the elimination of the need for additional land, as they are integrated directly beneath buildings. This dual functionality provides both structural support and efficient heat exchange.
This doctoral thesis delves into the design and performance evaluation methods for large diameter, high capacity thermal piles, proposing optimal design strategies for their use in energy-efficient buildings.
Chapter 1 presents the background of the study, setting the stage and underscoring the significance of the research. It emphasizes the importance of thermal piles. The chapter outlines the research objectives, concentrating on devising novel methodologies for the design and performance evaluation of thermal piles.
Chapter 2 offers a comprehensive literature review of the existing research on spiral tube GHEs and their integration into thermal piles. This chapter sets the foundation for the development of novel design and evaluation methods proposed in this thesis, aiming to bridge the identified research gaps.
Chapter 3 introduces a novel computational approach for double spiral tube GHEs, designed to enhance the precision and efficiency of heat transfer calculation. This method employs the Capacity and Resistance Model (CaRM) approach, offering a comprehensive examination of the heat transfer dynamics in thermal piles. A key innovation is the integration of fin efficiency, which substantially streamlines heat transfer calculations for spiral pipes. The chapter also provides a detailed introduction to a Zero-Energy Building (ZEB) in Sapporo, which serves as the data collection site for method validation. This new calculation method has successfully integrated into the GroundClub and rigorously validated within a GSHP system for winter heating and summer cooling applications. Simulation

results demonstrate a close correlation with actual measured data, characterized by a low Root Mean Squared Error (RMSE) and highly precise fluid temperature variations. The method's superiority in terms of precision and practicality is further underscored by a comparative analysis with another model employed in studying spiral tube GHEs. The comparison reveals that the application of fin efficiency for simplified heat transfer in this model results in more precise calculated outcomes.

Chapter 4 provides an empirical analysis of the performance of double spiral tube GHEs in the ZEB, based on nearly two years of operational data. This chapter improves upon previous research by introducing a novel, comprehensive metric: the coefficient of heat extraction/injection, for a more precise evaluation of GHE performance. The chapter describes the methodology employed to calculate this metric, offering a more precise evaluation of GHE performance. The methodology for calculating this metric is detailed, with a focus on assessing the heat exchange capability of GHEs. An extensive analysis of the measurement data is carried out, employing linear regression and histograms for data simplification and clearer visualization. This method determines an efficiency rate for thermal piles with double spiral tube GHEs at approximately 4 W/mK, significantly higher than conventional U-tube GHEs. These results demonstrate the effectiveness of the new evaluation metric and affirm its practical applicability. Furthermore, the chapter assesses the performance of the GSHP system. This involves calculating the System Coefficient of Performance (SCOP), Seasonal COP, and the annual heat extraction/injection rates of GHEs using the gathered data. The study observes that climate warming, characterized by rising summer temperatures in colder regions, leads to an increased cooling demand, sometimes surpassing winter heating needs. This imbalance in heat extraction and injection causes fluctuations in underground temperatures, affecting heat pump efficiency. These findings emphasize the necessity of incorporating climatic considerations in the design and implementation of future GSHP systems.

Chapter 5 combines the computational methods for double spiral tube GHE, introduced in chapter 3 with the performance evaluation metrics for GHEs discussed in chapter 4. It develops an optimal design approach for thermal piles used in GSHP systems. This approach enables rapid calculation of the ideal pitch length for double spiral tube GHEs and aids in determining the most cost-effective installation techniques for thermal piles. This chapter comprehensively explains the detailed calculation procedures of this optimized design method. Furthermore, the chapter includes simulations of this design methodology under a range of conditions, including daily operating hours, undisturbed ground temperature, underground soil conductivity, underground depth, and the diameter of thermal piles. These factors are crucial in the design of GSHP systems. The results reveal that the spiral length of double spiral GHEs has a significant impact on its thermal efficiency. Several variables markedly affect the optimization process, leading to considerable variations in optimal spiral length and total investment costs under different scenarios. Based on the simulation results, this chapter summarizes patterns in thermal pile design that could guide future projects.

Chapter 6 summarizes the key findings from the previous chapters, recognizing the limitations of the research and outlines potential directions for future studies.