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Research paper

A novel hybrid design algorithm for spiral coil energy piles that considers groundwater advection

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HIGHLIGHTS

- New design algorithm for spiral coil energy piles is proposed.
- Effect of groundwater advection on the design length of heat exchangers is investigated.
- Heat advection due to the groundwater flow can considerably influence the thermal interference effect.
- Hybrid GSHPs design can provide suitable alternatives that reduce the total heat exchanger length.

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ABSTRACT

This paper presents a novel hybrid design algorithm for spiral coil energy piles that considers groundwater advection. The design algorithm considers the groundwater advection effect using an analytical model. During this study, the accuracy of the analytical model was verified for its design application using a finite element (FE) numerical model, and the effect of groundwater advection on the design results was investigated. According to these results, groundwater advection attenuates thermal interference between piles, as well as long-term ground thermal resistance, which contributes to the economical design of energy piles. Moreover, when there is an extreme disparity between cooling and heating loads, hybrid design was achieved using hourly building energy load data calculated by the design builder program. Hybrid design decreases the total heat exchanger length of the energy piles, and reduces the entering water temperature (EWT) variance caused by heat interference. Furthermore, the pile arrangement can influence the impact caused by separation distance. For a square arrangement of piles, the shorter the separation distance, the less the effect from the hybrid system. In contrast, for a linear arrangement of piles, there is no influence caused by the separation distance, and generally, a high reduction rate of heat exchanger length is shown.

1. Introduction

Along with recent rises in fuel costs and global warming problems, it has become a growing interest in alternative energy sources that are renewable and pollute less. In particular, Ground Source Heat Pump (GSHP) systems have become very attractive for space cooling and heating in residential and commercial buildings owing to their high efficiency and reliable operation [1–9]. These systems use the relatively uniform temperature underground as a heat reservoir: it is a source for heating in winter, and a sink for cooling in summer. Though there are various types of GSHP systems, the closed loop system using vertical-borehole ground heat exchangers is the most common type. However, the high initial installation cost of drilling the boreholes, is drawing attention to the use of foundation piles of buildings for heat exchange (called energy piles) [10–13]. This innovative idea has led to notable progress in the use of GSHP systems by making them more sustainable and by reducing their spatial requirements [14]. Compared to conventional vertical boreholes, energy piles are shorter and of larger diameter (Fig. 1). In general, energy piles less than 30 m deep are most widely used in Korea because bedrock is shallow there. Owing to its shortness, the energy pile requires a novel heat exchange pipe configuration (e.g., spiral coil heat exchanger). This type, compared with serial or parallel U-tubes, has the advantage of a greater heat transfer area

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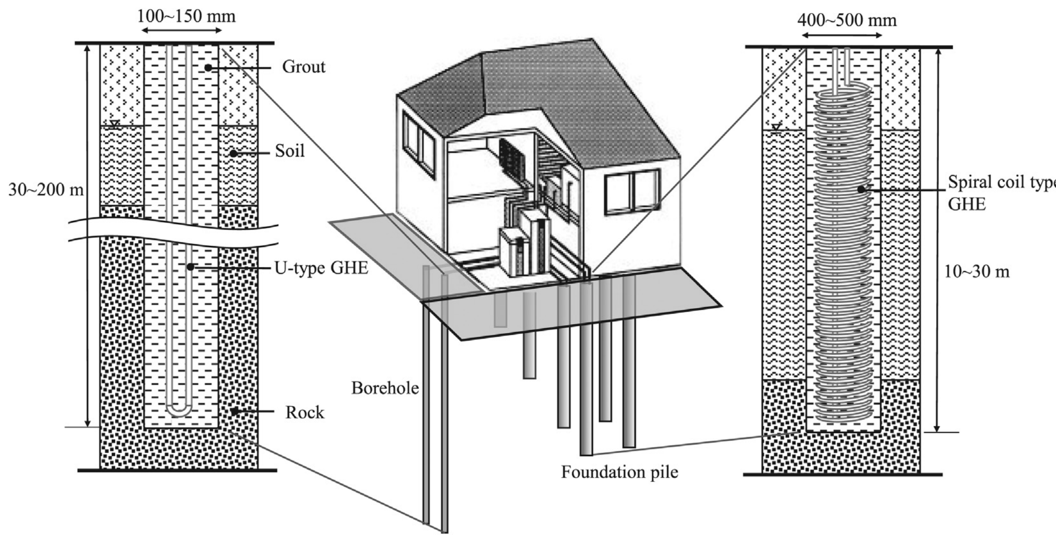

Fig. 1. Schematic diagram of vertical borehole and energy pile [22].

and a better flow pattern that eliminates air-choking in the pipes [15].

For these reasons, a number of studies have been conducted to investigate the thermal behavior of spiral coil energy piles [13,16–23]. Cui et al. [13] developed the ring coil heat source model to investigate transient heat transfer around spiral coil energy piles. They evaluated and discussed the influence of the coil pitch and locations on specific solutions. Zhang et al. [16] illustrated existing heat transfer models, and considered the ring coil model as the most realistic standard, based on heat transfer analysis of spiral coil energy piles. More recently, Zhang et al. [17] developed a new mathematical model for describing the heat transfer of energy pile considering groundwater seepage effects. Man et al. [18] developed a spiral heat source model, which provides a desirable tool for simulating a spiral coil heat exchanger, which is advantageous in dealing with short-term temperature response. Park et al. [19] suggested an efficient spiral coil source model that considered the effects of three-dimensional shape, and the radial dimension effect, using Green's function. The model used an error function to improve and simplify computation for engineering applications. Li and Lai [20] presented a continuous cylindrical surface model (which could consider composite media) for a spiral coil heat exchanger. Zarrella et al. [21] conducted a comparative study of spiral coil and triple U-tube configurations inside a foundation pile using field tests and numerical analysis. The results showed that the spiral coil energy pile provided better thermal performance than the triple U-tube configuration; there was an increase of about 23% at peak. Go et al. [22] suggested a multiple regression equation for estimating the effective borehole thermal resistance of spiral coil energy piles, and verified its accuracy via a field thermal response test (TRT) test. Park et al. [23] examined the relative constructability and thermal performance of coil type heat exchange pipes in cast-in-place concrete piles using thermal response and thermal performance tests.

Meanwhile, GSHP systems, including those with energy piles, sometimes face challenges. When there is extreme disparity between the heating and cooling loads, the change of ground temperature in the region of the GSHP system becomes more severe over time. This undesirable effect could be moderated by increasing the length of the heat exchangers, but the higher cost might be unacceptable. Another alternative would be to add an additional heat sink or source [24]. Especially in cooling dominated areas, GSHP systems could be combined with auxiliary heat rejection systems to avoid load imbalance, producing what is called a hybrid GSHP system [25,26]. Though cooling towers are the most common heat sink devices, solar power generating systems and solar water heating systems could also be used to reduce summer cooling loads.

In hybrid GSHP systems, the optimum capacity and control strategy of the supplementary equipment can be important factors, considering their long-term operation. Yavuzturg and Spitler [26] compared several control strategies for hybrid GSHP systems. Thornton [27] performed an analysis of a hybrid GSHP system for a building at the U.S. Navy Oceana Naval Air Station. Several researchers [28–35] have investigated the performance of hybrid GSHP systems using energy analysis or experimental analysis. Man et al. [36] considered the operation of a hybrid GSHP system with a cooling tower and studied the system using computer simulations. Man et al. [37] studied a hybrid ground coupled heat pump system for air conditioning in hot weather areas such as Hong Kong to discern the mitigation of the soil thermal imbalance problem. Ozgener [38] analyzed thermal loads of the heated solar greenhouses and investigated wind energy utilization in greenhouse heating which is modeled as a hybrid solar assisted geothermal heat pump and a small wind turbine system. Lubis et al. [24] conducted a thermodynamic analysis of a hybrid GSHP system with a cooling tower. System performance was evaluated in terms of coefficient of performance and exergy (energy efficiency). Sagia et al. [39] carried out a theoretical analysis of a cooling dominated hybrid GSHP system utilized to cover the energy demands of an office building. Fan et al. [31] conducted a theoretical analysis with TRNSYS software and elementary experimental research to determine the influence of various factors on soil heat imbalance and system operation efficiency. Klein et al. [40] suggested a hybrid heat pump system for existing buildings consisting of a retrofitted air water heat pump and a gas boiler, and examined its performance in full-year dynamic numerical simulations.

Most previous studies of hybrid GSHP systems were conducted to confirm the strengths of hybrid systems and to determine optimum operation strategies. However, little attention has been paid to study of design applications of hybrid GSHP systems for energy piles, considering realistic ground conditions. Therefore, this study proposed a novel hybrid design algorithm for spiral coil energy piles that considers groundwater advection. As shown in Fig. 2, the