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Research Paper

Investigation on the thermal response of full-scale PHC energy pile and ground temperature in multi-layer strata

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HIGHLIGHTS

- In-situ TRT was conducted on a PHC pipe pile installed in multi-layered ground.
- The thermal conductivity of ground was compared to results from laboratory tests.
- The heat transfer process in pile and layered ground was analyzed.

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ABSTRACT

A thermal response test (TRT) was conducted on a full-scale precast high strength concrete (PHC) pipe pile installed in multi-layered ground, in order to investigate the thermal response of the pile and soils in inhomogeneous ground. The thermal properties of each layer were tested in the laboratory and compared to the estimation from the TRT. The ground temperature evolution was monitored using 4 boreholes around the pile, and the pile temperature distribution was captured from transducers prefabricated in the pile wall. The system thermal conductivity estimated from TRT results was 2.11 W/(m K) which is about 2 times that from the lab test (1.15–1.71 W/(m K)). The comparison with other TRTs suggests that fitting time and heating power may influence the estimated results. The ground temperature response varied along the depth. Comparing the layers, more conductive soil was cooler near the pile but warmer at a distance. Up to 23% difference of temperature increment (1.1 °C) was found. The pile temperature was less influenced by soil stratification but was evidently affected by end effects, which caused a maximum difference of 16% (3.2 °C) from the average temperature increment. The average ground and pile temperature increased by 1.1 °C and 1.5 °C respectively at 37 days after heating. This suggests that an accumulated temperature increase could happen in a cooling-dominated district.

1. Introduction

Air pollution has become a severe problem in China, especially in winter, as the district heating systems in the country are supported by boilers and thermal power plants. Coal, which emits more CO_2 and other pollutants, is the most common fuel used for heating [1]. Facing environmental and social pressure, China has to improve the energy mix by supporting the clean energy industry. The 60% of energy consumption in the building sector was used for air-conditioning and heating [2]. Therefore, the great energy-saving potential in this area has aroused the interest of professionals in investigating the ground source heat pump (GSHP) as an alternative for heating and cooling.

GSHP systems utilize the ground as the heat source or sink through the heat transfer between the fluid circulating in ground heat exchangers (GHE) and the ground. For a stable temperature and high thermal capacity of the ground, GSHP systems are more efficient than conventional air-conditioners. A vertical borehole ground heat exchanger (BHE) extending to 50–150 m depth [3] occupies less land than the horizontal type that is generally adopted in GSHP systems. However, rapid urbanization has left limited room for GHEs to be installed. Recently, energy piles serving as both bearing structures and heat exchangers have become popular across the world [4,5] as they can save costs associated with land usage and drilling costs.

Knowledge of the heat transfer process of GHEs and their influence on the ground temperature field is crucial for a successful GSHP system design. Thus, many mathematical models have been developed for the BHE and energy pile. Analytical models like the infinite line source model [6] and cylinder model [7] assume the ground as an infinite

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homogeneous medium, regardless of the boundary effect. However, Loveridge et al. [8] suggested that the line source model can be only applied to the smallest diameter piles with larger aspect ratios. Eskilson [9] calculated a g-function curve using the finite difference method for selected BHE configurations considering the finite length of BHE. Zeng et al. [10] developed a finite line heat source from a point source solution, then Lamarche et al. [11] improved the computation method and made it more efficient. Diao et al. [12] evolved the thermal resistance expression inside the borehole, taking the interference of two legs of the U-tube. Cui et al. [13] established an analytical solution for an inclined borehole temperature field. Philippe et al. [14] compared the borehole wall temperature of infinite/finite line sources and infinite cylindrical source and suggested the validation domains of three solutions. With the application of energy piles, the line or hollow cylindrical geometric assumption may be invalid when applied to these larger and shorter pile heat exchangers. Man et al. [15] considered the radial dimension and heat capacity inside the GHE and developed a solid cylindrical source model that was able to express the transient temperature response. Loveridge and Powrie [16,17] presented new pile G-functions to reflect transient response of pile concrete and the interaction of multiple energy piles. Cui et al. [18] simplified spiral coils buried in the energy pile as a number of ring coils, then solved the problem using Green’s function. Min et al. [19] focused on the anisotropy of soil conductivity, then established line, cylindrical and spiral-line source models in semi-finite anisotropic soil. Murphy et al. [20] calculated the transient thermal conductivity of soil by measuring the temperature gradient of pile in the radial direction. Analytical solutions are computationally efficient compared with numerical models and widely used in GSHP system design and thermal response test (TRT) analysis [21]. Also, as summarized above, the evolution of an analytical solution allows models that are closer to the realistic heat transfer condition. However, these models still assume the GHE to be located in a homogeneous medium, which is not the real case.

In practice, GHEs usually penetrate through several geological strata with different formations. Thermal conductivity is related to mineralogical composition, density and water content [22]. Thus, sedimentary rock, stratified soil and the ground water level can result in variations of the thermal conductivity with depth. This inhomogeneity may make it difficult to accurately estimate the thermal properties, further resulting in miscalculation of the performance of the GSHP system. Moreover, soil mechanical behaviors such as stiffness, shear strength, pore water pressure and volume change are sensitive to the temperature Laloui [23]. The mechanical behavior of the energy pile is closely related to its temperature and the concrete stress may exceed the limit value [24]. Therefore, precise estimation of the temperature response of the pile and surrounding soil is vital for preventing the hazard of structural damage.

Many scholars have continued to explore the heat transfer process in heterogeneous ground conditions, mainly considering multiple ground layers and the ground water level. Reported multi-layered analytical solutions are rare in the literature. Hu [25] improved the finite line heat source, which was validated by a TRT experiment, to cater for multi-layered ground and groundwater flow. Stratification of the long-term temperature field in different strata was clearly observed. Zhou et al. [26] established solid cylindrical and ring-coil heat source models using Green's function in double-layered ground. The computational error of the temperature field was strongly related with the Fourier number and depth compared with the homogeneous model.

Since the numerical model is more promising and flexible for complex or, in other words, realistic experimental conditions, researchers have usually studied these aspects numerically. Cecinato and Loveridge [27] developed a finite element model for analysis of transient heat exchange in energy piles and investigated the influence of number of pipes, pile length, concrete conductivity on energy efficiency. Signorelli et al. [28] developed a 3D finite element model and investigated the TRT under stratification and groundwater flow conditions. Great error occurred in the thermal conductivity estimation if the non-layered model was used in stratified ground with ground water flow. Fujii et al. [29] recorded the temperature distribution of BHEs during TRT tests by optical fiber. A multi-layered cylindrical model and nonlinear regression were used to calculate the thermal conductivity distribution. It was found that the average value matched the result derived from the line source method. Lee [30] modified a three-dimensional finite difference model for BHE in multiple ground without ground water flow, and generated synthetic TRT data under various ground compositions. The long-term system performance estimated by the single ground-layer model differed a little from that of the modified model. The short-term TRT of the pile in partially saturated soil was successfully simulated by Park et al. [31]. Go et al. [32] addressed the restriction of borehole thermal resistance calculation under the assumption of a homogeneous medium. Yoon et al. [33] reported an experimental and numerical study of TRTs on a pre-cast energy pile and vertical BHEs in two- layered soil. A simple equation to calculate the equivalent thermal conductivity of multi-layered ground was proposed and validated by traditional TRT analysis. Yang et al. [34] introduced a model which divided the ground into saturated and unsaturated parts and it was validated by a field TRT experiment. Raymond and Lamarche [35] conducted a layered numerical simulation and found that the heat transfer rates changed with depth. The significant contrasts of thermal properties between layers may have an influence on the accuracy of thermal conductivity assessment. Thermal load stratification was also presented along a BHE that was partially submerged in ground water, according to Lee and Lam [36]. Choi et al. [37] treated the nonlinearity of the soil thermal properties in a geotechnical way. The soil water characteristic curve was used to determine the proportion of three phases in the soil with depth, from which the thermal properties were calculated. Ground temperature variations were revealed in detail.

Although the characteristics of GHEs in layered subsurface have been extensively investigated through numerical and analytical studies, the results still need experimental validation. Olfman et al. [38] monitored the thermal response of a deep BHE and proved that the heat exchange rate varied with depth, as is found in other numerical studies [35,36], and time. The recorded ground temperature varied apparently with depth, even within single strata. Li et al. [39] reported that the heat-affected distance changed with depth and proposed that the GHE spacing should consider the layered subsurface. Long-term monitoring of the borehole temperature was presented by Zhou et al. [40].

It is obvious that the published research on the thermal characteristics of the energy pile considering stratification of the ground is very limited. In this paper, a detailed in-situ experimental study is presented to investigate the thermal response of prototype precast-high strength concrete (PHC) pipe energy piles, which are widely used in China for their reliable quality and cost efficiency. The pile was driven into stratified ground whose thermo-physical properties were investigated in depth using a boring test and piezocone penetration test. Single U-type heat exchanger was inserted into the pile hole, which was filled with water, to apply thermal load to the PHC pile. Then, a TRT was implemented and the result was analyzed according to the geology investigation and compared to other TRTs on energy piles [31,41–45]. The influence of the multi-layered ground on the ground temperature response and transient pile response was analyzed using detailed instrumentation of the soil and pile. Finally, the temperature recovery after the TRT was reported and suggestions were made for PHC energy pile application.

2. Experimental setup

2.1. Thermal response test procedure

The thermal response test (TRT) in this study was conducted on a full-scale instrumented PHC energy pile driven in stratified ground. The