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# Energy Piles and GSHPs: A Pathway to Sustainable Urban Development in Southeast Asia

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## Abstract

This investigation explores ways to enhance the performance of ground source heat pump (GSHP) systems and energy piles as part of sustainable urban planning, with special attention to conditions in Southeast Asia. By drawing on stable geothermal heat, GSHPs provide an environmentally friendly alternative to conventional HVAC systems, capitalizing on the near-constant underground temperatures for efficient space heating and cooling. A key factor in boosting system effectiveness lies in thoroughly understanding how heat migrates through soil—particularly the soft marine clay deposits widespread in Southeast Asia. The research uses a one-dimensional finite-difference numerical model to assess the influence of soil thermal conductivity and density on operational outcomes. Results demonstrate that GSHP installations, especially those coupled with energy piles, can dramatically reduce electricity demand and cut greenhouse gas emissions, offering meaningful relief from the urban heat island effect in crowded metropolitan areas. Although the persistently warm and humid regional climate may pose challenges to sustained performance, the work calls for expanded research—including real-world field testing and more refined simulation methods—to fine-tune GSHP arrangements and unlock the full potential of shallow geothermal resources in city settings. These findings on subsurface thermal processes and optimized system configurations help advance climate-resilient, resource-efficient urban infrastructure.

**Keywords** Energy pile, Finite difference method, Ground source heat pump system, Soil thermal conductivity, Sustainable urban development, Urban heat island effect

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## Introduction

The transition toward intelligent, low-carbon cities relies heavily on integrating energy piles and accurately characterizing subsurface heat exchange to achieve genuinely sustainable urban environments. Ground source heat pump (GSHP) systems, which belong to the family of shallow geothermal technologies, capture the readily available geothermal energy stored in the upper ground layers to deliver heating or cooling. This method effectively satisfies the thermal loads of indoor Heating, Ventilation, and Air-Conditioning (HVAC) equipment, as explained by Sarbu and Sebarchievici [1]. Several design variants exist: vertical closed-loop GSHPs embedded within foundation piles (especially valuable for energy piles in smart-city projects), horizontal loop arrangements, and systems that employ a thermal storage pond for heat rejection. In small residential applications, a closed-loop design is typically favored for its reliable performance and relatively simple maintenance, as depicted in Figure 1. According to Eugster and Sanner [2], shallow GSHP installations operate at depths of 3 to 100 m and treat the surrounding soil body as a large, naturally regenerating thermal battery. This strategy guarantees a stable thermal source across all seasons, in stark contrast to the wide swings in ambient air temperature

observed at ground level [3, 4]. Shallow geothermal technology is most commonly deployed for space heating and cooling where subsurface temperatures remain below 25 °C, making it particularly appropriate for domestic and small commercial buildings in diverse geographic settings. Deep geothermal systems, by comparison, pursue much higher temperatures—exceeding 25 °C and sometimes approaching 200 °C—to serve other energy demands [2].

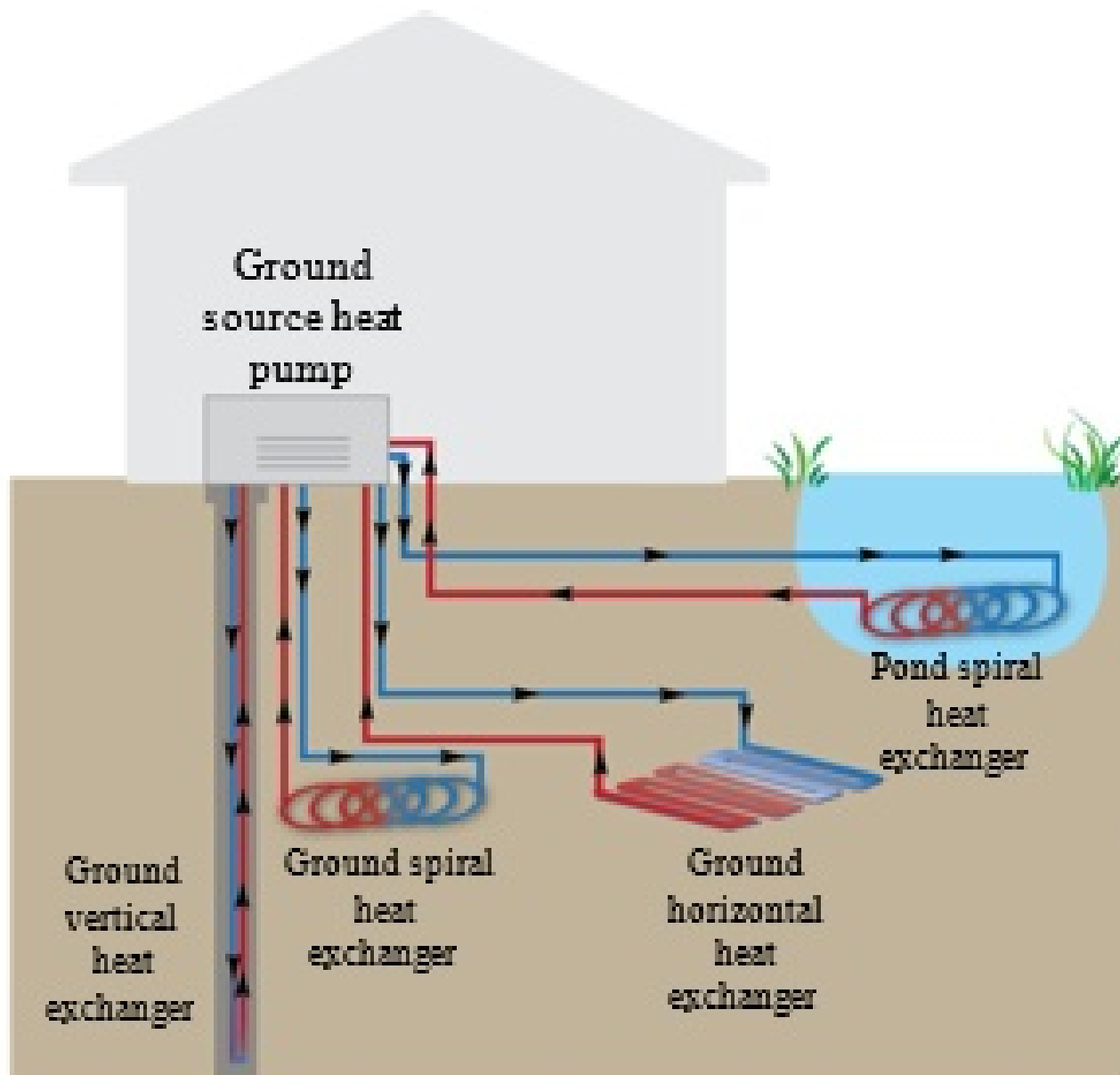


**Figure 1.** General overview of shallow ground source heat pump (GSHP) installations.

This research investigates the application of ground-source heat pump (GSHP) systems—particularly shallow geothermal technologies—to advance smart city initiatives. These systems leverage stable subsurface temperatures to deliver effective heating and cooling, thereby meeting the thermal needs of indoor HVAC systems with high efficiency. A central theme is the incorporation of energy piles, which serve the dual role of providing structural foundation support while acting as integral components of the GSHP network, offering substantial advantages for eco-friendly urban building practices. The work pays special attention to analyzing heat migration patterns in the ground, especially within the soft marine clays that dominate many Southeast Asian areas, thereby deepening knowledge on tailoring GSHP performance to tropical

environments where the urban heat island phenomenon creates major difficulties. A key feature of the investigation is the deployment of a one-dimensional finite-difference model to forecast temporal temperature profiles around energy piles, enabling a straightforward yet reliable assessment. This methodology supports the examination of how variations in soil thermal conductivity and density influence overall GSHP effectiveness. Outcomes reveal that higher soil density enhances thermal conductivity, thereby boosting system performance. Concentrating on real-world implementation in smart urban contexts—such as Bangkok, which faces distinctive geotechnical hurdles—this analysis delivers practical guidance for rolling out renewable energy strategies. It stresses the value of continued research to refine GSHP designs and operational settings, ensuring the maximum harnessing of geothermal resources for city growth. Broader consequences of smart city projects include reduced energy use, lower greenhouse gas emissions, and higher HVAC operational efficiency, paving the way for more environmentally responsible urban habitats.

Although prior research has largely focused on the engineering performance and cost implications of GSHP systems under temperate conditions, the present work broadens the scope to tropical zones, addressing a notable knowledge gap. In contrast to earlier efforts that seldom examine the interplay between soil thermal characteristics and GSHP performance in warm, moist climates, this investigation employs a one-dimensional finite-difference model to examine the impacts of soil thermal conductivity and density on efficiency. This method stands out for its application to the soft marine clays typical of Southeast Asia, which exhibit markedly different behavior compared to soils more frequently examined in temperate regions. By embedding energy piles—typically serving as foundation supports—directly into the GSHP framework, the study capitalizes on multifunctional infrastructure that enhances both load-bearing capacity and energy performance. The findings clarify how shifts in soil attributes influence operational outcomes, an essential factor for architects, engineers, and city developers planning similar deployments. What makes this work distinctive is its innovative modeling technique combined with its emphasis on a setting where elevated surface temperatures and intensified urban heat island impacts create particular obstacles. Combining on-site trials with sophisticated simulations yields fresh perspectives on fine-tuning GSHP setups, which is vital for fully capitalizing on geothermal potential within urban sustainability efforts. Beyond bridging a key research void, this contribution lays the groundwork for forthcoming breakthroughs in geothermal applications across tropical metropolitan areas.

## Evaluation and Prospects of GSHP Systems

### GSHP systems and thermal movement evaluation

The assessment of subsurface thermal migration takes on heightened significance when energy piles are incorporated, proving indispensable for reliable GSHP operation, particularly in cooling-dominated scenarios. At its foundation, a GSHP setup comprises three primary components: the heat source, the heat sink, and the heat exchanger. In this context, the building's HVAC equipment serves as the heat source, managing indoor conditions, while the subsurface soil functions as the heat sink, absorbing surplus thermal energy. The heat exchanger moves heat between these elements. A circulating fluid—commonly a mixture of water and antifreeze—is driven by a pump to enable heat transfer by conduction and convection. Heat exchangers fall into two main categories: open-loop and closed-loop configurations. Open-loop designs extract groundwater from wells for cooling, then reinject the warmed water into the aquifer. Closed-loop arrangements, however, rely on networks of High-Density Polyethylene (HDPE) pipes arranged in series or parallel layouts, as illustrated in [Figure 2 \[5\]](#). The simplest variant features a U-shaped exchanger installed vertically within boreholes or integrated into foundation piles, creating a conduit for the circulating fluid. To enhance heat transfer efficiency, alternative setups are employed, including double U-pipes configured in parallel or crossed patterns, as well as spiral or coil geometries, all aimed at expanding the interfacial area for optimal thermal exchange.

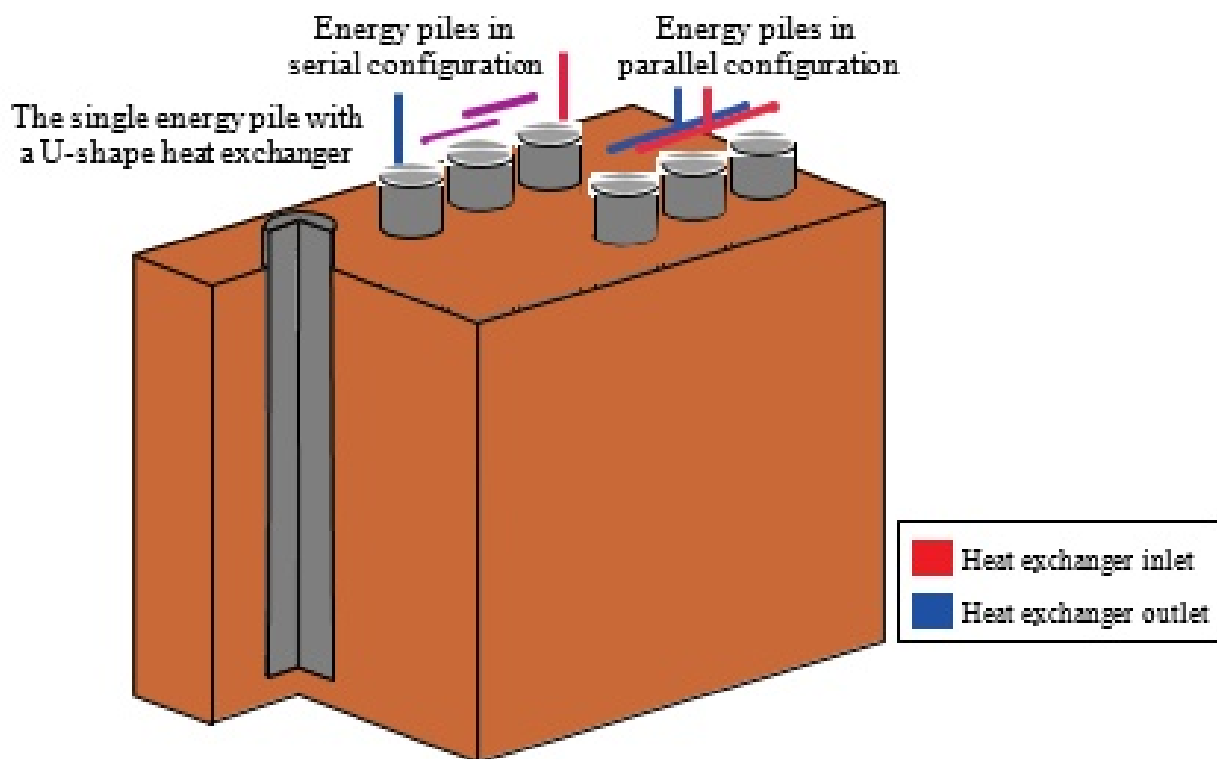


**Figure 2.** Schematic mechanism of a heat exchanger in an energy pile.

Grasping and assessing heat transfer processes within the subsurface is essential when deploying energy piles. This assessment relies heavily on thermal conductivity, which measures a material's ability to conduct heat. Clay soils typically exhibit thermal conductivity in the range of about 1 to 2.5 W/(m·K), far surpassing that of air at just 0.026 W/(m·K)—indicating that the ground conducts heat nearly 40 times more effectively [6]. This property highlights one of the key ecological advantages of GSHP systems: they achieve substantial reductions in electricity demand and greenhouse gas emissions compared with conventional air-source heat pumps. Their adaptability positions GSHPs as an excellent solution across diverse applications, from homes and offices to industrial facilities, as noted by Tissen *et al.* [7]. Compared with air-source alternatives, GSHPs operate more quietly, offer extended service life, and require less frequent maintenance. While the upfront cost of GSHP installations tends to exceed that of air-source systems, the cumulative energy savings over time generally offset the initial expenditure. Between 1995 and 2020, global uptake of ground source heat pumps rose dramatically, reflecting increasing awareness of their performance and advantages. The latest available figures identify the top countries by installed GSHP thermal capacity as China (26,450 MWt), the United States (20,230 MWt), Sweden (6,680 MWt), Germany (4,400 MWt), and Finland (2,300 MWt) [8, 9]. This worldwide expansion demonstrates the growing acceptance of GSHP technology as a reliable, sustainable option for smart urban development. It underscores the importance of precisely evaluating geothermal resources during city planning and construction.

## Regional focus on Europe and southeast Asia

GSHP technology first gained prominence in Europe, where systems are predominantly used in heating mode to supply thermal energy to buildings and district heating networks. Sayegh *et al.* [10] examined how the expansion of district heating across Europe has supported progress in heat pump technologies—including GSHPs—by improving overall system efficiency and operational flexibility, thereby lowering carbon footprints. Four principal approaches exist for incorporating heat pumps into district heating: (i) adding heat pumps to existing infrastructure with minimal modifications, (ii) integrating them into expanded networks, (iii) undertaking comprehensive upgrades of current district heating setups,

and (iv) developing entirely new heat-pump-driven district heating systems. Presently, heat pumps are classified as renewable energy sources in Europe, contributing between 5% and 20% toward the continent's renewable energy objectives. Effective execution of these policies is expected to accelerate Europe's progress toward its environmental targets, delivering long-term benefits to residents.

In European residential and commercial buildings, the primary heat source for GSHP systems is the shallow subsurface layer. Bryś et al. [11] presented findings from a decade-long thermal study (August 2007–July 2017) in Wrocław, Poland, based on measurements of net solar radiation (incoming minus reflected) and resulting ground heat fluxes (positive  $G > 0$  and negative  $G < 0$ ) in bare and vegetated (grassy) soil. Seasonal and annual variations in heat flux were observed, with bare soil consistently recording higher fluxes than grass-covered areas. Over the ten years, cumulative negative soil heat fluxes—favorable for heating-mode GSHP operation—averaged 91.8 kWh/m<sup>2</sup> in bare soil and 47.4 kWh/m<sup>2</sup> in turfed soil. The lowest negative heat flux occurred in May, while the peak was recorded in October. These patterns confirm the suitability of shallow ground for year-round use as a stable, low-impact heat source for GSHP applications.

In contrast, Southeast Asia has only recently emerged as a region of interest for GSHP adoption, where rapid urbanization plays a central role. Swift city growth and large-scale migration to urban cores intensify the urban heat island effect, causing city temperatures to rise markedly above surrounding rural levels due to heat absorption and retention by concrete, asphalt, and built structures. These elevated temperatures degrade the performance of traditional air-source HVAC equipment and increase its energy use.

Given the persistently hot and humid conditions, air conditioning dominates building climate control throughout Southeast Asia. In densely populated cities, the sheer number of units creates significant acoustic pollution. Inadequate upkeep of air conditioners—stemming from worn parts, loose fittings, or suboptimal functioning—further amplifies noise levels. Lax enforcement of noise standards and limited regulatory oversight often allow property owners to overlook mitigation strategies, worsening the issue. Outdoor components such as condensers, cooling towers, and compressors are often installed in tight spaces near living areas, including on street-facing facades or in narrow passageways. This placement concentrates and directs noise toward public and residential zones, readily disturbing nearby occupants and degrading living conditions.

## Performance metrics and future prospects

### Performance metrics for GSHP

To quantify the superior efficiency of ground-source heat pumps (GSHPs) relative to conventional air-source heat pumps (ASHPs), several standardized performance indicators are used. The Coefficient of Performance (COP) represents the ratio of useful thermal energy output (in watts) to the electrical energy input (in watts). A higher COP indicates that the system delivers greater heating or cooling output for the same energy consumption under optimal conditions, resulting in reduced electricity usage and lower utility costs. In contrast, the Seasonal Coefficient of Performance (SCOP) provides a broader seasonal evaluation of efficiency, accounting for fluctuations in outdoor temperatures and weather patterns over an extended period, typically several months. Elevated SCOP values reflect improved year-round performance, contributing to decreased greenhouse gas emissions and a smaller overall ecological footprint.

Another key indicator is the Energy Efficiency Ratio (EER), which assesses instantaneous cooling performance by dividing cooling capacity (in BTU/h) by electrical power input (in watts). Higher EER ratings indicate more effective cooling with less energy demand at a specific test condition. Similarly, the Seasonal Energy Efficiency Ratio (SEER) extends this concept to evaluate average cooling efficiency over an entire cooling season, accounting for variations in ambient conditions. Systems with higher SEER scores consistently deliver better cooling performance across varying seasonal demands.

When comparing ASHPs and GSHPs, the latter consistently outperforms in all major metrics: COP ranges of 2.5–4.0 for ASHPs versus 3.1–5.0 for GSHPs; SCOP ranges of 2.5–3.5 for ASHPs versus 3.5–4.5 for GSHPs; EER ranges of 8.0–

12.0 for ASHPs versus 14.0–20.0 for GSHPs; and SEER ranges of 13.0–20.0 for ASHPs versus 16.0–30.0 for GSHPs. This advantage stems primarily from the ground's far more stable temperature profile compared to that of the air's, enabling more consistent and efficient heat transfer. Although GSHP systems generally involve higher upfront installation costs—owing to the excavation and installation of ground loops—they offer significantly lower long-term operating costs than ASHPs, which are less expensive to install initially but tend to incur higher energy costs during use.

### Challenges and prospects in southeast asia

Deployment of energy piles and ground-source heat pump (GSHP) systems in Southeast Asia remains at a nascent stage, with limited empirical data from field implementations and simulation-based research. The region's persistently elevated ambient temperatures raise valid questions regarding the technical viability, long-term efficiency, and environmental suitability of these systems. Consequently, comprehensive performance data specific to local conditions is currently sparse. Nevertheless, substantial potential exists for future advancement, and GSHP technology holds promise for eventual commercial maturity in the area. Over time, adoption is likely to grow steadily; due to elevated initial capital requirements, early applications may concentrate in high-rise commercial buildings and large-scale developments, yet gradual cost reductions and technological refinements could lead to widespread integration into standard residential cooling infrastructure.

Amid these constraints, GSHP systems present a compelling strategy for alleviating the impacts of urban heat islands. However, the region's tropical climate—characterized by consistently high temperatures and humidity—introduces distinctive technical difficulties. The narrow temperature gradient between the ground and outdoor air means GSHPs would function almost exclusively in cooling mode. Over extended periods, this continuous heat rejection into the subsurface could cause ground temperatures to gradually approach ambient levels, thereby diminishing the system's cooling capacity and overall effectiveness. Despite the evident relevance of such concerns, dedicated field trials and in-depth performance studies tailored to tropical environments remain scarce. This knowledge deficit underscores the urgent need for systematic, region-specific investigations to assess feasibility, identify optimal configurations, and develop strategies to maximize GSHP performance under Southeast Asian climatic conditions.

### Case studies and soil analysis in southeast Asia

**Figure 3** [4] illustrates the spatial distribution of research on ground source heat pump (GSHP) systems across Southeast Asia, revealing a broad geographical spread of investigations in Thailand [12–16], Indonesia [17], Malaysia [18], Singapore [19], and Vietnam. Among these, the pioneering work by Yasukawa *et al.* [16] in Kamphaeng Phet stands out as the earliest documented exploration of GSHP technology in the region, demonstrating promising advantages for implementation at that location. Most of these investigations were conducted at sites characterized by soft marine clay layers, with soil sampling conducted at depths of 5–20 m below ground level. As shown in **Table 1**, the tested clay samples exhibit specific gravity (Gs), liquid limit (LL), plastic limit (PL), and particle-size distribution (sand-silt-clay fractions) values comparable to those of Bangkok clay. **Table 1** [20–32] further indicates that these materials are uniformly classified as marine sedimentary clays. Formed through depositional processes in coastal and deltaic marine environments, these clays include well-known examples such as Ariake clay (Japan), Singapore marine clay, Hong Kong marine clay, Kuantan clay (Indonesia), and Ho Chi Minh City marine clay. The latter shares important geotechnical traits with Bangkok soft clay, including high plasticity index, very low hydraulic conductivity, and pronounced compressibility. These properties create considerable engineering difficulties for construction, especially in densely built urban zones where foundation stability is paramount for high-rise and multi-story developments. Incorporating GSHP systems in these challenging settings demands a detailed understanding of site-specific soil behavior to ensure optimal system design and long-term performance, underscoring the need to analyze subsurface thermal processes as a core element of intelligent urban infrastructure planning. Emphasis is placed on energy piles and shallow GSHP applications in areas dominated by soft marine clays. One emerging focal point is the Bangkok metropolitan region, where efforts to deploy GSHP technology are gaining momentum. Successful outcomes from Bangkok-based studies could serve as valuable references for other locations sharing similar subsurface conditions. Baseline soil temperatures in the Bangkok vicinity were documented in 2011 [15] through an extensive survey involving 56 temperature-depth profiles across central Thailand. Readings were

recorded at 2 m intervals with a precision of 0.01 °C. From the surface down to 50 m depth, shallow ground temperatures ranged between 27 °C and 30 °C, on average approximately 5 °C cooler than the monthly mean maximum air temperature.

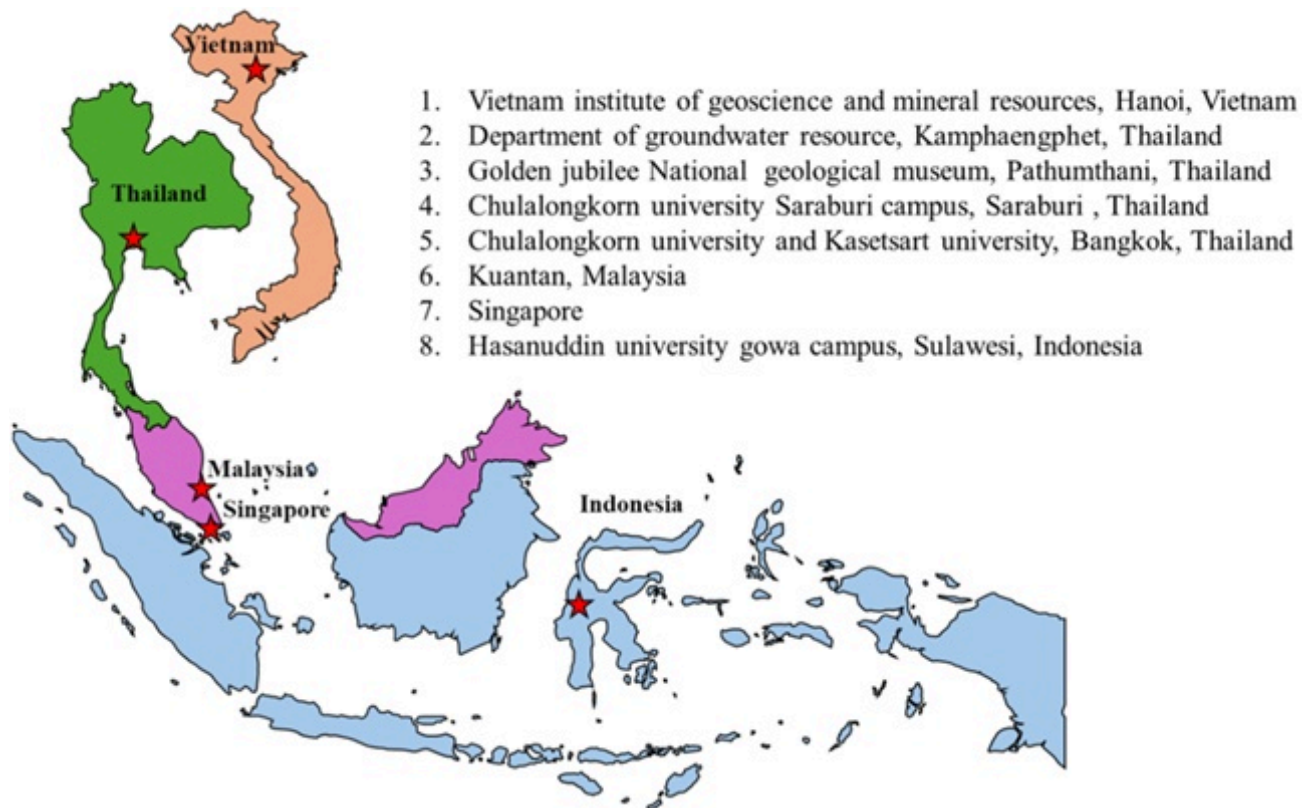


**Figure 3.** Locations of GSHP experiments within Southeast Asian countries in tropical climates [4].

**Table 1.** Basic engineering properties of clay sedimentary formations in different countries.

| Reference | Soil type                | Unit weight (kN/m <sup>3</sup> ) | Water content (%) | Thickness (m) | Thermal conductivity (W/m·°C) | Specific gravity | Plastic limit (%) | Liquid limit (%) |
|-----------|--------------------------|----------------------------------|-------------------|---------------|-------------------------------|------------------|-------------------|------------------|
| [20-22]   | Ariake clay (Japan)      | 13.50 – 14.00                    | 90.0 – 120.0      | 15.0 – 20.0   | 0.65 – 0.75                   | 2.65             | 25.0 – 56.0       | 61.6 – 88.7      |
| [23, 24]  | Singapore marine clay    | 14.23 – 15.70                    | 80.0 – 95.0       | 14.0 – 17.0   | Not available                 | 2.60 – 2.72      | 20.0 – 28.0       | 80.0 – 95.0      |
| [25]      | Hong Kong marine clay    | 13.9 – 18.25                     | 40.8 – 98.6       | 10.0 – 55.0   | Not available                 | 2.62 – 2.67      | 18.6 – 50.8       | 36.7 – 87.3      |
| [26, 27]  | Kuantan clay (Indonesia) | 15.00                            | Not available     | Not available | 0.45                          | 2.64 – 2.78      | 18.9 – 25.7       | 30.5 – 63.5      |
| [28-32]   | Bangkok clay             | 15.20 – 16.18                    | 60.0 – 80.0       | 10.0 – 14.0   | 0.80 – 1.00                   | 2.56             | 95.0 – 100.0      | 60.0 – 80.0      |

In 2020, a joint research initiative involving Japanese and Thai scholars, notably the study by Shimada *et al.* [14], was carried out at Chulalongkorn University. The project combined field experiments and numerical simulations on a

functioning GSHP installation. A Thermal Response Test (TRT) was performed to calibrate and verify the simulation model at a pilot-scale facility. The tested GSHP arrangement featured two boreholes spaced 6 m apart, each extending 50 m deep with a diameter of 0.23 m. One borehole incorporated two U-tube sets positioned at 10 m and 15 m depths and linked in series, while the second borehole contained U-tubes installed at the 50 m level. This GSHP system was connected to the air-conditioning system of a small campus building named “Parot Racha” on the Bangkok site. Findings revealed that the GSHP outperformed conventional air-source heat pumps, delivering an electricity savings of roughly 30% until the heat pump inlet temperature exceeded ambient conditions by 5 °C. These outcomes highlight the considerable capacity of GSHPs to achieve sustained energy reductions in building operations, even under Bangkok’s high daytime temperatures. Additional advancements in 2020 were reported by Jotisankasa *et al.* [13], who performed an in-depth investigation of energy piles within a residential structure. The study utilized a 17.5 m-long steel pipe pile with a 152 mm diameter, fitted with a U-tube heat exchanger arranged in parallel. The GSHP configuration included two separate circuits: loop number 1, comprising six interconnected piles, and loop number 2, comprising seven piles. Initial assessments of system thermal conductivity produced values of 2.01 W/m·K for loop 1 and 1.49 W/m·K for loop 2. Conducted in the stiff clay strata typical of Bangkok, these measurements also illustrated the pronounced influence of groundwater movement on GSHP performance. The research reinforces the essential need to characterize subsurface thermal behavior for successful deployment of GSHP solutions—particularly energy pile configurations—in smart city projects.

Comprehending subsurface heat migration processes is vital for developing smart cities and effectively incorporating energy piles. Thermal conductivity—the key property governing heat propagation through soil—differs across soil types, even when their basic geotechnical parameters appear comparable. Primary influences on this property include moisture levels and bulk density. In Southeast Asia, shallow natural soft clays are typically fully saturated with water. Elevated water saturation minimizes air pockets, which function as thermal insulators within inter-particle voids. Furthermore, fluid movement through these pores promotes convective heat transfer, thereby elevating overall thermal conductivity. Soil density similarly exerts a strong effect: greater compaction improves particle-to-particle contact, facilitating greater conductive heat flow and thus increasing thermal conductivity.

The adoption of ground-source heat pump (GSHP) and energy pile technologies across Southeast Asia remains at an early stage, offering substantial opportunities for in-depth research and innovation. The precise impacts of fluctuations in effective thermal conductivity within GSHP systems, along with the thermal conductivity and density characteristics of soft clays, on subsurface temperature regulation and heat dispersion are not yet well characterized. Thailand, a leading regional player in GSHP research and with comprehensive datasets on the properties of Bangkok soft clay, offers an ideal setting for targeted case studies. Outcomes from such investigations could yield transferable knowledge for other Southeast Asian locales exhibiting analogous geotechnical profiles, thereby supporting progress in GSHP viability assessments, optimized system configurations, and performance forecasting. This line of inquiry is indispensable for unlocking the full potential of GSHP technologies in fostering sustainable, smart city infrastructure.

## Fundamental Theory of Heat Transfer in Soil Using Finite Difference Method

In standard preliminary design stages, heat transfer assessments from energy foundations to the adjacent soil volume are typically based on projected temperature variations at different radial distances from the foundation. These evaluations are indispensable for forecasting the behavior of ground-source heat pump (GSHP) systems before foundation engineering is completed.

The essential concepts underpinning the application of the finite difference method (FDM) to soil heat transfer analysis can be outlined as: 1. The definition and benefits of the finite difference method, 2. Simplifications of the model and boundary conditions, 3. Definition of the computational domain and meshing (node placement), and 4. Conversion of differential equations into solvable algebraic forms.

The finite difference method (FDM) provides multiple practical benefits, notably a straightforward computational workflow. It replaces intricate differential heat transfer equations—common in alternative approaches—with simpler algebraic expressions. Moreover, analyses can be conducted efficiently using basic spreadsheet tools by inputting derived mathematical relations from the original differential equations along with relevant parameters. FDM enables simulation of time-evolving soil-temperature distributions around energy piles, with a flexible time-step resolution ranging from seconds to days, depending on project needs. Given the temporal scope of the present research, the finite difference approach is the most straightforward and suitable technique.

In this investigation, the energy pile is modeled as a slender cylindrical element embedded in an infinite soil medium, allowing the three-dimensional problem to be reduced to a one-dimensional radial analysis centered on temperature gradients extending outward from the pile axis. The model domain is conceptualized as a vertical cross-section through the energy pile, incorporating a heat exchanger held at constant temperature to replicate GSHP heating operation. Heat propagates radially outward from the exchanger into an unbounded soil volume composed of three distinct densities of soft marine clay. Before computations, the reference model domain must be established, delineating all boundaries and specifying necessary parameters and variables. **Figure 4** depicts the constant-temperature boundary, termed a “Dirichlet boundary,” which treats the surrounding soil mass as an extensive, effectively infinite thermal reservoir. Along designated edges or surfaces of the domain, temperature is held fixed at the undisturbed background soil value, disregarding temporal fluctuations. This condition promotes numerical stability and precision by averting divergence. As indicated in **Figure 4**, No. 1, the lower and lateral boundaries of the soil domain are assigned the natural ambient soil temperature.

In contrast, the energy pile surface (**Figure 4**, No. 2) simulates GSHP operation by imposing a constant temperature equivalent to that of the heat exchanger fluid. Subsequently, computational nodes (**Figure 4**, No. 3) are defined as discrete points within the domain via a structured grid overlay. The radial spacing  $\Delta r$  denotes the interval between successive nodes, with  $\Delta r = 0$  at the pile centerline. Time steps  $\Delta t$  govern the interval between successive iterations, enabling capture of transient soil temperature dynamics. Neighboring node temperatures  $T_0$ ,  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$  within the grid support the formulation of the heat transfer process.

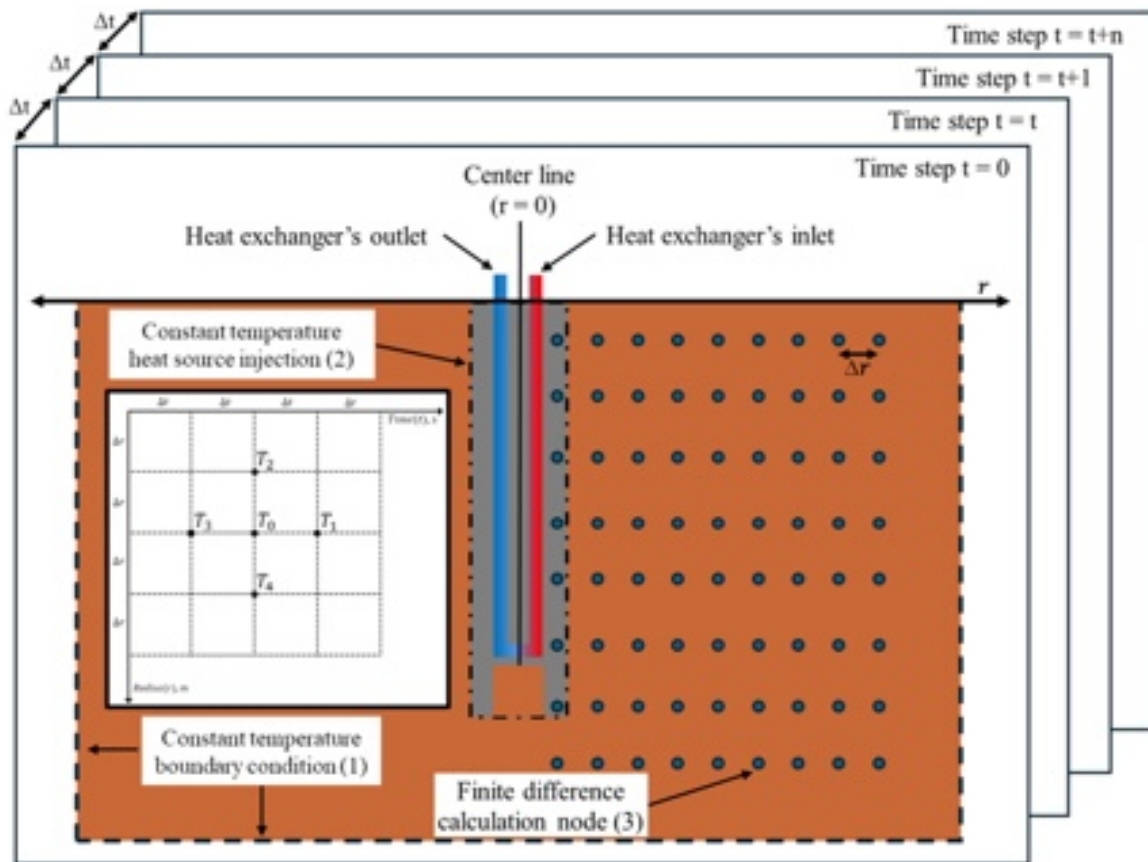


**Figure 4.** Analysis domain for the FDM model with calculation node and boundary conditions.

The temperature increase ( $T$ ) at any point within the computational domain can be determined through the one-dimensional transient heat conduction differential equation, presented as [Eq. 1](#):

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} = \rho \frac{1}{\alpha_d} \frac{\partial T}{\partial t} \quad (1)$$

Where thermal diffusivity ( $\alpha_d$ ) is defined as thermal conductivity ( $\lambda$ ) divided by the product of soil density ( $\rho$ ) and specific heat capacity ( $c$ ),  $t$  denotes time, and  $r$  represents the radial distance from the center.

The finite difference approximation of [Eq. 1](#) is decomposed into [Eqs. 2–4](#), which are then solved individually in explicit form. The labeled nodes  $T_1$  through  $T_4$ , as indicated in [Figure 4](#), enable the conversion of the differential terms into standard algebraic expressions.

$$\frac{\partial T}{\partial t} = \frac{T_1 - T_0}{\Delta t} \quad (2)$$

$$\frac{\partial T}{\partial r} = \frac{1}{2} \cdot \left( \frac{T_4 - T_0}{\Delta r} + \frac{T_0 - T_2}{\Delta r} \right) = \frac{T_4 - T_0}{2\Delta r} \quad (3)$$

$$\frac{\partial^2 T}{\partial r^2} = \frac{1}{\Delta r} \left( \frac{T_4 - T_0}{\Delta r} - \frac{T_0 - T_2}{\Delta r} \right) = \frac{T_4 + T_2 - 2T_0}{(\Delta r)^2} \quad (4)$$

Substituting the discretized forms from **Eqs. 2 and 3** into the overall heat balance yields the explicit expression for the updated temperature at node T1, as expressed in **Eq. 5**:

$$T_1 = T_0 + \left[ \frac{T_4 + T_2 - 2T_0}{(\Delta r)^2} + \frac{1}{r} \cdot \frac{T_4 - T_2}{2\Delta r} \right] \alpha_d \Delta t \quad (5)$$

Where the parameters required to compute the evolving temperature using **Eq. 5** include the temperatures at adjacent nodes (T0, T2, and T4), the radial position of each node from the centerline (r), the radial grid spacing ( $\Delta r$ ), the thermal diffusivity ( $\alpha_d$ ), and the time increment ( $\Delta t$ ).

## Finite Difference Modeling for Geothermal Temperatures in GSHP Systems

### Methodology

In the context of smart city development, embedding energy piles within urban structures and accurately assessing the consequent subsurface heat transfer are essential priorities. These elements are fundamental to maximizing the performance and environmental sustainability of ground-source heat pump (GSHP) systems, which are a cornerstone of intelligent urban energy strategies. The present research employs a one-dimensional finite difference method (FDM) to forecast and simulate soil temperature profiles surrounding an energy pile across multiple radial distances and time scales. Input data encompassing the physical and thermal properties of both the soil and system components were compiled through a thorough review of regional GSHP literature focused on Southeast Asia, along with established design guidelines and authoritative textbooks [12–16, 33]. Model development was further informed by detailed experimental work and measurements obtained from an operational GSHP pilot facility and energy pile setup at Kasetsart University in Thailand [13].

The investigation centers primarily on two key variables: the soil's effective thermal conductivity and bulk density. In the model, thermal conductivity is assumed to increase in proportion to the temperature rise at the heat exchanger linked to the GSHP. Differences in soil density are incorporated to represent the diverse geological settings across Southeast Asia, where GSHP and energy pile applications might be implemented. This framework enables a systematic evaluation of the influence of soil density on temperature distribution patterns, with specific density values and their selection criteria to be elaborated in a subsequent section.

A notable strength of the finite difference modeling approach lies in its capacity to reduce intricate real-world heat transfer phenomena to a tractable numerical representation. By simplifying the problem in this manner, the method effectively

captures the behavior of the vertical heat exchanger embedded within the energy pile, thereby supporting practical advancements in sustainable smart city infrastructure design and implementation.

## Model definition

With the ongoing expansion of urban centers throughout Southeast Asia, there is a corresponding rise in the construction of small- to medium-scale buildings to accommodate increasing population and development needs. These buildings frequently require pile foundations that extend into more stable strata to limit differential settlement, particularly when penetrating the overlying soft clay layers (Table 1). Constructing a one-dimensional finite difference method (FDM) model requires appropriate simplifying assumptions.

The modeling approach for energy piles and their foundational integration within the FDM framework is depicted in Figure 5. The model presumes that the energy pile is embedded within a soft clay stratum averaging 10 to 15 m in thickness beneath the ground surface. For incorporating a ground-source heat pump (GSHP) system, the selected pile type is a spun (prestressed) pile with an outer diameter of 0.3 m and an internal opening width of 0.15 m, extending the full pile length. Following installation of the GSHP components, the pile interior is filled with concrete. The total pile length is set at 12 m, while the effective heat exchange length is taken as 10 m, accounting for the soil plug occupying the upper portion. The U-tube heat exchanger, a core element of the GSHP, has a combined length of 20 m, symmetrically allocated between the downward-flowing inlet leg and the upward-flowing outlet leg. The inlet segment (shown in red on the right side of the pile schematic) handles the descent of the high-temperature heat transfer fluid over 10 m. In contrast, the outlet segment (shown in blue on the left) manages the ascent of the cooled fluid over the same 10 m. All thermal input parameters of the GSHP system components and the energy pile itself—drawn from guidelines published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [34] and the text Analysis and Design of Energy Geostructures [6]—are compiled in Table 2 for application in the numerical simulation.

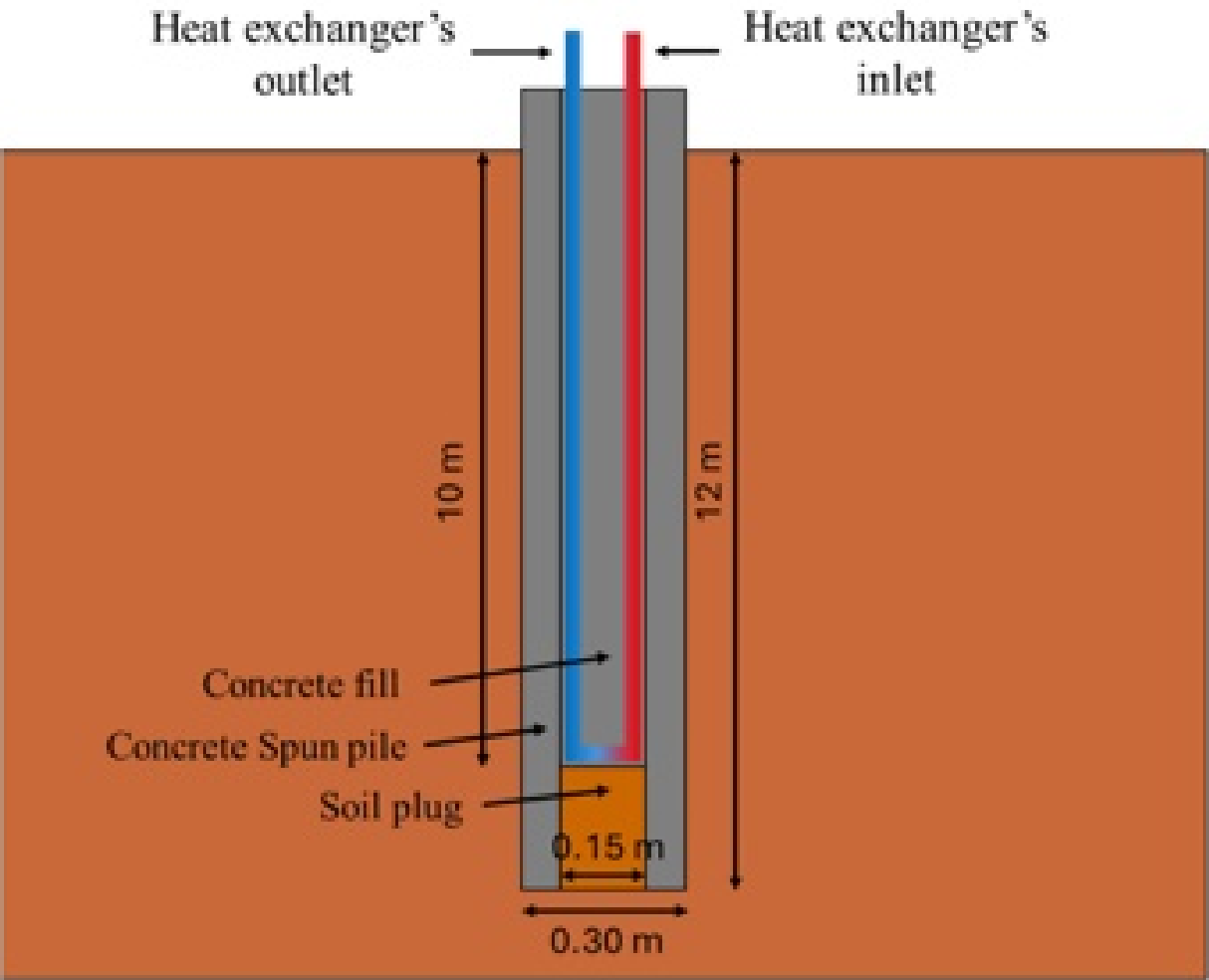


**Figure 5.** General definition of energy pile in the FDM model.

**Table 2.** Input parameters for FDM analysis.

| Parameter                       | Value | Unit |
|---------------------------------|-------|------|
| Global parameters               |       |      |
| Background temperature          | 29    | °C   |
| Inlet U-tube temperature        | 37    | °C   |
| Outlet U-tube temperature       | 33    | °C   |
| Time step ( $\Delta t$ )        | 7200  | s    |
| Radial increment ( $\Delta r$ ) | 0.15  | m    |
| GSHP on/off cycle duration      | 12    | h    |
| HDPE U-tube heat exchanger      |       |      |
| Heat exchanger length           | 20    | m    |
| Wall thickness                  | 0.005 | m    |

|                                                      |                       |                   |
|------------------------------------------------------|-----------------------|-------------------|
| Density ( $\rho$ )                                   | 950                   | kg/m <sup>3</sup> |
| Specific heat capacity ( $c_{\text{HDPE}}$ )         | 2400                  | J/(kg·K)          |
| Thermal conductivity ( $\lambda_{\text{HDPE}}$ )     | 0.48                  | W/(m·°C)          |
| Thermal diffusivity ( $\alpha_{\text{HDPE}}$ )       | $2.11 \times 10^{-7}$ | m <sup>2</sup> /s |
| <b>Concrete pile</b>                                 |                       |                   |
| Diameter ( $\phi$ )                                  | 0.30                  | m                 |
| Concrete thickness                                   | 0.15                  | m                 |
| Density ( $\rho_{\text{concrete}}$ )                 | 2400                  | kg/m <sup>3</sup> |
| Specific heat capacity ( $c_{\text{concrete}}$ )     | 900                   | J/(kg·K)          |
| Thermal conductivity ( $\lambda_{\text{concrete}}$ ) | 0.8                   | W/(m·°C)          |
| Thermal diffusivity ( $\alpha_{\text{concrete}}$ )   | $3.70 \times 10^{-7}$ | m <sup>2</sup> /s |
| <b>Marine clay soil</b>                              |                       |                   |
| Density ( $\rho$ )                                   | 1400, 1600, 1800      | kg/m <sup>3</sup> |
| Specific heat capacity ( $c_{\text{soil}}$ )         | 800                   | J/(kg·K)          |
| Thermal conductivity ( $\lambda_{\text{soil}}$ )     | varies                | W/(m·°C)          |
| Thermal diffusivity ( $\alpha_{\text{soil}}$ )       | varies                | m <sup>2</sup> /s |

The computational mesh consists of a grid of discrete nodes that discretize the solution domain to approximate the governing equations numerically. In a two-dimensional context, the domain is subdivided into small rectangular cells. Node density may be adjusted across different regions, with denser meshing applied where gradients are steep or where higher resolution is required for solution accuracy. At every node, the differential equations are replaced by finite difference approximations that depend on the values computed at adjacent nodes. The arrangement, spacing, and distribution of these computational nodes significantly influence both the precision and computational efficiency of the finite difference results.

Employing a finer mesh typically yields greater accuracy and detail in the solution but incurs substantially higher computational demand. In contrast, a coarser mesh accelerates calculations at the expense of reduced resolution and potential loss of accuracy. The mesh configuration adopted for the current study is illustrated in **Figure 4**: horizontal nodal spacing is fixed at 0.15 m, with this interval designated as the radial increment  $\Delta r$ . Vertically, the spacing between successive horizontal levels is established at 1.0 m to adequately capture the depth-dependent temperature variations introduced by the heat exchanger.

## Constant-temperature boundary condition

To replicate the initial operational state of the energy pile system, the temperature along a 20 m-long heat exchanger is set as a constant-temperature boundary condition in the analysis spreadsheet. This simplification omits radial convective heat transfer inside the heat exchanger and the circulating fluid. It remains essential, however, to differentiate the heat input contributed by the downward-flowing medium in the 10 m inlet leg from that of the upward-flowing medium in the 10 m outlet leg, treating each segment as a separate heat source.

Earlier investigations [12, 13, 16, 33] reported average fluid temperatures at the heat exchanger inlet and outlet, with inlet water at 37 °C and outlet water at 33 °C. Linear interpolation is applied to estimate the temperature profile at 1 m intervals

along the exchanger length, yielding a consistent decline of 0.2 °C per meter, as detailed in [Table 3](#). GSHP operation is typically synchronized with the building's air-conditioning load, requiring 12 hours of continuous activity to sustain exchanger temperatures between 33 °C and 37 °C (depending on depth), followed by a 12-hour shutdown period. During shutdown, the constant-temperature boundary is reset to the undisturbed ambient ground temperature.

**Table 3.** The temperature of the HDPE heat exchanger at different depths of the energy pile.

| Outlet side |                  | Inlet side |                  |
|-------------|------------------|------------|------------------|
| Depth (m)   | Temperature (°C) | Depth (m)  | Temperature (°C) |
| 0 to 1      | 33.0             | 0 to 1     | 37.0             |
| 1 to 2      | 33.2             | 1 to 2     | 36.8             |
| 2 to 3      | 33.4             | 2 to 3     | 36.6             |
| 3 to 4      | 33.6             | 3 to 4     | 36.4             |
| 4 to 5      | 33.8             | 4 to 5     | 36.2             |
| 5 to 6      | 34.0             | 5 to 6     | 36.0             |
| 6 to 7      | 34.2             | 6 to 7     | 35.8             |
| 7 to 8      | 34.4             | 7 to 8     | 35.6             |
| 8 to 9      | 34.6             | 8 to 9     | 35.4             |
| 9 to 10     | 34.8             | 9 to 10    | 35.2             |

Field measurements in the Bangkok region [\[12-14\]](#), derived from Thermal Response Tests (TRT) and active GSHP air-conditioning installations, indicate that the undisturbed temperature of Bangkok clay fluctuates seasonally between 29 °C and 31 °C. On average, this is approximately 5 °C below the prevailing air temperature [\[15\]](#). For the finite difference method (FDM) boundary calculations, the background temperature of Bangkok clay is set to 29 °C.

To clarify the conceptual model of the constant-temperature boundary, [Figure 6](#) shows the asymmetric temperature distribution around the energy pile within the soil mass. This visualization is based on linear interpolation of the constant boundary condition after 1 year of simulated operation, obtained from a finite element model (FEM) executed in PLAXIS 2D CONNECT V21.01.00.479 [\[35, 36\]](#), within a 3 m radial distance from the pile centerline.

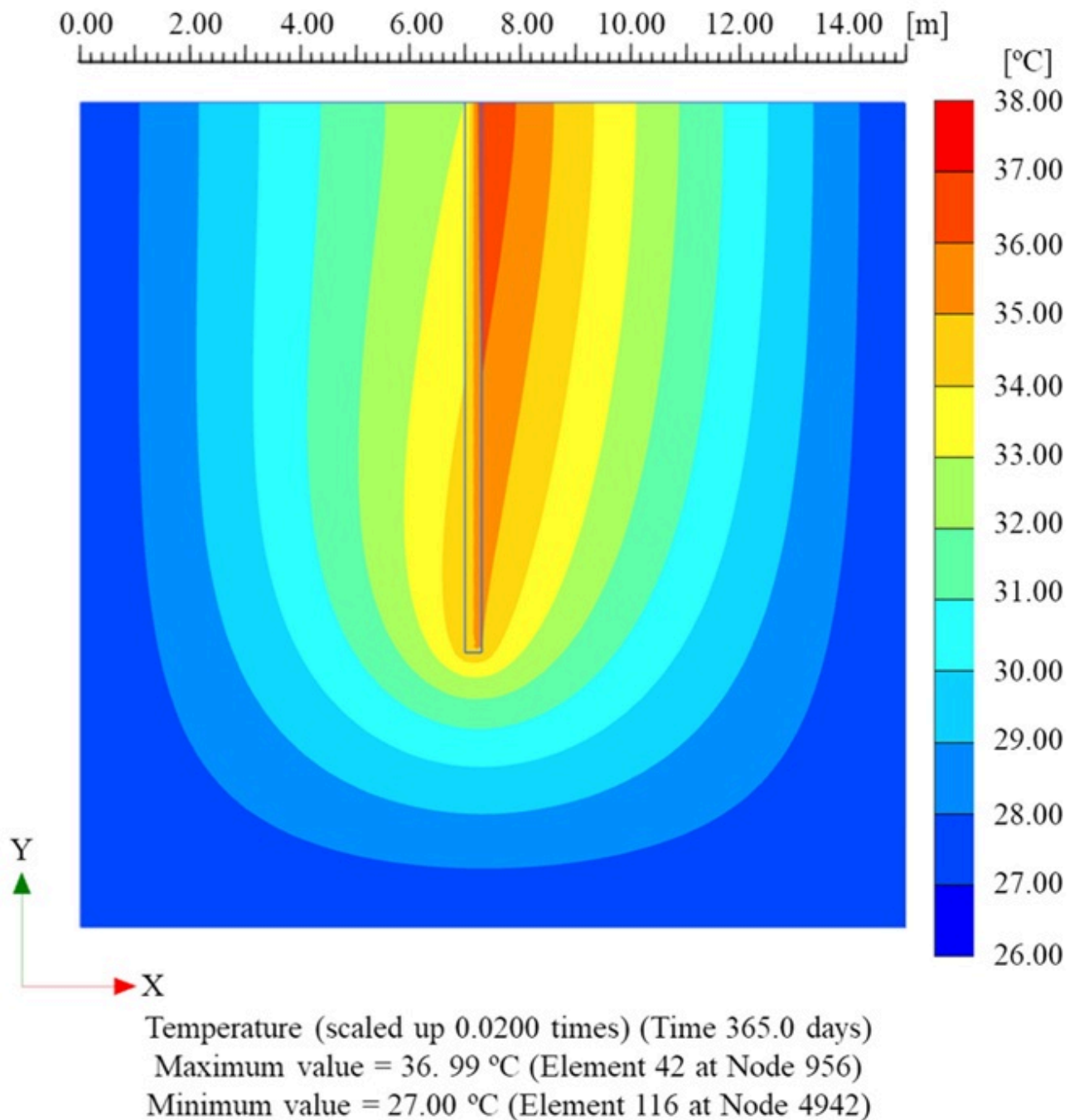


**Figure 6.** Asymmetrical soil temperature around the energy pile after 1 year, simulated with the FEM model.

## Variable thermal conductivities and soil densities

Multiple physical attributes of the soil and system components influence the effective thermal conductivity, which governs the performance of GSHP-integrated energy piles. Key factors include mineral composition, dry density, moisture content, and particle size distribution, as documented in prior research [37, 38]. Laboratory experiments on lateritic clay specimens from the Guilin and Liuzhou regions of Guangxi, China [39], demonstrated that thermal conductivity exhibits temperature dependence. Across test temperatures from 5 to 90 °C, saturated samples at moisture contents of 4%, 44.90%, and 83.90% displayed linear increases in thermal conductivity, ranging from 0.2 to 0.4 W/m·°C, 0.6 to 1.6 W/m·°C, and 0.9 to 1.3 W/m·°C, respectively, as illustrated in **Figure 7**.

Adopting a linear temperature–thermal conductivity relationship for clay materials, this correlation is implemented in the FDM model. The thermal conductivity of soft clay from various sites is modeled as a linear function of the GSHP system’s mean inlet–outlet fluid temperature. Bangkok soft clay, having been the subject of extensive characterization, is adopted as a representative material due to its close resemblance in thermal and geotechnical properties to other East Asian soft marine clays, including Ariake clay, Singapore marine clay, Hong Kong marine clay, Kuantan clay, and Ho Chi Minh City marine clay—offering valuable comparative insights into thermal behavior across similar deposits. Deposited during the Holocene within the Chao Phraya River delta, Bangkok clay is characterized by high water content, low shear strength, and high compressibility, posing persistent geotechnical challenges. Significant prior work includes that of Abuel-Naga *et al.* [28, 29], who employed temperature-controlled triaxial testing under undrained conditions from 20 °C to 90 °C and reported thermal conductivity values of 0.825, 1.1, and 1.3 W/m·°C. Jotisankasa *et al.* [13] conducted full-scale energy pile testing in a residential context and measured thermal conductivities of 1.49, 2.01, and 3.3 W/m·°C for steel and spun pile configurations. An additional study in Hanoi, Vietnam [40], documented heat exchanger fluid temperatures between 37 °C and 40 °C, corresponding to thermal conductivity values of 1.82 and 1.97 W/m·°C.

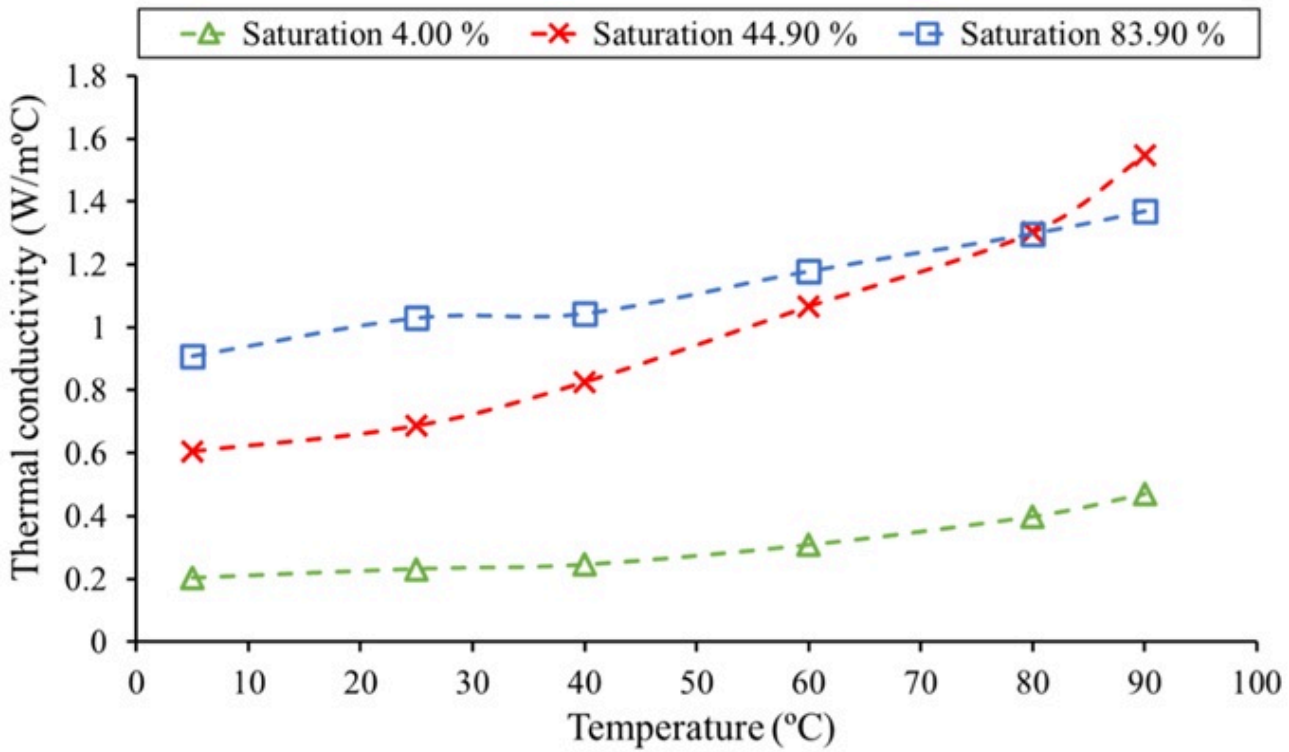


**Figure 7.** Guilin lateritic clay’s temperature-dependent thermal conductivity.

The study derives variable thermal conductivities for the GSHP system from these results, summarized in Table 4, which provides the data for constructing four variable thermal-conductivity equations. These linear equations relate the heat exchanger’s average temperature to its corresponding thermal conductivity. Cases no. 2 and no. 4 are directly based on data from Jotisankasa *et al.* [13] and Widiatmojo *et al.* [40], whereas cases no. 1 and no. 3 feature-modified slopes to create intermediate thermal-conductivity ranges suitable for the modeling scenarios. For visual comparison, all four thermal conductivity equations are plotted in Figure 8, beginning at a reference temperature of 32 °C with an initial thermal conductivity of 1.49 W/m·°C. Based on field GSHP experiments, the average heat exchanger temperature is not expected to exceed 40 °C.

**Table 4.** Summary of deriving variable thermal conductivities in GSHP systems for constructing four variable thermal conductivity equations.

| Case       | Temperature (°C) | Thermal conductivity (w/m·°C) | Thermal conductivity equation | R <sup>2</sup> |
|------------|------------------|-------------------------------|-------------------------------|----------------|
| no. 1      | 32 to 40         | 1.49 to 2.99                  | $y = 0.0500x - 14.5100$       | -              |
| no. 2 [13] | 32, 34, 38       | 1.49, 2.09, 3.31              | $y = 0.3046x - 8.2943$        | 0.9971         |
| no. 3      | 32 to 40         | 1.49 to 2.69                  | $y = 0.1500x - 3.3100$        | -              |
| no. 4 [40] | 32, 37, 40       | 1.49, 1.82, 1.97              | $y = 0.0606x - 0.4422$        | 0.9951         |

Soil density is another key variable closely linked to the GSHP installation's geographical setting. This investigation examines soft clay densities ranging from 1400 kg/m<sup>3</sup> (representative of Singapore marine clay and Ariake clay), through 1600 kg/m<sup>3</sup> (typical of Bangkok clay), up to 1800 kg/m<sup>3</sup> (characteristic of Hong Kong marine clay). Further details on additional variables and their influence on overall system behavior are presented in [Table 5](#).

Table 5. The difference in clay density across countries.

| Soil Name                             | Density (kg/m <sup>3</sup> ) |
|---------------------------------------|------------------------------|
| Singapore marine clay and Ariake clay | 1400                         |
| Bangkok clay                          | 1600                         |
| Hong Kong clay                        | 1800                         |

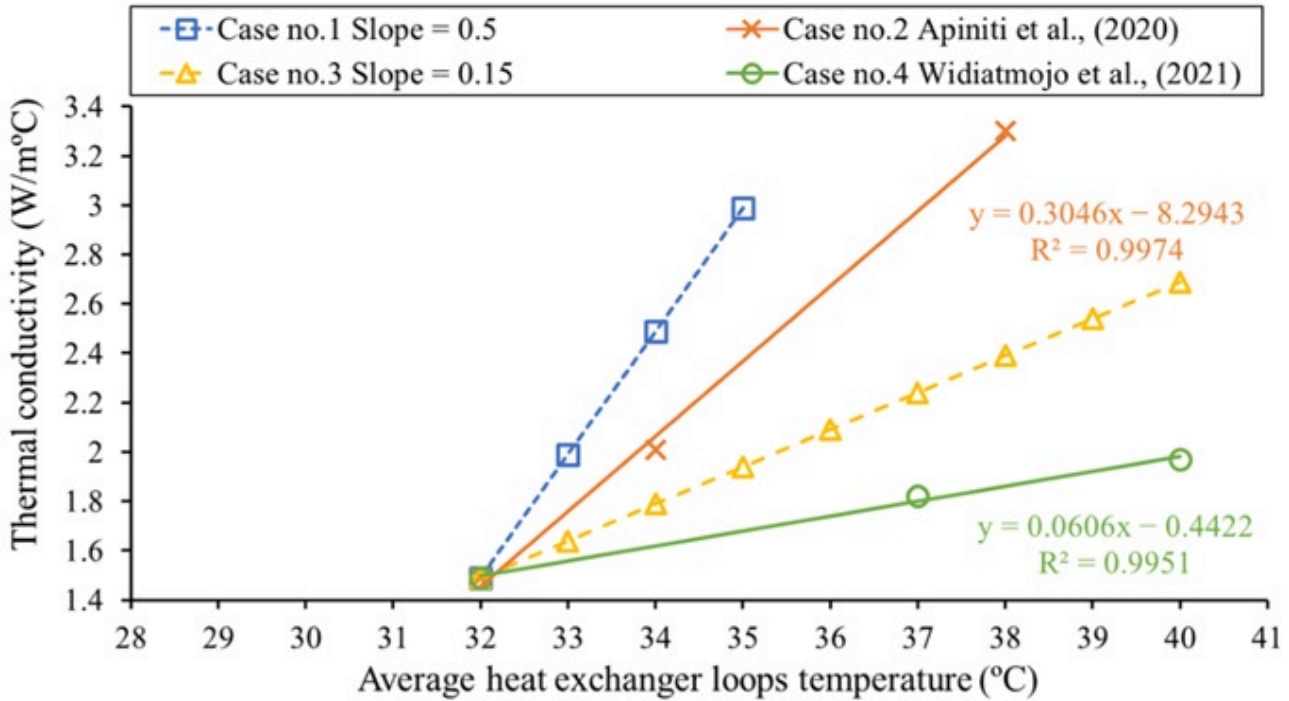


Figure 8. Comparative thermal conductivity in the GSHP operation range [13, 40].

## Results and Discussion

### Evaluation of temperature distribution around energy piles

Effective utilization of GSHP systems and energy piles is vital for enhancing the operational efficiency of smart cities, with typical daily running periods reaching up to 12 hours. This research conducts a thorough examination of soil temperature evolution around energy piles, spanning short-term observations (the first 7 days) to long-term annual patterns.

Over the initial seven-day monitoring period, temperature fluctuations near the energy pile exhibit pronounced cyclic behavior, resembling a sinusoidal pattern (Figure 9). This periodicity arises from the on–off cycling of the GSHP system. Despite daily fluctuations, an overall gradual temperature increase is evident, reflecting progressive heat accumulation in the soil volume. Heat transfer occurs predominantly through conduction and convection, with these effects becoming more attenuated as distance from the pile axis increases. At radial distances of 0.15 m, 0.30 m, 0.45 m, and 0.60 m from the pile centerline, the amplitude of temperature oscillation diminishes progressively. For instance, at 0.15 m, the daily variation spans from 31.25 to 30.25 °C (a 1 °C range), narrowing markedly to 0.25 °C at 0.30 m and 0.17 °C at 0.45 m, demonstrating the diffusive spread of thermal energy through the soil medium.

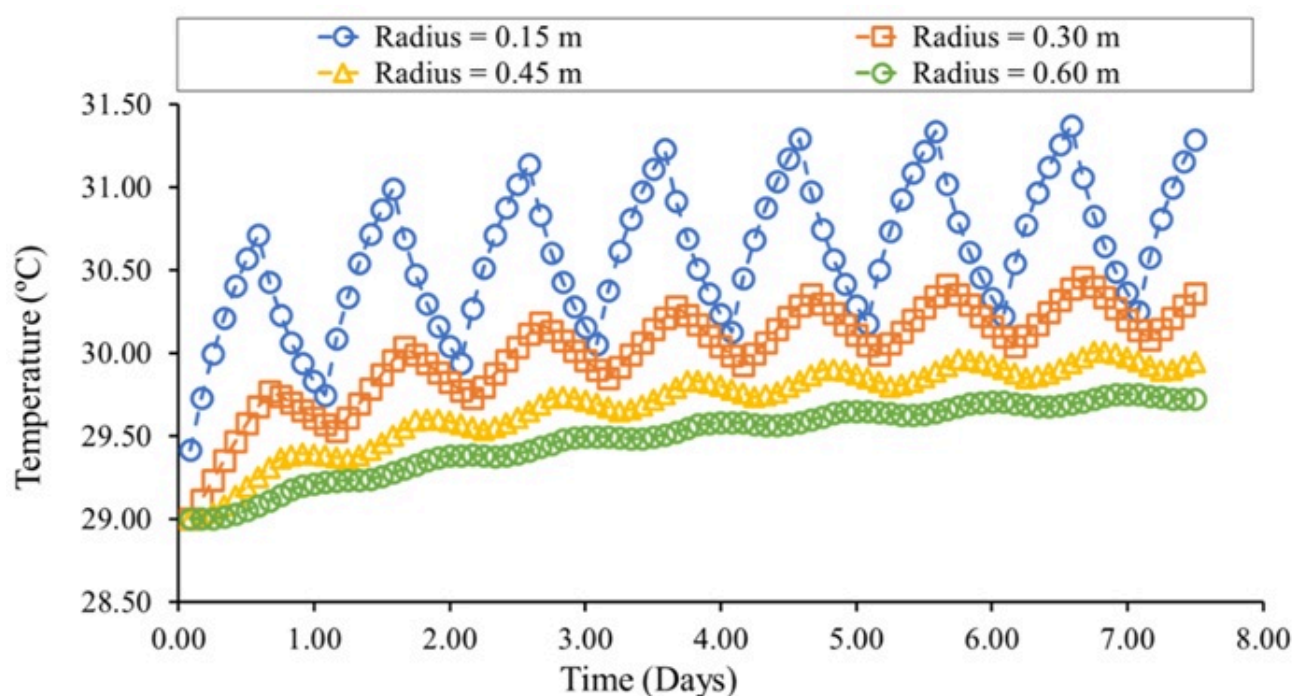


**Figure 9.** Seven-day temperature cycle at various radii.

From an annual perspective, the temperature field shows relative stability, with only minor long-term elevation. By the end of one year, the peak soil temperature near the energy pile (at a 0.15 m radius) levels off at approximately 31.5 °C, as depicted in Figure 10. This near-equilibrium condition highlights the balance established between heat injection from the GSHP and the soil's inherent capacity for long-term heat dissipation.

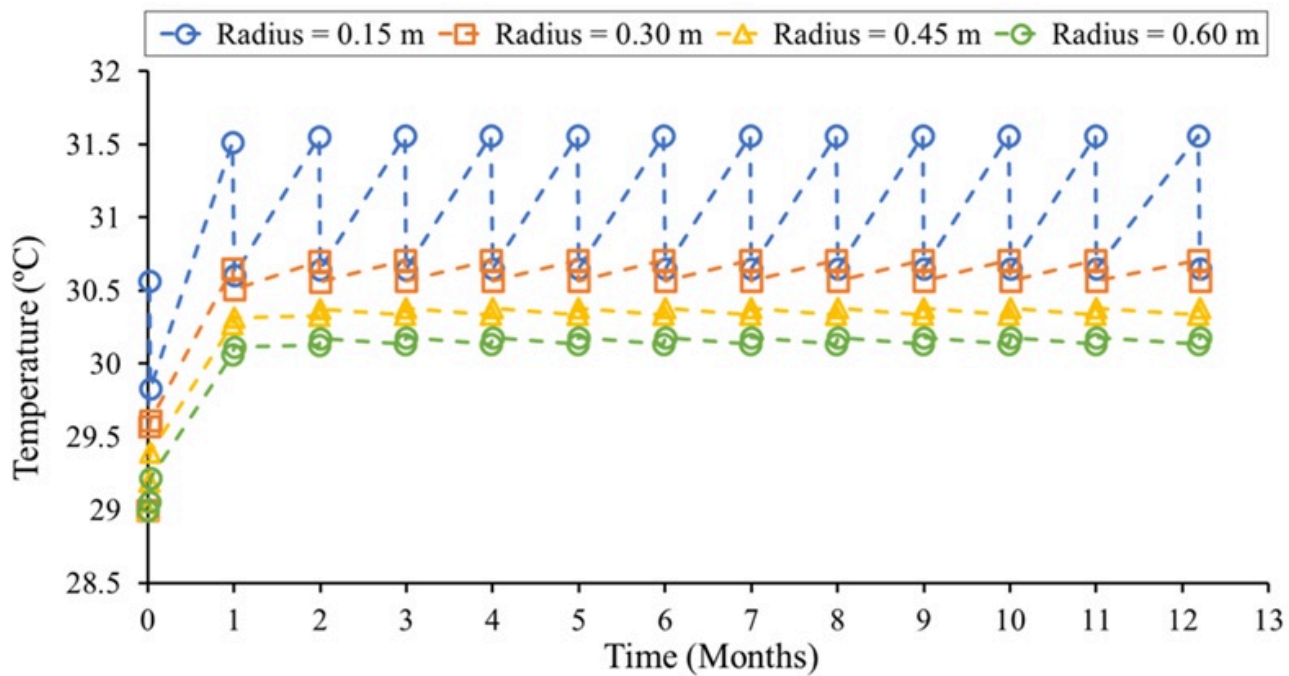
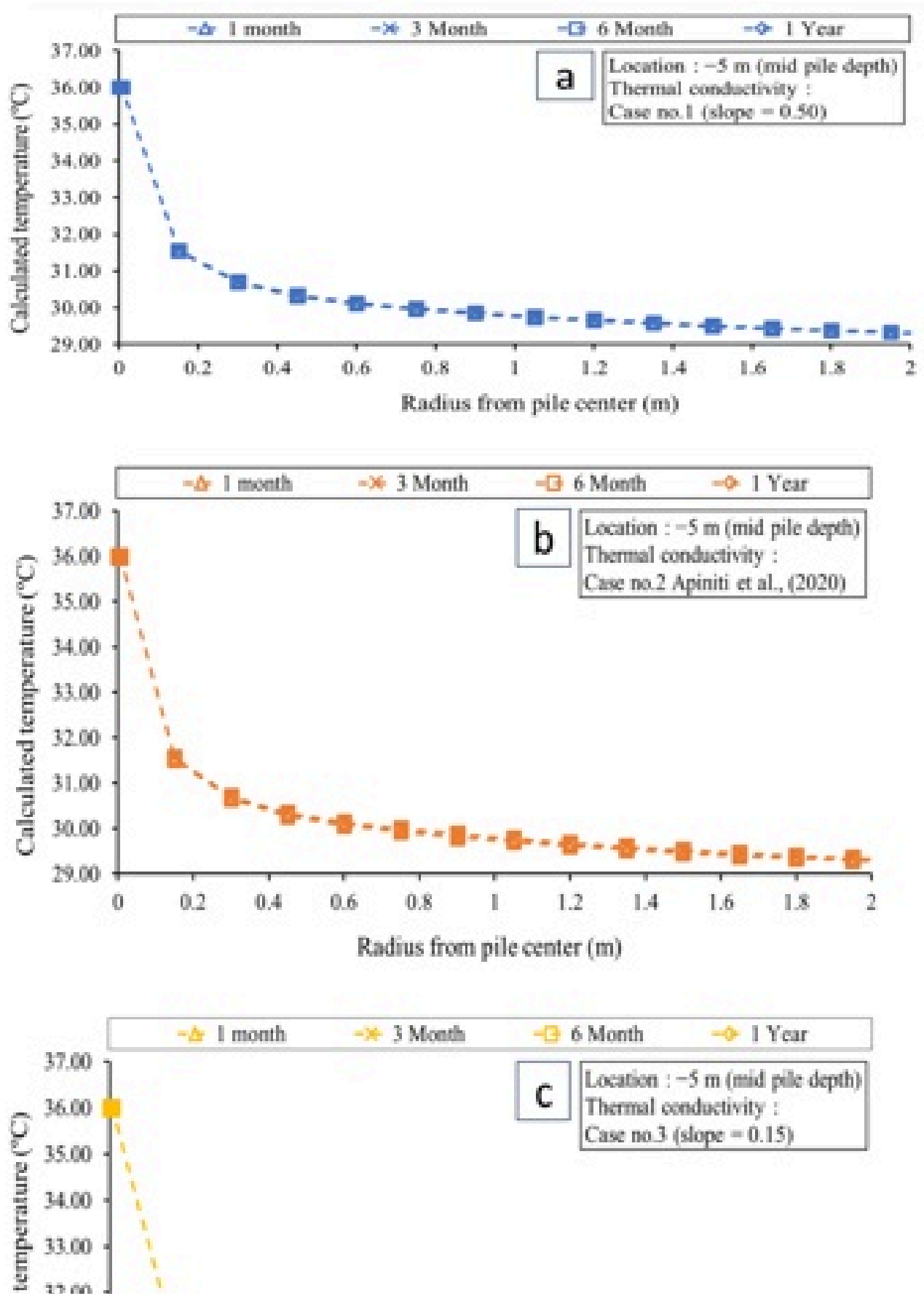


**Figure 10.** One-year temperature cycle at various radii.

**Figure 11** provides further insight by contrasting the temperature response to alternating 12-hour GSHP operating cycles at one-month and one-year time scales. Within a 1 m radius from the pile center, temperatures fluctuate between 29.5 and 32 °C. Beyond this zone, between 1 m and 2 m, the range narrows to 29.0 to 30 °C. These findings indicate that thermally induced consolidation—both primary and secondary—exerts a negligible impact on soil volume changes over the examined temperature interval (25 to 90 °C), consistent with observations by Abuel-Naga *et al.* [28, 29] on temperature-driven volumetric behavior in soft Bangkok clay.



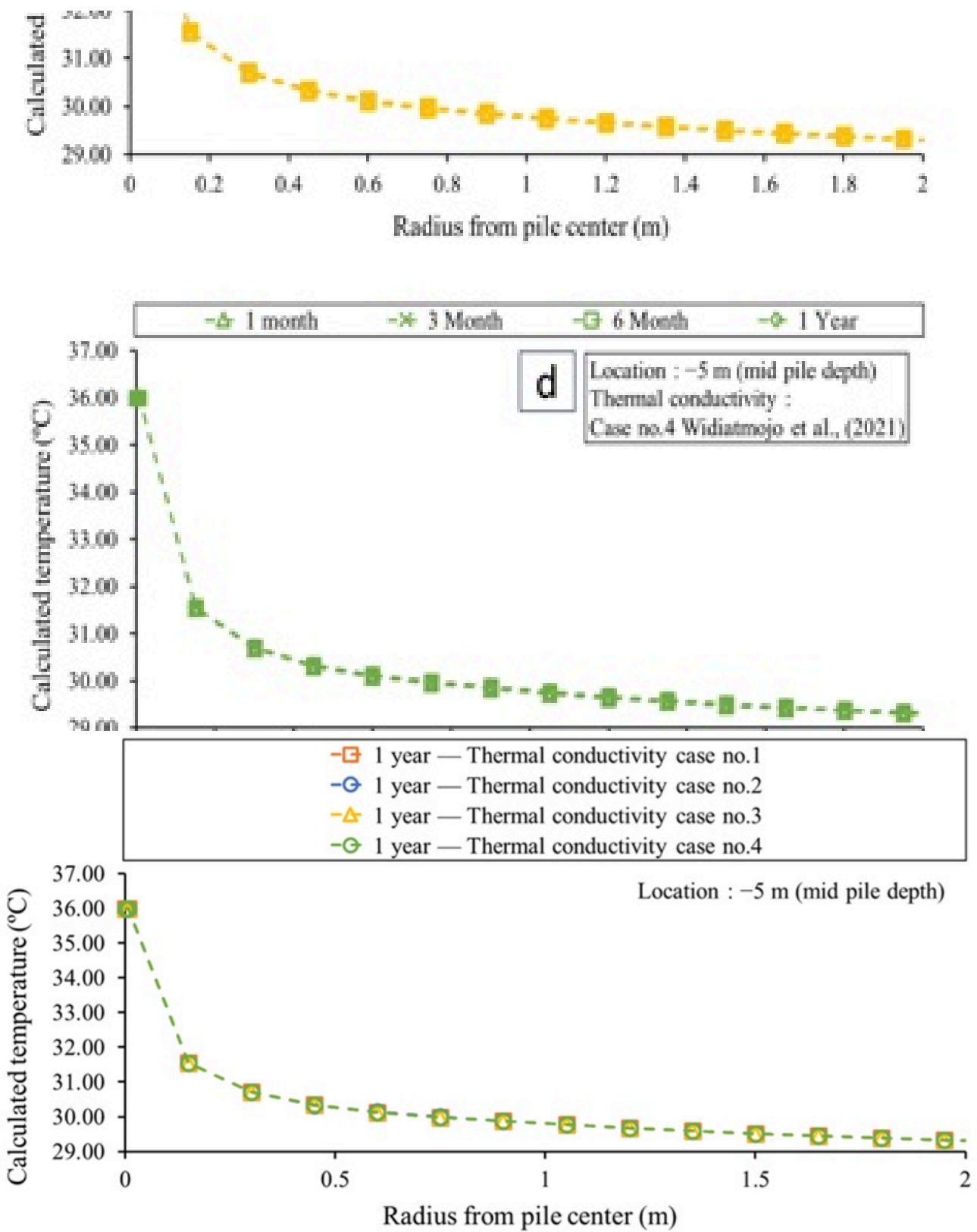


**Figure 12.** One-year predicted temperatures with different thermal conductivities.

The findings demonstrate notable consistency: within the examined spectrum of thermal conductivity values, the temperature distribution near the energy piles remains remarkably stable across all analyzed time scales. This pattern

indicates considerable robustness of the thermal regime against variations in soil thermal conductivity. Such resilience carries important implications for smart city design and implementation, where maximizing energy efficiency and long-term sustainability are primary objectives. The observed steadiness in temperature behavior, even under differing conductivity conditions, reveals a key characteristic of energy pile thermal processes. It indicates that system designs can incorporate a reasonable degree of tolerance regarding soil thermal properties. For engineers and city planners, this insight is highly practical, suggesting that small deviations in soil thermal conductivity are unlikely to necessitate significant modifications to GSHP system configuration or operational protocols.

That said, these conclusions must be viewed within the boundaries of the present investigation. While thorough, the analysis is confined to the specific range of thermal conductivity variations considered, which is closely tied to the soil types, moisture regimes, and environmental settings addressed in the study. Applying these observations to other geographic areas or soil profiles, therefore, requires prudent evaluation of site-specific characteristics and conditions. Beyond immediate engineering concerns, the documented stability has wider relevance for urban sustainability and adaptive capacity. In an era marked by growing climate uncertainty and environmental shifts, the capacity to develop energy infrastructure that remains effective despite changes in foundational environmental parameters is increasingly valuable. The outcomes of this work add to the expanding evidence base supporting the creation of more durable and eco-friendly urban systems.

## Impact of clay density variation on temperature predictions

This research delves into the complex relationship between soil density variations and the thermal response around energy piles, a vital aspect of thermal regulation strategies in smart cities. Employing the finite difference method (FDM), the study classifies soft clays into three density categories: 1400 kg/m<sup>3</sup> (corresponding to Singapore marine clay and Ariake clay), 1600 kg/m<sup>3</sup> (typical of soft Bangkok clay), and 1800 kg/m<sup>3</sup> (representative of Hong Kong clay, as contextualized in related discussions). These groupings are instrumental in elucidating the subtle yet meaningful effects of soil density on heat conduction properties and temperature control in the vicinity of energy piles. **Figure 13** visually captures the influence of density differences on the predicted temperature evolution over a full year, revealing progressive convergence of the temperature profiles with extended operation time. This trend illustrates a diminishing differential impact of density variations on temperature as the system matures, emphasizing the intricate connection between soil physical attributes and subsurface thermal processes while affirming the importance of density in governing the efficiency of geothermal energy systems.

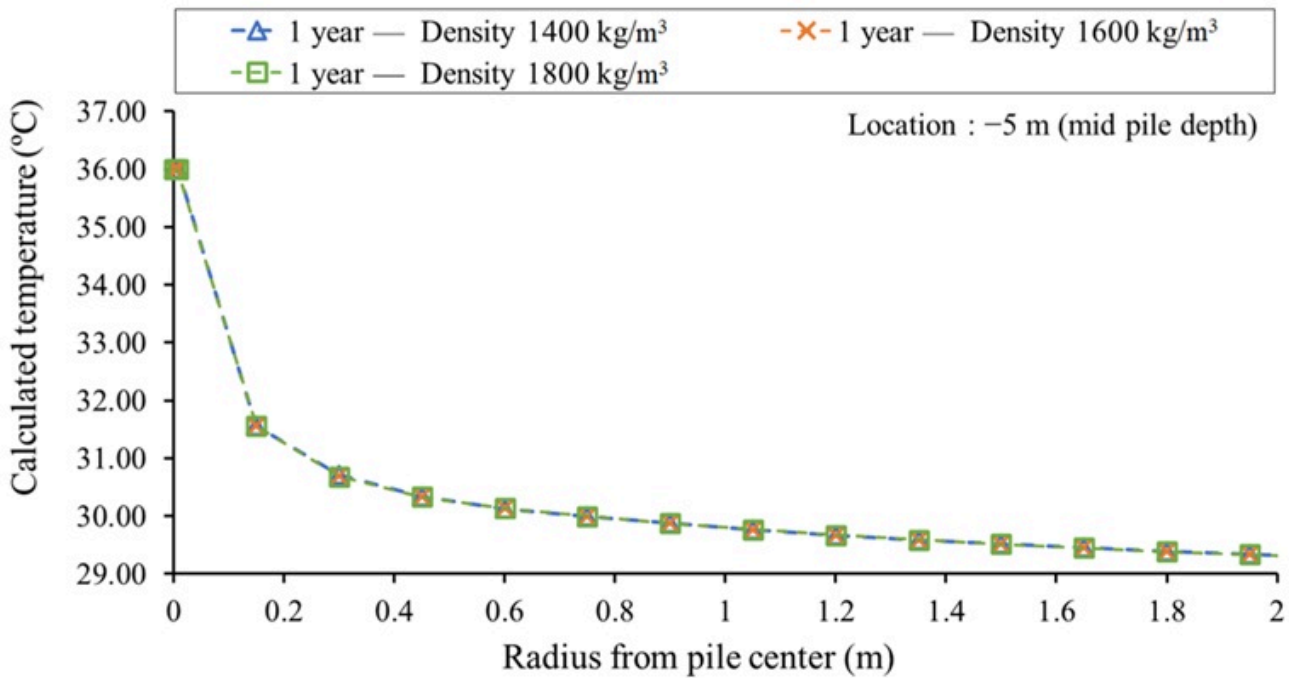


**Figure 13.** One-year predicted temperatures with different densities of Bangkok clay.

More detailed insights are provided in **Figures 14–16**, which systematically assess temperature responses to rising soil density at selected radial distances from the energy pile (0.3 m, 0.6 m, and 1.0 m) across multiple time horizons (3 months, 6 months, and 1 year). The analysis consistently shows that as soil density increases from 1400 to 1800 kg/m<sup>3</sup>—a 28.57% increase—the associated impact on soil temperature declines. Quantitatively, each incremental increase in density produces temperature reductions of 0.02, 0.01, and 0.0025 °C over the specified periods. This relationship is further refined by noting that a 10% increase in density corresponds to an average temperature drop of 0.007 °C at a radial distance of 0.3 m from the pile centerline. The detailed evaluation extends to greater distances, as depicted in **Figures 14–16**: at 0.6 m, each 10% density increment yields an average temperature decrease of 0.003 °C, while at 1 m the corresponding reduction averages 0.0009 °C. These results collectively offer a refined perspective on how soil density modulates thermal behavior, demonstrating a clear inverse relationship between density and the elevation of surrounding ground temperature.

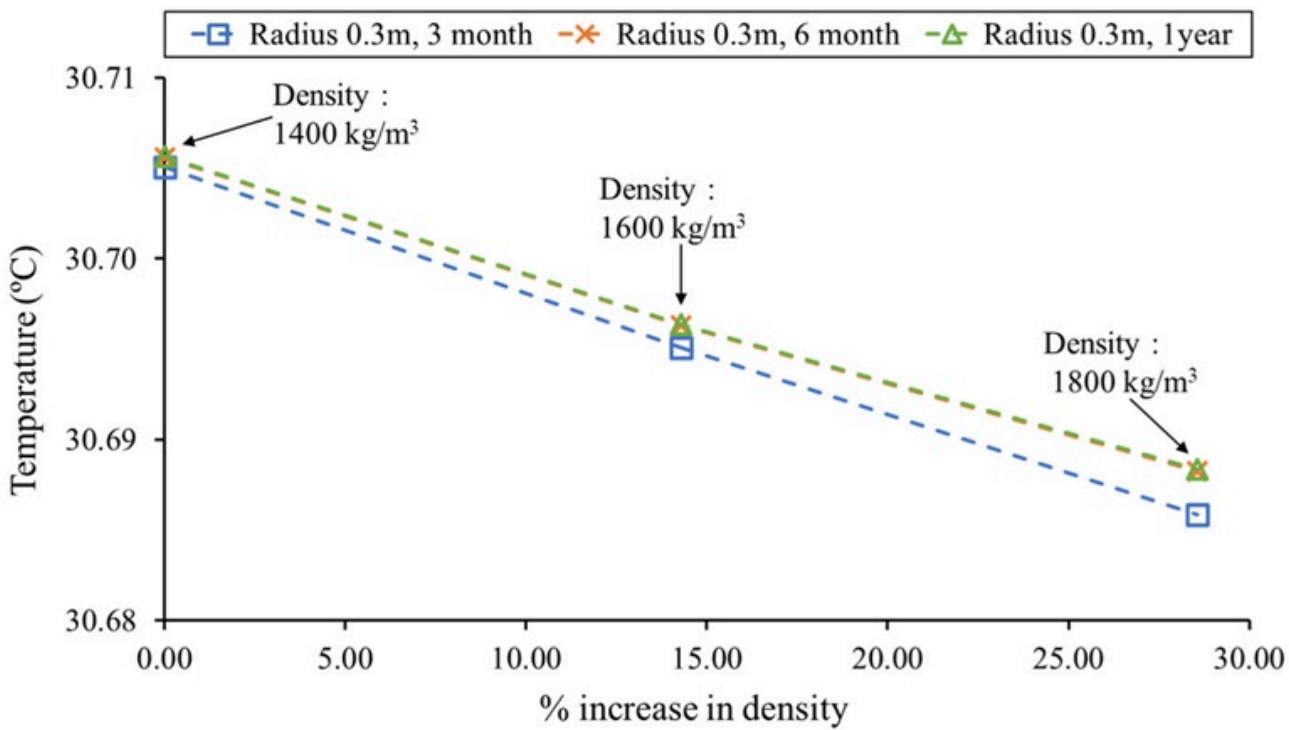


**Figure 14.** Temperature prediction in 1 month, 6 months, and 1 year, and the Bangkok clay density correlation over time at a 0.3 m radius.

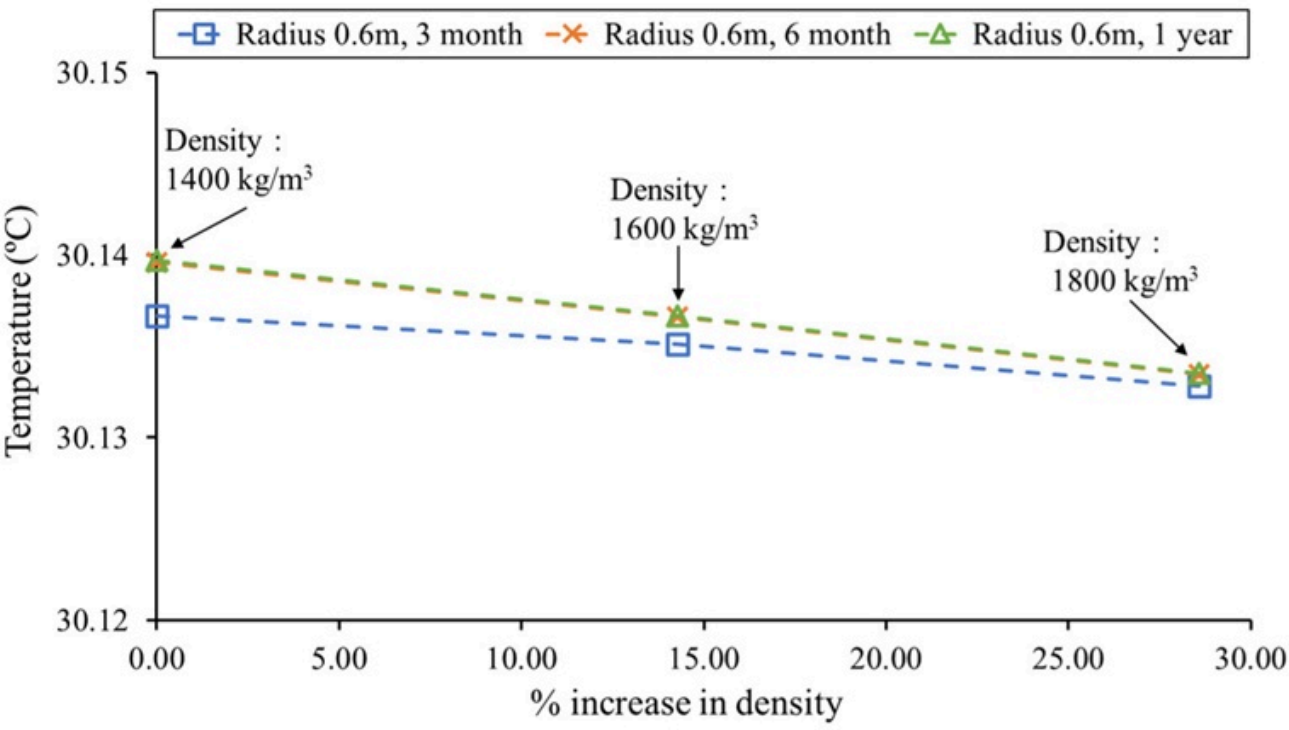


**Figure 15.** Temperature prediction in 3 months, 6 months, and 1 year, and the Bangkok clay density correlation over time at a 0.6 m radius.

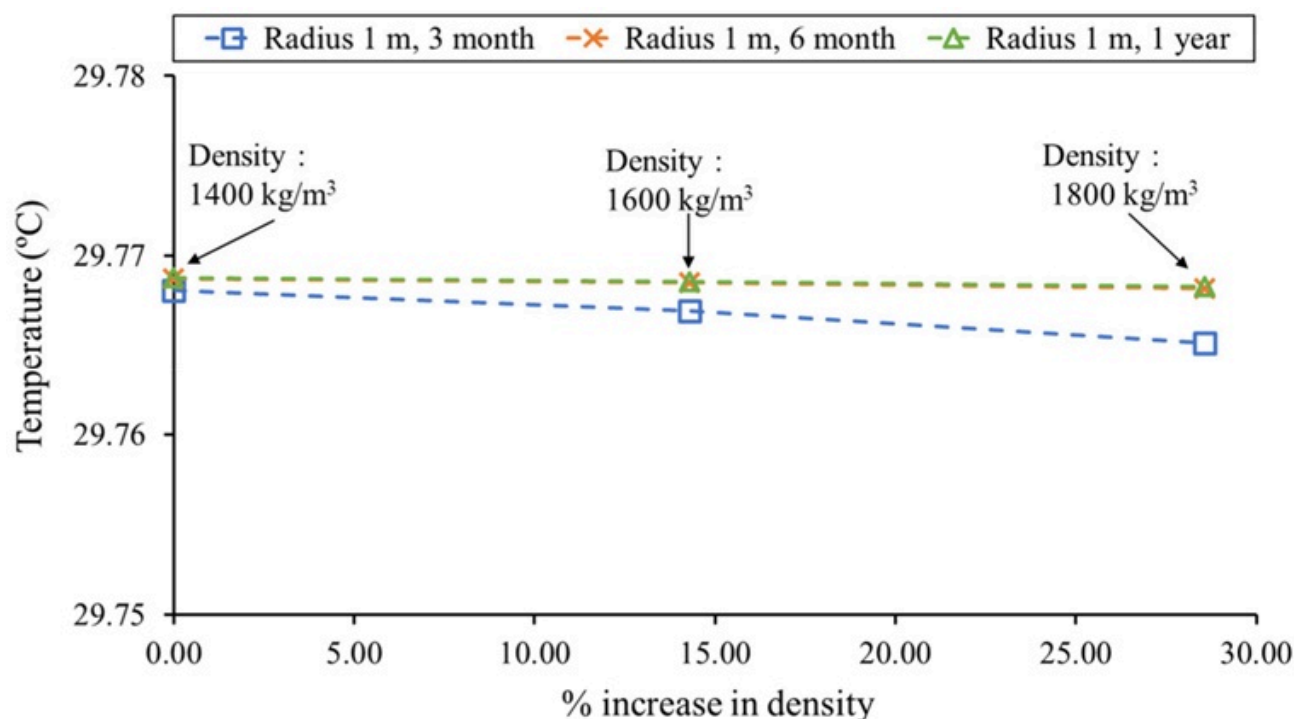


**Figure 16.** Temperature prediction for 3 months, 6 months, and 1 year, and Bangkok clay density at a 0.3 m radius.

This in-depth investigation into the influence of soil density on subsurface thermal processes surrounding energy piles delivers important guidance for the engineering and management of geothermal installations in smart urban settings. It stresses the pivotal role played by soil's physical characteristics—most notably density—in shaping heat exchange dynamics within the ground, which ultimately governs the performance and long-term viability of energy pile applications. The outcomes indicate that careful attention to soil density improves the reliability of thermal simulation models, enabling more refined and effective design approaches for underground energy systems. Moreover, the findings reinforce the need to integrate comprehensive geotechnical characterization at every stage of geothermal project development. A clearer understanding of how density fluctuations affect temperature control can foster more effective heat management strategies, bolstering the durability and eco-friendliness of city-scale infrastructure. Beyond enriching theoretical knowledge of soil–heat interactions, this work serves as a practical resource for engineers and urban developers seeking to embed high-efficiency geothermal solutions into smart city frameworks seamlessly.

## Conclusion

The research examining the deployment of ground source heat pump (GSHP) systems and energy piles within smart city initiatives has produced several key takeaways:

- (1) GSHP installations, particularly those combined with energy piles, demonstrate strong efficiency and sustainability for urban space conditioning, achieving substantial cuts in electricity demand and greenhouse gas releases.
- (2) The investigation underscored the essential need to characterize subsurface heat migration—especially in the soft marine clays widespread across Southeast Asia—to ensure successful GSHP deployment. Thermal conductivity and soil density emerged as primary determinants of overall system effectiveness.
- (3) Employing a finite difference method (FDM), the study accurately simulated temperature fields around energy piles and quantified the consequences of varying soil thermal conductivity and density on operational efficiency.

(4) GSHP technology represents a viable strategy for alleviating the urban heat island phenomenon, offering particular advantages in high-density districts where traditional HVAC equipment underperforms.

Drawing from these results, the following directions for future investigation are proposed:

(1) Although the FDM yielded useful outcomes, subsequent research could adopt more advanced numerical approaches—such as the finite element method (FEM)—to enhance precision in forecasting subsurface temperature evolution and system behavior.

(2) Further experimental work is required to establish precise temperature-dependent thermal conductivity values for various clay soils, with priority given to Bangkok clay, to strengthen the fidelity of thermal distribution predictions near energy piles.

(3) Examining how accelerated urban expansion and the resulting intensification of the urban heat island effect influence GSHP performance would generate actionable knowledge for city planning and smart city advancement.

(4) Upcoming efforts should concentrate on refining GSHP design configurations and control strategies to optimize geothermal resource utilization in metropolitan contexts.

(5) Additional research could assess the broader incorporation of GSHP systems into comprehensive frameworks for sustainable and climate-resilient urban infrastructure, accounting for shifting climatic patterns and ecological pressures.

This research makes a meaningful contribution to the expanding literature on sustainable urban growth and illuminates the considerable promise of GSHP systems and energy piles for smart city applications. By pursuing the recommended future research pathways, the full potential of shallow geothermal energy in city environments can be more fully harnessed, accelerating progress toward energy-efficient, environmentally responsible urban living.

Several limitations inherent to this work warrant recognition. First, the relatively brief data acquisition period may fail to capture extended seasonal cycles and long-term trends in ground-source heat pump (GSHP) behavior. Second, the scarcity of temperature measurements from thermal response tests (TRTs) and active GSHP facilities throughout Southeast Asia restricts the depth of region-specific analyses and cross-site benchmarking. Third, although computationally practical, the adopted one-dimensional finite difference model inherently simplifies heat transfer by neglecting vertical gradients and potentially overlooking site-specific heterogeneities. Lastly, the study points to the advantage of specifying heat flux as a boundary condition in finite element method (FEM) simulations to elevate modeling fidelity, implying that more elaborate numerical techniques could address current shortcomings. These constraints delineate promising avenues for subsequent studies to advance the accuracy and applicability of GSHP simulation within the region.

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# Ethics statement

None

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