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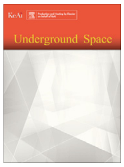

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Review Article

Review on heat transfer and thermo-mechanical behaviour of energy geostructures

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Abstract

Energy geostructures represent a novel building energy-saving technology derived from ground source heat pump technology. Heat transfer and thermo-mechanical response characteristics stand out as pivotal issues in the investigation and design of such energy geostructures. This paper provides an overview of the research on heat transfer models, factors influencing heat exchange performance, and thermo-mechanical behaviour concerning energy piles, energy walls, and energy tunnels. The future perspectives are also presented. Four types consisting of ten basic heat transfer models for energy piles were summarized, and their advantages, limitations, and applicable scenarios were comprehensively discussed from multiple aspects. The heat transfer models for energy walls and energy tunnels are scarce, and only one model was introduced for each of them. The influences of some controllable design parameters on the thermal performance of energy geostructures and the thermal-induced mechanical behaviour were summarized. The key conclusions are that the fluid flow rate should not be too high or too low, which is generally considered sufficient to ensure that the flow state is turbulent; and properly intermittent operation is beneficial to the recovery of geothermy, thereby improving the heat exchange performance. Due to the differing conditions considered, it is not possible to draw a definitive conclusion regarding whether heating can increase or decrease the shaft resistance or bearing capacity of energy piles. Generally, thermal effects within energy walls are unlikely to cause severe damage to structural stability. The issues related to thermal-induced ground deformation are considered more critical than those concerning the energy tunnel structure deformation. This paper highlights the aspects that require further research and the new aspects worth exploring in the future. Energy geostructures are not limited to new construction projects, and combining with other renewable energy utilization methods and integrating into district energy networks are the future development trends.

Keywords: Energy geostructure; Energy pile; Energy wall; Energy tunnel; Heat transfer; Thermo-mechanical behaviour

1 Introduction

The issue of energy depletion and environmental pollution caused by the excessive use of fossil fuels is threatening the sustainable development of societies and economies worldwide. Altering the current energy structure, reducing the use of fossil fuels, and developing renewable energy sources are inevitable trends for global sustainable energy utilization (Loveridge et al., 2020). Geothermal energy, a vast renewable clean energy source, was estimated to be 140 million times the heat energy released by all the coal buried in the Earth (Xia et al., 2015; G. Zhang et al., 2021). The comprehensive utilization of geothermal energy is gaining increasing favor from countries around the world (G. Zhang et al., 2021). Utilizing shallow (less than about 200 m depth) and low-enthalpy geothermal resources (typically less than 40 °C) is economically feasible (Cunha & Bourne-Webb, 2022). The ground temperature below the uppermost 10–15 m is largely stable (about 10–25 °C in

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China, 10–15 °C in Europe, and 20–25 °C in the Tropics), and is more or less the annual average air temperature (Cunha & Bourne-Webb, 2022; Xia et al., 2015). The shallow geothermal energy in this stable temperature zone can be extracted through a ground source heat pump technology to provide space heating and cooling for nearby buildings.

Energy geostructure is a new building energy-saving technology derived from traditional ground source heat pump technology. It utilizes the fact that the underground structure is located at a certain depth in a shallow geothermal layer with constant temperature throughout the year. By embedding the ground pipes of the ground source heat pump system into the underground structure, they form an underground heat exchanger. This system extracts or releases heat from the surrounding ground layers to meet the cooling, heating, and hot water system needs of underground buildings and nearby structures. Its advantages include synergistic construction with underground engineering structures, minimal additional engineering costs, no need for extra space, elimination of outdoor units or cooling towers, and efficient heat transfer (strong heat transfer capacity of reinforced concrete), typically resulting in energy savings of 30% to 50% compared to traditional air conditioning systems (Xia et al., 2015). Energy geostructures can be applied in various scenarios (Fig. 1). The underground heat exchange systems can be installed in underground structures with suitable temperature conditions such as excavation support structures (such as diaphragm walls and sheet piles), foundation slabs, pile foundations (such as bored piles, precast piles, precast high-strength concrete (PHC) piles), and within tunnel linings (or embedded in tunnel rock as energy anchor rods). This technology holds immense potential for development and broad application prospects.

The earliest applications of energy geostructures were in Austria and Switzerland. Initially, they were applied to shallow foundation elements such as base slabs and base walls, followed by the use in bearing piles (mid-1980s), diaphragm walls (mid-1990s), and tunnels (early-2000s) (Adam & Markiewicz, 2009; Bourne-Webb et al., 2016b; Brandl, 2006). Figure 2 shows the developments of energy piles, energy walls, and energy tunnels. Currently, the most researched and applied energy geostructures are energy piles, followed by energy walls and energy tunnels (Laloui & Rotta Loria, 2020). Energy piles have been implemented in engineering projects in many countries, including Austria (Brandl, 2013), Switzerland (Pahud et al., 1999), Germany (Laloui et al., 2006), Japan (Hamada et al., 2007), the United Kingdom (Amis & Loveridge, 2014), South Korea (Moon & Choi, 2015), Australia (Ayaz et al., 2024), and China (Liu et al., 2014). Large-scale energy pile projects, such as the Landsea International Block project in Nanjing, China, and the Expo Axis project of Expo 2010 Shanghai, China, have installed approximately 1200 and 6000 energy piles, respectively (Liu et al., 2014). Typical examples of energy wall engineering applications include the diaphragm walls of the Vienna metro line extension U2 in Austria (Adam & Markiewicz, 2009), the diaphragm walls of the Shanghai Natural History Museum in China (Xia et al., 2012, 2015), and the diaphragm walls of a 6-storey residential building located in Tradate, Varese, Italy (Sterpi et al., 2018, 2020). Additionally, a novel and very shallow energy wall system, to

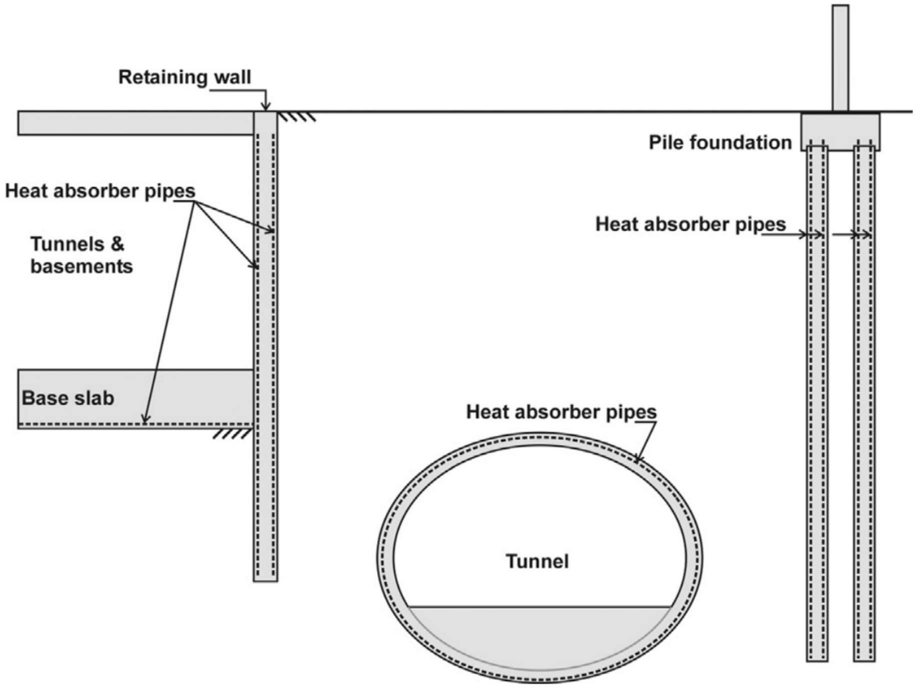


Fig. 1. Examples of energy geostructures: Energy pile, energy wall, and energy tunnel (Bourne-Webb et al., 2016b; reproduced with permission, courtesy of Elsevier).

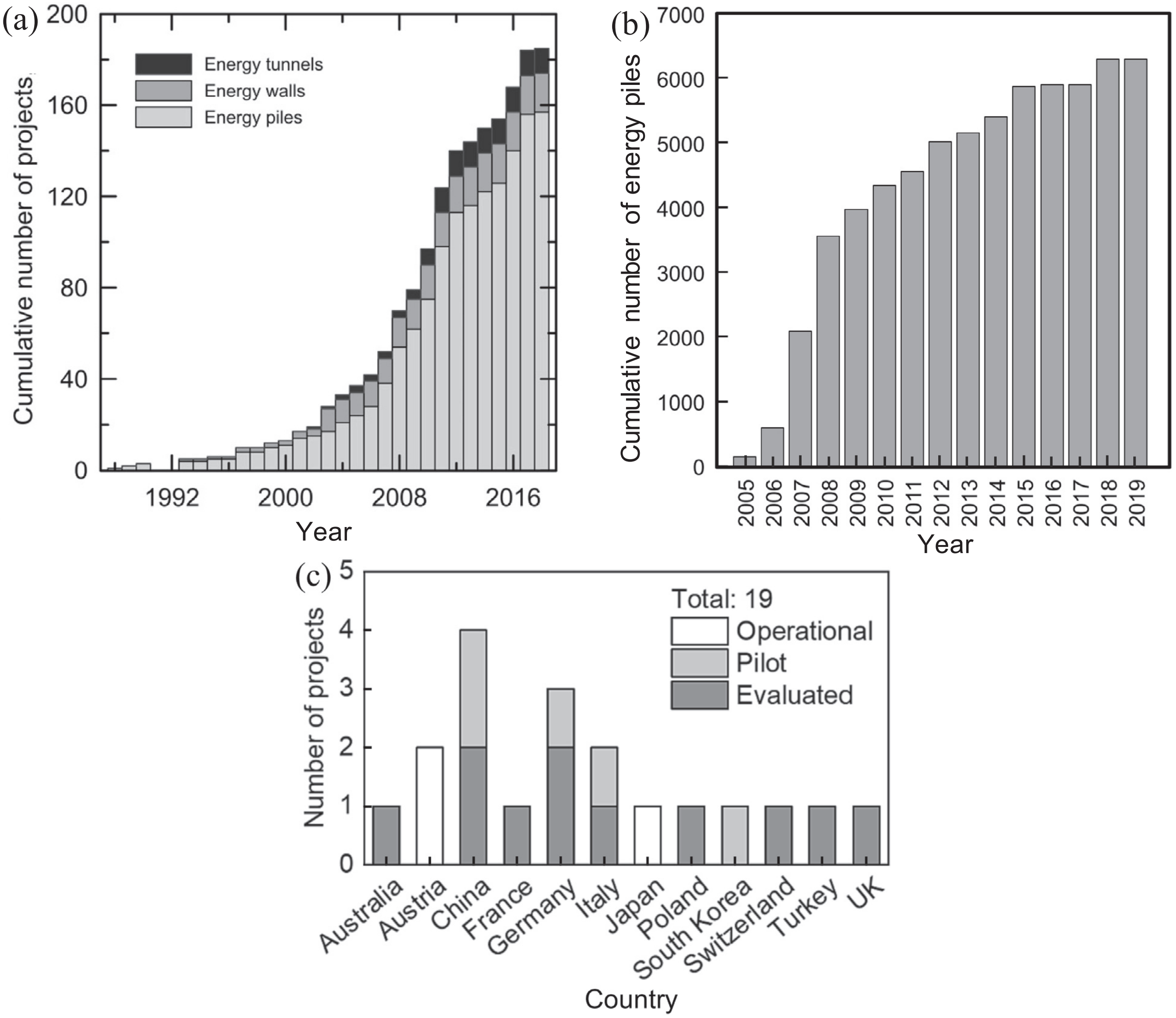


Fig. 2. Some statistics of developments of energy piles, energy walls, and energy tunnels. (a) Cumulative number of the three types of energy geostructure projects around the world (after Laloui & Rotta Loria, 2020), (b) cumulative number of energy piles installed in the UK (after Sadeghi & Singh, 2023), and (c) number of reported energy tunnels including the operational, pilot and evaluated projects (X. Dai et al., 2023) (Reproduced with permission, courtesy of Elsevier).

overcome some of the limitations affecting traditional energy geostructures and horizontal collectors, developed at the Polytechnic University of Turin, has been installed in the Energy Center building in Turin, Italy (Baralis & Barla, 2021). Currently, the construction of energy tunnels is still in the engineering trial stage, with typical examples including the Lainzer tunnel in Vienna, Austria (Adam & Markiewicz, 2009; Brandl, 2006), a high-speed railway tunnel in Germany (Franzius & Pralle, 2011), a bidirectional high-speed railway tunnel in Jenbach, Austria (Franzius & Pralle, 2011; Frodl et al., 2010), the tunnel excavated by tunnel boring machine (TBM) of Turin Metro Line 1 South Extension in Italy (Barla & Perino, 2015; Barla et al., 2016, 2019; Barla & Di Donna, 2018; Insana & Barla, 2020), the Zhadunhe tunnel on the Boya expressway in Inner Mongolia, China (Xia et al., 2015), and the Nanaori-Toge tunnel in Japan (Islam et al., 2006, 2007).

In the design of energy geostructures, a clear understanding of heat transfer and thermo-mechanical behaviour of the system is crucial. In most problems involving energy geostructures, heat transfers primarily through conduction and convection. Convection controls the heat flow of fluid circulating in pipes within energy geostructures, the heat flow in the ground with groundwater flow, and the heat flow generated in the underground building (such as underground parking lots and tunnel spaces) environment adjacent to energy geostructures due to airflow. In energy geostructures, unless there is groundwater flow, conduction dominates the heat flow across the walls of the pipes, the materials of the structure (such as reinforced concrete), and the ground (such as soil and rock). Thermal insulation between energy geostructures and the underground building environment can minimize heat transfer through convection to these environments as desired (Rotta Loria,

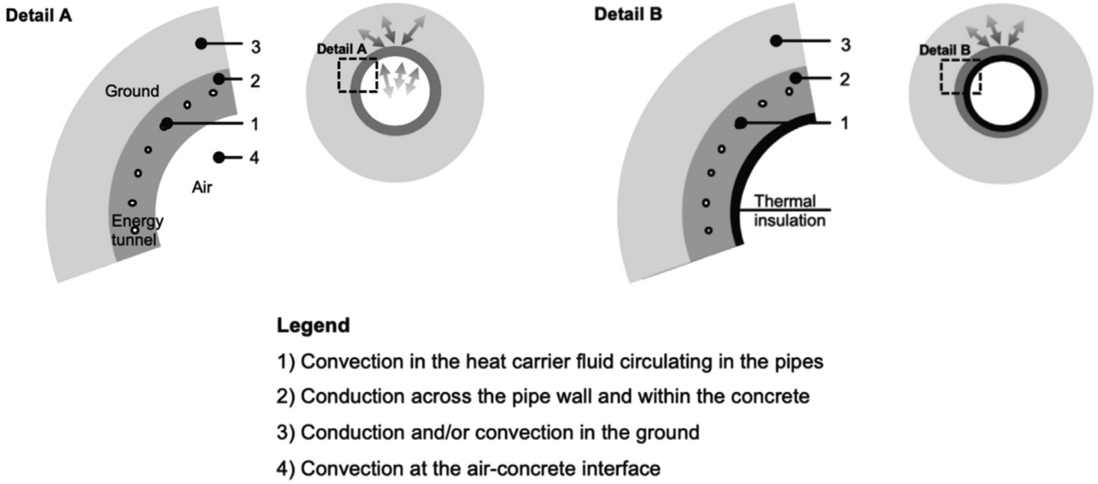


Fig. 3. Possible modes of heat transfer in energy geostructures (Rotta Loria, 2020).

2020). Possible heat transfer modes in energy geostructures are shown in Fig. 3. Under quasi-static conditions, deformation develops due to the influence of mechanical and thermal loads applied to energy geostructures. Compressive loads lead to mechanical contraction of the concrete constituting the energy geostructures and the surrounding ground. Tensile loads cause mechanical expansion. Heating thermal loads result in thermal expansion of the concrete constituting the energy geostructures. Cooling thermal loads induce thermal contraction of the concrete. Restraint of thermal expansion results in compressive stress. Restraint of thermal contraction leads to a decrease in compressive stress. This reduction in compressive stress can result in the system under low compressive stress experiencing tensile stress. It is worth noting that heating thermal loads can cause soil expansion or contraction, and the latter phenomenon is commonly referred to as heating-induced contraction. Generally, it is believed that cooling thermal loads only cause soil contraction (Rotta Loria, 2020). The deformation characteristics of energy geostructures under mechanical and thermal loads are shown in Fig. 4. Therefore, heat transfer and thermo-mechanical behaviour are two important problems that researchers focus on when studying energy geostructures.

This paper mainly reviews the research on heat transfer and thermo-mechanical behaviour of energy piles, energy walls, and energy tunnels. Comprehensive future perspectives were also presented. Table 1 presents the differences of topics between this paper and existing energy geostructure review papers in recent years. The existing reviews mainly focus on energy piles, while there are very few reviews concerning energy walls, energy tunnels, and all three types of energy geostructures. This paper focuses on analytical heat transfer models because they can save a lot of time for the initial design of energy geostructures, as well as some important heat exchange performance influence factors and thermo-mechanical behaviour, as understanding these aspects can provide references for design. The differences from the existing review papers are as follows: Four types consisting of ten basic heat

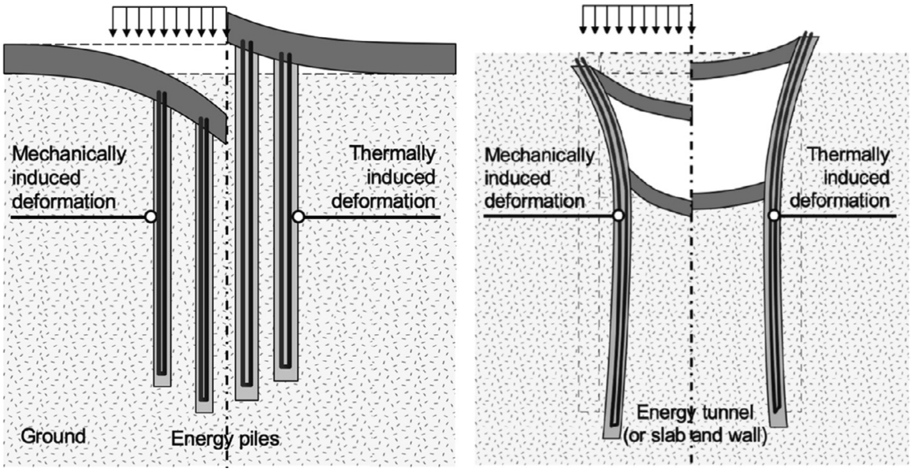


Fig. 4. Deformations of energy geostructures subjected to mechanical and thermal loads (Rotta Loria, 2020).

Table 1
Review articles of energy geostructures in recent years.

Review article	Main objects	Topic
This article	Energy pile, energy wall, and energy tunnel	Analytical heat transfer models, heat exchange performance influence factors, and thermo-mechanical behaviour
Loveridge et al. (2020)	Energy pile, energy wall, and energy tunnel	Analysis approaches, in situ testing, and model scale experiments
Sani et al. (2019)	Energy pile	Performance, design process, and applications
Bourne-Webb et al. (2019)	Energy pile	Pile-soil interactions of isolated piles
Saaly and Maghoul (2019)	Energy pile	Thermal imbalance and mitigation strategies for sustainable development in cold regions
Bourne-Webb and Bodas Freitas (2020)	Energy pile	Isolated piles and pile groups under monotonic and cyclic thermal loading
Mohamad et al. (2021)	Energy pile	Design, evaluation, and optimization
Laloui and Sutman (2021)	Energy pile	Experimental investigation from laboratory to field testing
Xie and Qin (2021)	Energy pile	Heat transfer and bearing characteristics
Cunha and Bourne-Webb (2022)	Energy pile	The knowledge on the use of energy piles to enhance the energy efficiency of sustainably climatize buildings
Sadeghi and Singh (2023)	Energy pile	Design and construction of driven precast concrete energy piles
Lupattelli et al. (2024)	Energy pile	Temperature dependence of soil-structure interface behaviour
Zhang et al. (2024)	Energy pile	Challenges and prospects of low carbon energy pile technologies based on the life-cycle perspective
Q. Dai et al. (2023)	Energy wall	Mechanical assessment in the long term
X. Dai et al. (2023)	Energy tunnel	Thermal and thermo-mechanical performance

transfer models for energy piles were summarized, and the comments on their temperature field characteristics, heat source simplification, boundary condition simplification, soil simplification, and applicability were carried out. The energy wall heat transfer model and energy tunnel heat transfer model established by the team of the authors were introduced. The influences of some controllable design parameters on the thermal performance of energy geostructures and the thermal-induced mechanical behaviour were summarized. Many original innovations from the team of the authors, especially regarding the energy walls and energy tunnels, were integrated. The future perspectives of energy geostructures, including the aspects that require strengthening in the research, new methods for evaluating thermal performance and thermo-mechanical behaviour, new methods and technologies for improving thermal performance, new application scenarios, and the future development trends, were provided. The new application scenarios include some new directions explored by the team of the authors, such as anti-freezing of tunnel drainage systems in cold regions, high-temperature tunnel cooling, and improvement of the thermal environment in subway tunnels. The purpose of this paper is to fill in or deepen the review of these aspects that other review papers have either not covered or have only briefly touched upon, comprehensively including energy piles, energy walls, and energy tunnels. The framework of this paper is shown in Fig. 5.

2 Research on heat transfer

2.1 Heat transfer of energy piles

2.1.1 Existing heat transfer models of energy piles

In the analysis of heat exchangers, different assumptions and simplifications should be adopted based on specific requirements to establish corresponding heat transfer models. Due to the relatively weak influence of different equivalent heat transfer models on the internal conditions of energy piles on the thermal response over longer periods, while the heat transfer model of the external ground and its temperature field are crucial for the design of system heat transfer efficiency, this paper mainly reviews external heat transfer models of piles.

Researchers have inherited and innovatively developed the heat transfer models of energy piles based on the mathematical models of borehole heat exchangers. The fundamental principle is to consider the buried pipes carrying thermal fluid as continuous heat sources, and to regard the ground where the piles are located as a semi-infinite heat transfer medium. By setting different boundary conditions and initial conditions, various mathematical and physical models are established. Depending on the size of the piles and the form of the buried pipes, established heat source analysis models include the line heat source model, cylinder heat source model, ring heat source model, spiral heat source model, etc.

As vertical borehole buried pipes were buried deep and had small diameters, they were often analyzed using simple line heat source models, including infinite and finite line heat source models (Fig. 6(a) and (b)). This model simplifies cylinder ground heat exchangers to a heat transfer model with a linear heat source located at the central axis. The main assumptions of line heat source models are: (1) The ground is an infinite/semi-infinite medium. (2) The thermal properties of the ground are uniformly isotropic, constant and not affected by temperature. (3) The contact surface between the borehole wall and the ground is a constant heat flux boundary. (4) Only ground heat conduction is considered, and the convective effects in porous media are neglected. Due to the simpli-

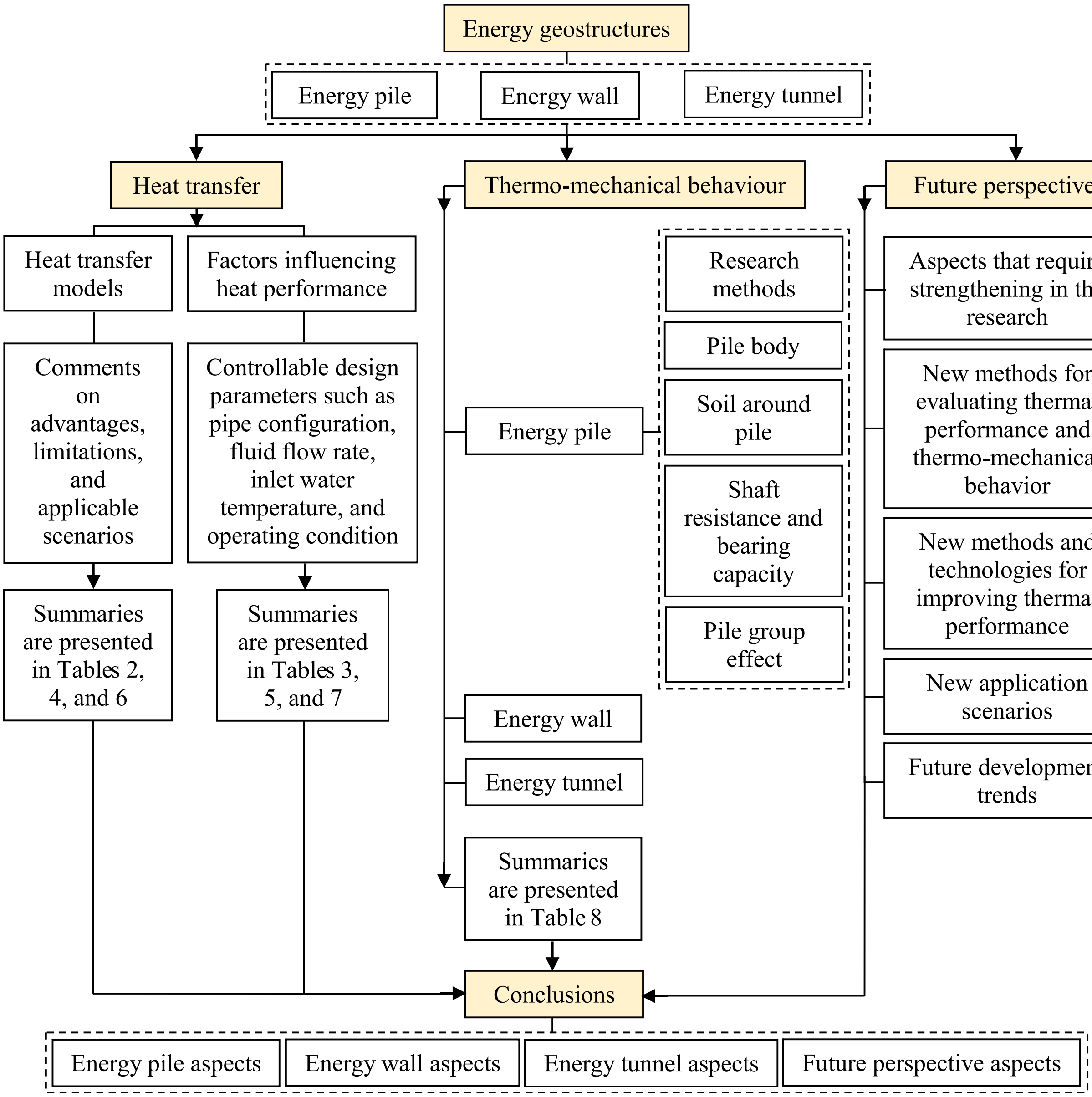


Fig. 5. Framework of this paper.

fication of the heat source dimensions in the line heat source theory, subsequent researchers considered the influence of the heat exchanger size on the temperature field of the adjacent ground and proposed cylinder heat source theories, including infinite/finite hollow cylinder heat source models (Fig. 6(c) and (d)) and infinite/finite solid cylinder heat source models (Fig. 6(e) and (f)). When simulating piles with spiral pipes, the above models can only simplify the spiral pipes to a continuous cylinder surface, without considering the discontinuity of the spiral heat source and the influence of spiral pitch on the temperature field. This led to the development of infinite/finite ring heat source models (Fig. 6(g) and (h)) and infinite/finite spiral heat source models (Fig. 6(i) and (j)). The following provides a brief overview of each heat transfer model.

2.1.1.1 Line heat source model

(1) Infinite line heat source model

Ingersoll et al. (1954) established a vertical buried pipe heat exchanger model based on Kelvin line heat source theory, which is a widely used heat transfer model. The analytical solution of this model is

$$\theta = T(r,t) - T_0 = -\frac{q}{4\pi k} Ei\left(-\frac{r^2}{4\alpha t}\right), \tag{1}$$

where θ is the temperature excess defined as $\theta = T–T_0$, T is the calculated ground temperature, T_0 is the initial ground temperature, α represents the soil thermal diffusivity, r is the radial coordinate, t is the heat transfer time, q denotes the heating rate per unit length of the heat source, k stands

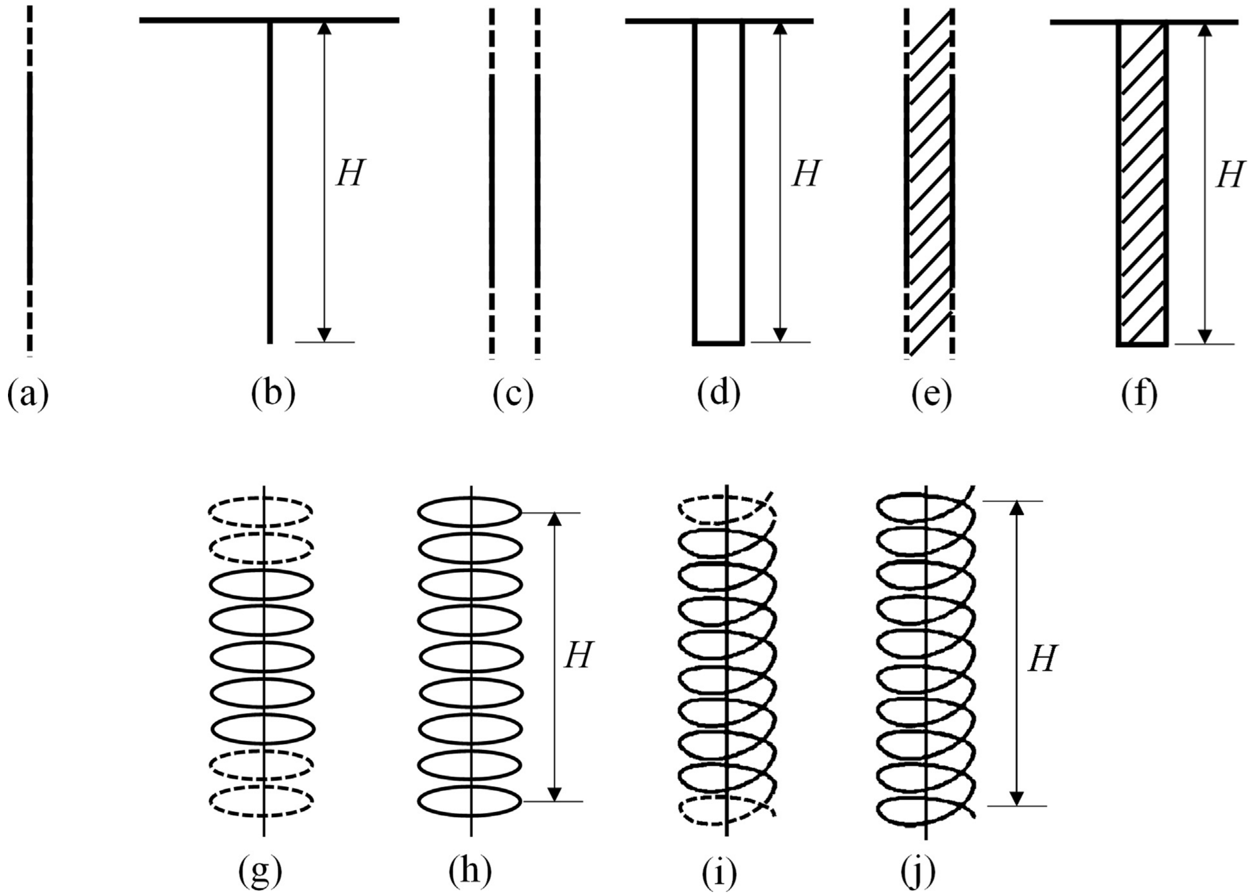


Fig. 6. Heat transfer models of energy piles. (a) Infinite line heat source, (b) finite line heat source, (c) infinite hollow cylinder heat source, (d) finite hollow cylinder heat source, (e) infinite solid cylinder heat source, (f) finite solid cylinder heat source, (g) infinite ring heat source, (h) finite ring heat source, (i) infinite spiral heat source, and (j) finite spiral heat source.

for the soil thermal conductivity, and Ei represents the exponential integral, i.e., $Ei(-u) = \int_u^\infty \frac{e^{-y}}{y}\,dy$.

(2) Finite line heat source model

Zeng et al. (2002) regarded the ground as a homogeneous semi-infinite medium, and the ground surface was assumed to be a constant temperature boundary. Set a virtual heat source with a strength of –q and a length of H on symmetry to the ground boundary. By applying the Green's function method and linear superposition principle, the analytical solution for a finite line heat source is obtained as

$$\theta = \frac{q}{4\pi k}\int_0^H \left\{ \frac{\operatorname{erfc}\left[\frac{\sqrt{r^2+(z-z')^2}}{2\sqrt{\alpha t}}\right]}{\sqrt{r^2+(z-z')^2}} - \frac{\operatorname{erfc}\left[\frac{\sqrt{r^2+(z+z')^2}}{2\sqrt{\alpha t}}\right]}{\sqrt{r^2+(z+z')^2}} \right\} \mathrm{d}z', \quad (2)$$

where erfc(x) is the complementary error function, H is the length of the heat source, z is the depth coordinate, and z' is integrating parameter (the coordinate of a point heat source in the heat source).

2.1.1.2 Cylinder heat source model

(1) Infinite hollow cylinder heat source model

The cylinder heat source theory was first proposed by Carslaw and Jaeger (1946), and further developed by Ingersoll et al. (1954). The infinite hollow cylinder heat source model considers the actual shape of the heat source by simplifying it to a hollow cylinder surface. The heat flux generated by the fluid inside the pipe is distributed onto this surface as the heat flux boundary, while ignoring the material inside the borehole (Liu et al., 2010). The formula for calculating the temperature increment is

$$\theta = q\frac{G(R, F_o)}{k}, \quad (3)$$

where $G(R,\ F_o)$ is the theoretical solution function G, defined as

$$G(R, F_o) = \frac{1}{\pi^2}\int_0^\infty \left(e^{-\beta^2 \cdot F_o} - 1\right) \frac{J_0(R\beta)Y_1(\beta) - J_1(\beta)Y_0(R\beta)}{\beta^2\left[J_1^2(\beta) + Y_1^2(\beta)\right]}\mathrm{d}\beta, \quad (4)$$

where J_0, J_1, Y_0, and Y_1 represent the Bessel functions of the first kind and second kind of zeroth and first order, respectively. $F_o = \alpha t / r_0^2$ is the Fourier number, $R = r/r_0$ is the ratio of the distance from the calculation point to the heat source center to the cylinder radius, and β is the integrating parameter.

The calculation in Eq. (4) is complex and not convenient for practical use. Ingersoll et al. (1954) compiled a fitting table of the G function with common radii as a function of F_o for easy reference during design.

(2) Finite hollow cylinder heat source model

Shi et al. (2025) proposed a model describing a finite length hollow cylinder surface heat source, solved it by using Green's function method, and obtained the analytical solution of the finite hollow cylinder heat source model in a semi-infinite ground region:

$$\begin{aligned}\theta = & -\frac{\alpha q}{2\pi^2 k r_0}\int_{t'=0}^{t}\int_{\beta=0}^{\infty}\\ & \times\frac{\mathrm{e}^{-\alpha\beta^2(t-t')}}{J_1^2(\beta r_0)+Y_1^2(\beta r_0)}[J_0(\beta r)Y_1(\beta r_0)-J_1(\beta r_0)Y_0(\beta r)]\mathrm{d}\beta\\ & \cdot\left\{2\mathrm{erfc}\left[\frac{z}{2\sqrt{\alpha(t-t')}}\right]-\mathrm{erfc}\left[\frac{z-H}{2\sqrt{\alpha(t-t')}}\right]-\mathrm{erfc}\left[\frac{z+H}{2\sqrt{\alpha(t-t')}}\right]\right\}\mathrm{d}t',\end{aligned} \tag{5}$$

where t' is the heating time of the point heat source.

(3) Infinite solid cylinder heat source model

Liu et al. (2010) proposed an infinite solid cylinder heat source model considering the heat capacity inside the borehole. By employing the Green's function method, the temperature at location r is obtained through the integration of point heat sources in cylinder coordinates:

$$\begin{aligned}\theta = & \int_0^t \mathrm{d}t'\int_{-\infty}^{\infty}\mathrm{d}z'\int_0^{2\pi}\frac{q}{16\pi\rho c\left[\sqrt{\pi\alpha(t-t')}\right]^3}\\ & \cdot\exp\left[-\frac{r^2+{r_0}^2-2rr_0\cos(\varphi-\varphi')+(z-z')^2}{4\alpha(t-t')}\right]\mathrm{d}\varphi',\end{aligned} \tag{6}$$

where ρ is the soil density, c is the specific heat capacity, and φ' is the angular coordinate of the point heat source.

Solution 1: First integrate the point heat sources along the z direction to form line heat sources parallel to the z direction, then integrate over t, to obtain the expression for the temperature field:

$$\theta = -\frac{q}{4\pi k}\int_0^{\pi}\frac{1}{\pi}Ei\left(-\frac{r^2+r_0^2-2rr_0\cos\varphi'}{4\alpha t}\right)\mathrm{d}\varphi'. \tag{7}$$

Solution 2: Differentiate the cylinder heat source along the z direction into an infinite number of circular ring heat sources. Therefore, the circumferential integration over the φ' in Eq. (6) is performed first, and ultimately the expression (Man et al., 2010) is

$$\begin{aligned}\theta = & \frac{q}{\rho c}\int_0^t \mathrm{d}t'\int_{-\infty}^{\infty}\frac{1}{8\left[\sqrt{\pi\alpha(t-t')}\right]^3}\\ & \cdot\exp\left[-\frac{r^2+r_0^2+z'^2}{4\alpha(t-t')}\right]\cdot I_0\left[\frac{rr_0}{2\alpha(t-t')}\right]\mathrm{d}z',\end{aligned} \tag{8}$$

where $I_0(x)=\frac{1}{\pi}\int_0^{\pi}\exp(x\cos\varphi)\mathrm{d}\varphi$ is the zero-order modified Bessel function.

(4) Finite solid cylinder heat source model

Man et al. (2010) proposed a finite cylinder heat source model for piles considering longitudinal heat transfer. The difference between this model and the infinite cylinder heat source model lies in the consideration of the ground boundary and heat source length. The temperature response of this model is obtained using Green's function and the virtual heat source approach:

$$\begin{aligned}\theta = & \frac{q}{\rho c}\int_0^t\int_0^H\frac{1}{8\left[\sqrt{\pi\alpha(t-t')}\right]^3}I_0\left[\frac{rr_0}{2\alpha(t-t')}\right]\\ & \cdot\left\{\exp\left[-\frac{r^2+r_0^2+(z-z')^2}{4\alpha(t-t')}\right]-\exp\left[-\frac{r^2+r_0^2+(z+z')^2}{4\alpha(t-t')}\right]\right\}\mathrm{d}z'\mathrm{d}t'.\end{aligned} \tag{9}$$

2.1.1.3 Ring heat source model

(1) Infinite solid ring heat source model

Cui et al. (2011) proposed dividing the spiral heat source into equivalent equally spaced ring heat sources in the z direction. The vertical coordinates of each ring are $z'=\pm(n+0.5)b$, where $n = 0,1,2,\cdots,+\infty$, and b is pitch. The solution is obtained using the Green's function method:

$$\begin{aligned}\theta = & \tfrac{qb}{2\pi\rho c}\left[\textstyle\sum_{n=-\infty}^{0}\int_0^t\mathrm{d}t'\int_0^{2\pi}G(z'=nb-0.5b)\mathrm{d}\varphi'\right.\\ & \left.+\textstyle\sum_{n=0}^{\infty}\int_0^t\mathrm{d}t'\int_0^{2\pi}G(z'=nb+0.5b)\mathrm{d}\varphi'\right]\\ = & \frac{qb}{8\rho c}\sum_{n=0}^{\infty}\int_0^t\frac{1}{\left[\sqrt{\pi\alpha(t-t')}\right]^3}I_0\left[\frac{rr_0}{2\alpha(t-t')}\right]\\ & \cdot\left\{\exp\left[-\frac{r^2+r_0^2+(z-nb-0.5b)^2}{4\alpha(t-t')}\right]\right.\\ & \left.+\exp\left[-\frac{r^2+r_0^2+(z+nb+0.5b)^2}{4\alpha(t-t')}\right]\right\}\mathrm{d}t'.\end{aligned} \tag{10}$$

(2) Finite solid ring heat source model

Cui et al. (2011) also investigated a finite solid ring model considering the finite length of piles and the ground boundary, assuming a constant ground surface temperature, with circular rings buried at depths ranging from H_1 to H_2. Similarly, employing the virtual heat source approach, the temperature response is obtained as

$$
\begin{aligned}
\theta &= \frac{qb}{2\pi\rho c}\int_0^t \mathrm{d}t'\left[\sum_{n=0}^{m}\int_0^{2\pi} G(z'=H_1+nb+0.5b)\mathrm{d}\varphi'\right.\\
&\left.\quad -\sum_{n=0}^{m}\int_0^{2\pi} G(z'=-H_1-nb-0.5b)\mathrm{d}\varphi'\right]\\
&= \frac{qb}{8\rho c}\int_0^t \frac{1}{\left[\sqrt{\pi\alpha(t-t')}\right]^3} I_0\left[\frac{rr_o}{2\alpha(t-t')}\right]\\
&\quad \cdot \exp\left[-\frac{r^2+r_0^2}{4\alpha(t-t')}\right]\\
&\quad \cdot \sum_{n=1}^{m}\left\{\exp\left[-\frac{(z-H_1-nb-0.5b)^2}{4\alpha(t-t')}\right]\right.\\
&\quad \left. -\exp\left[-\frac{(z+H_1+nb+0.5b)^2}{4\alpha(t-t')}\right]\right\}\mathrm{d}t', \qquad (11)
\end{aligned}
$$

where m is the number of circular rings.

2.1.1.4 Spiral heat source model

(1) Infinite spiral heat source model

Li (2011) proposed a more realistic spiral heat source model, describing the spiral pipe as a continuous spiral heat source, avoiding the simplification of the heat source shape.

The parametric equation for the spiral is given by

$$
\begin{cases}
x = r_0\cos\varphi\\
y = r_0\sin\varphi\ .\\
z = H\varphi
\end{cases} \qquad (12)
$$

The pitch of the spiral is

$$
b = 2\pi H. \qquad (13)
$$

By integrating the set of point heat sources, the temperature field function is obtained as

$$
\begin{aligned}
\theta &= \frac{qb}{16\pi\rho c}\int_0^t \mathrm{d}t'\int_{-\infty}^{\infty}\frac{1}{\left[\sqrt{\pi\alpha(t-t')}\right]^3}\\
&\quad \cdot \exp\left[-\frac{r^2+r_0^2-2rr_0\cos(\varphi-\varphi')+(z-b\varphi'/2\pi)^2}{4\alpha(t-t')}\right]\mathrm{d}\varphi'. \qquad (14)
\end{aligned}
$$

According to the theory of the complementary error function, the final temperature field function is obtained as

$$
\begin{aligned}
\theta &= \frac{qb}{8\pi^2 k}\int_{-\infty}^{\infty}\frac{1}{P}\left[1-\frac{2}{\sqrt{\pi}}\int_0^{P/2\sqrt{\alpha t}}\exp\left(-\eta^2\right)\mathrm{d}\eta\right]\\
&= \frac{qb}{8\pi^2 k}\int_{-\infty}^{\infty}\frac{1}{P}\mathrm{erfc}\left(\frac{P}{2\sqrt{\alpha t}}\right)\mathrm{d}\varphi', \qquad (15)
\end{aligned}
$$

where $P=\sqrt{r^2+r_0^2-2rr_0\cos(\varphi-\varphi')+(z-b\varphi'/2\pi)^2}$.

(2) Finite spiral heat source model

Due to the inability of an infinite heat source to reflect heat transfer in the depth direction, the finite size of piles, and long-term effects, the virtual heat source method was used to establish the finite spiral heat source model. Assuming a spiral pipe buried at depths ranging from H_1 to H_2 with a pitch of b, the temperature response is obtained as (Li, 2011)

$$
\theta = \frac{qb}{8\pi^2 k}\int_{2\pi H_1/b}^{2\pi H_2/b}\left[\frac{1}{P}\mathrm{erfc}\left(\frac{P}{2\sqrt{\alpha t}}\right)-\frac{1}{S}\mathrm{erfc}\left(\frac{S}{2\sqrt{\alpha t}}\right)\right]\mathrm{d}\varphi', \qquad (16)
$$

where $S=\sqrt{r^2+r_0^2-2rr_0\cos(\varphi-\varphi')+(z+b\varphi'/2\pi)^2}$.

2.1.2 Comments on heat transfer models of energy piles

2.1.2.1 Temperature field characteristics

In the above heat transfer models, the infinite heat source models assume that the vertical heat transfer in the ground is very slow, allowing the vertical heat transfer to be neglected, simplifying the problem to a one-dimensional heat transfer in the radial direction, where only the radial temperature field is calculated. The finite heat source models consider both radial and vertical heat transfer, constituting two-dimensional heat transfer models capable of calculating the temperature field in both the radial and vertical directions.

The temperature field of the infinite line heat source model exhibits rapid growth in the initial stage, followed by a slowdown in the increase rate. As time progresses, the temperature eventually fails to stabilize and tends towards infinity. The initial temperature field of the finite line heat source model closely resembles that of the infinite line heat source model, with a subsequent slowdown leading to stabilization. The stabilization time and temperature are related to the length-to-diameter ratio (Diao et al., 2004; Ingersoll et al., 1954).

As shown in Fig. 7, the initial temperature field of the hollow cylinder heat source model exhibits a faster growth rate compared to the line heat source model, resulting in a

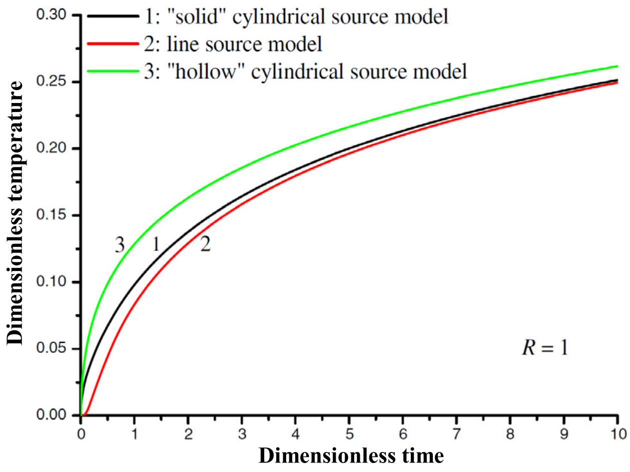
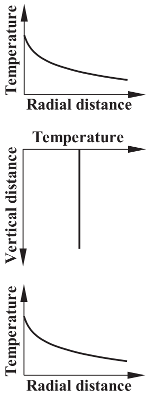
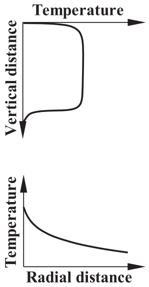
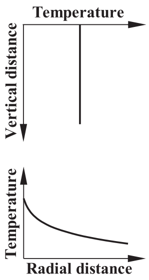
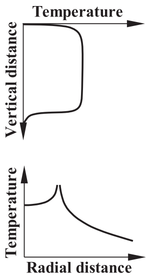
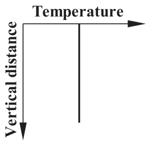


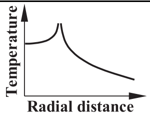
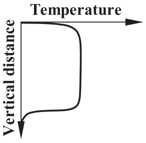
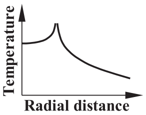
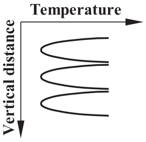
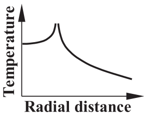
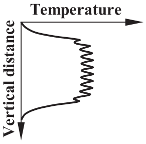
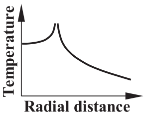
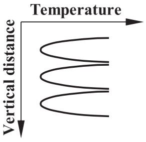
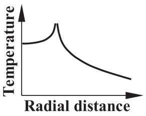
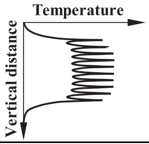
Fig. 7. Comparison of the temperature of different models at the dimensionless radius $R = 1$ (Man et al., 2010) (Reproduced with permission, courtesy of Elsevier).

Table 2
Summary of temperature distribution characteristics, advantages, limitations, and application scenarios of heat transfer models of energy piles.

Model	Temperature distribution characteristics	Advantages	Limitations	Application scenarios
Infinite line heat source		The calculation formula is simple, and the design is convenient.	Considering only radial heat transfer, the short-term thermal response significantly differs from reality, and the temperature does not eventually stabilize.	It was mainly used for short-term temperature field calculation of a borehole ground source heat pump.
Finite line heat source		Considering both radial and vertical heat transfers, the temperature tends to be stable.	Although the design is more realistic compared with the infinite line heat source, it requires a larger computational effort.	It was mainly used for long-term temperature field calculation of a borehole ground source heat pump, and the applicability to piles with small length-to-diameter ratios remains debatable.
Infinite hollow cylinder heat source		Considering the influence of the actual shape of the heat source.	Only radial heat transfer is considered, and the error caused by the heat capacity inside the energy pile is ignored.	It is more suitable for the temperature field calculation of a borehole ground source heat pump.
Finite hollow cylinder heat source		Considering both radial and vertical heat transfers.	The error caused by the heat capacity inside the energy pile is ignored.	It is more suitable for the temperature field calculation of a borehole ground source heat pump.
Infinite solid cylinder heat source		The influence of heat capacity inside the energy pile is considered.	Only radial heat transfer is considered.	It is suitable for simulating the short-term effects of energy piles and the scenarios with frequent heat load variations.

(continued on next page)

Table 2 (*continued*)

Model	Temperature distribution characteristics	Advantages	Limitations	Application scenarios
Finite solid cylinder heat source	 	Considering both radial and vertical heat transfers and the influence of heat capacity inside the energy pile.	The calculation is relatively complex.	It is more suitable for energy piles with small length-to-diameter ratios.
Infinite solid ring heat source	 	It reflects the fluctuation characteristics of the ground temperature field of the buried spiral pipe, and can obtain the exact temperature at the pile wall, which can be used to optimize the parameters of spiral pipe pitch and pile diameter.	Only radial heat transfer is considered.	It is suitable for energy piles with a spiral pipe.
Finite solid ring heat source	 	Considering both radial and vertical heat transfers, the exact temperature at the pile wall can be obtained.	The calculation is relatively complex.	It is suitable for energy piles with a spiral pipe.
Infinite spiral heat source	 	It is more realistic compared with the ring heat source model.	Only radial heat transfer is considered.	It is suitable for energy piles with a spiral pipe.
Finite spiral heat source	 	It is the most realistic for spiral pipe.	The calculation is relatively complex.	It is suitable for energy piles with a spiral pipe.

significant difference. Subsequently, the increase rate slows down, approaching the temperature of the line heat source model. The initial temperature field of the solid cylinder heat source model shows a slightly faster growth rate compared to the line heat source model, with a smaller difference. The increase rate then slows down, approaching the temperature of the line heat source model (Man et al., 2010; Zhang et al., 2009).

The temperature variation with depth described by the infinite ring heat source model exhibits a wave-like pattern (see Table 2), with temperatures at each ring source tending towards infinity, reflecting the fluctuating characteristics of the ground temperature field of the buried spiral pipe. Its analytical solution can be used to optimize parameters such as the spiral pipe pitch and pile diameter (Li, 2011). As shown in Table 2, the temperature fluctuation at the top and bottom ends of the ground temperature field in the finite ring heat source model decreases, indicating the influence of boundary conditions and vertical heat transfer on the short-term temperature field. As time progresses, the boundary effects penetrate deeper into the ground layers, making the characteristics of the temperature field in the finite ring heat source model more pronounced. The temperature at the hole wall in the ring heat source model fluctuates significantly along the depth direction, with smaller fluctuations further away from the heat source, approaching the temperature of the cylinder heat source model (Cui et al., 2011; Li, 2011).

The temperature field of the infinite spiral heat source model also exhibits periodic fluctuations along the depth direction (Table 2). As it is an infinite model, the temperatures tend towards infinity with time, and the temperatures at various points on the cylinder heat source do not stabilize ultimately. The shape of the temperature field in the finite spiral heat source model is similar to that of the infinite spiral heat source model, with temperatures showing periodic fluctuations along the depth (Table 2). The temperatures of the ground at the upper and lower parts of the heat source are not affected in the short term. After a certain period, the effects of vertical heat transfer become evident, leading to temperature changes at both ends. The temperature field of the spiral heat source model is essentially the same as that of the ring heat source model (Li, 2011).

2.1.2.2 Simplification of heat source

Due to the fact that actual ground heat exchanger borehole or energy pile internal materials possess a certain amount of thermal capacitance, the line heat source model neglects the response of the borehole to short-term or close-range external ground temperature variations, leading to errors. Furthermore, the line heat source model overlooks the radial dimensions of the borehole and buried pipe, whereas energy piles have diameters much larger than those of boreholes. Therefore, for ground heat exchangers in piles, the line heat source model oversimplifies the system. The hollow cylinder model also neglects errors caused by the thermal capacitance within the energy pile, whereas the solid cylinder heat source model takes into account this thermal capacitance. In addition, for piles with spiral pipe, both the ring model and the spiral model can provide accurate temperatures at the pile wall, making their temperature responses more realistic.

2.1.2.3 Simplification of boundary conditions

The infinite heat source models consider the ground as an infinite medium, neglecting the temperature boundary at the ground surface. The temperature field remains unstable as time approaches infinity, leading to significant errors in simulating long-term heat transfer. The effects of the seasonal thermal imbalances in ground source heat pumps will impact the long-term ground temperature field and must be considered in the calculation of long-term heat transfer performance. Finite heat source models can better reflect the long-term effects of boundaries on ground temperature, provide a better description of short-term unsteady-state heat transfer in ground heat exchangers, and ultimately stabilize.

2.1.2.4 Simplification of soil around pile

Existing models mostly assume the thermal properties of the ground to be homogeneous. However, in natural sedimentary conditions, soils exhibit stratification and the presence of groundwater, leading to anisotropy and non-uniformity in the thermal conductivity of the ground (Li & Lai, 2012). For piles or short borehole heat exchangers, the vertical heat transfer effects, especially their long-term impacts, cannot be ignored. These effects are closely related to the thermal properties of the soil layers, which are rarely considered in existing models (Hu, 2017; D. Zhang et al., 2022; Zhou et al., 2025). Therefore, it is essential to fully consider the variations in thermal properties of different soil layers and the distribution of groundwater when burying heat exchangers, in order to construct a more refined model for enhancing the accuracy and applicability of existing models.

2.1.2.5 Applicability of heat transfer models

The infinite heat source models are characterized by their simple formulas, convenient designs, and wide applications, but they exhibit significant discrepancies in short-term thermal response compared to reality. Additionally, the temperature does not ultimately stabilize, and it requires $\alpha t/r^2 > 20$ for better engineering applicability; otherwise, notable errors may arise (Ingersoll et al., 1954). The finite heat source models stabilize temperatures, representing the influence of boundary effects on the temperature field as it propagates with depth. The time at which the maximum temperature range occurs is related to the relative radial radius. The finite heat source models are more practical, but involve a large amount of calculation. Therefore, pre-calculation is required, followed by table look-up for design purposes. The models can be incorporated into design software for ease of use, but lack flexibility. In conclusion, the selection of the appropriate model should be based on the borehole length-to-diameter ratio and the simulation duration. The line heat source models have traditionally been used for slender borehole heat exchangers, and their applicability to piles with small length-to-diameter ratios remains debatable.

The hollow cylinder heat source models exhibit significant short-term calculation errors and involve a complex process. The temperature field generated by a solid cylinder heat source is greater than that of a line heat source but less than that of a hollow cylinder heat source. This indicates its ability to characterize the influence of thermal capacitance within the borehole on the short-term temperature field, making it suitable for simulating the short-term effects of pile heat exchangers. The temperature rise in the solid cylinder model is relatively low, suggesting that pile heat exchangers can handle short-term heat loads and are suitable for scenarios with frequent heat load variations (Zhang et al., 2009). The temperature field of the finite solid cylinder heat source model considers vertical heat transfer varying with different positions, resulting in different stable temperatures (Man et al., 2010), making it more suitable for pile heat exchangers with small length-to-diameter ratios.

The heat generation powers of the cylinder heat source, ring heat source, and spiral heat source models are the same, with only minor differences in the specific heating locations. Therefore, the temperature difference is significant only in the vicinity of the heat source. When calculating the precise temperature of borehole or pile walls, the ring model and spiral model are more accurate.

2.1.2.6 Summary of the comments

The summary of temperature distribution characteristics, advantages, limitations, and application scenarios of each energy pile heat transfer model is listed in Table 2, based on the comments on heat transfer models. The infinite heat source models can only calculate the radial temperature, and the temperature tends to infinity as time goes on. It can only be used to investigate the short-term temperature, and the influence of long-term changes in ground surface temperature cannot be considered. In contrast, the finite heat source models can calculate both radial and vertical temperatures, and the temperatures tend to be stable over time, which can be used to investigate the long-term temperature. Infinite heat source models are only suitable for energy piles with a large length-to-diameter ratio; however, most piles do not possess a significant length-to-diameter ratio, rendering the finite heat source models more suitable. The finite line heat source model and the hollow cylinder heat source model ignore the influence of pile size and heat capacity, respectively, which will cause some errors to the short-term temperature and the temperature near the pile. The solid cylinder heat source model is more appropriate for energy piles, while for energy piles with spiral pipe configurations, more accurate ring heat source and spiral heat source models should be employed to inform the optimization of parameters such as spiral pitch. Furthermore, considering varying thermal characteristics of different soil layers and changes in groundwater distribution is crucial for enhancing the accuracy and applicability of existing models.

2.1.3 Factors influencing heat exchange performance of energy piles

2.1.3.1 Heat exchange performance

The heat exchange performance of the energy pile is a key aspect in the design of energy pile systems. The heat exchange rate between the energy pile and the surrounding soil can be determined through thermal performance tests. In the test, a constant temperature circulating water is injected into the inlet pipe, and the water temperature in the outlet pipe and flow rate are monitored (You et al., 2014). The heat exchange rate (Q) and the average heat exchange rate per meter length (q) of the energy pile are calculated as follows:

$$Q = Mc_{\mathrm{w}}(T_{\mathrm{out}} - T_{\mathrm{in}}), \tag{17}$$

$$q = Q/H_{\mathrm{p}}, \tag{18}$$

where c_{w} represents the specific heat capacity of the fluid inside the pipe, M is the mass flow rate, T_{in} and T_{out} denote the inlet and outlet fluid temperatures, and H_{p} stands for the length of the pipe.

The heat exchange rate represents the magnitude of heat exchange between the energy pile and the surrounding soil per unit time, with a higher value indicating more efficient heat exchange between the pile and the surrounding soil. The unit length heat exchange rate describes the amount of heat exchange per unit length of the pipe and serves as a measure of heat exchange efficiency. Generally, higher values for both parameters indicate better heat exchange performance. In addition to field and indoor thermal performance tests, researchers have also conducted studies on the heat exchange performance of energy piles using theoretical calculations and numerical simulations. The main factors influencing heat exchange performance include pile type, pile size, buried pipe configuration, flow rate of the circulating water, inlet water temperature, operating condition, etc. These factors can be intentionally designed and controlled. Thus, the following provides a comprehensive overview of the impact of these factors on heat exchange performance (a brief summary is presented in Table 3).

2.1.3.2 Influence of pile type

Currently, the main types of energy piles include cast-in-place reinforced concrete piles, prefabricated piles, steel pipe piles, and soil–cement mixed piles. The type of energy pile is primarily determined by the form of the pile body (Liu et al., 2014). Reinforced concrete piles have a large heat storage capacity and good heat transfer performance, making them the most widely used worldwide (Gao et al.,

Table 3
Influences of some factors on heat exchange performance of energy piles.

Factor	Influence on heat exchange performance
Pile type	The main types include cast-in-place reinforced concrete piles, prefabricated piles, steel pipe piles, and soil–cement mixed piles. Reinforced concrete piles have a large heat storage capacity and good heat transfer performance. Steel piles exhibit excellent heat conduction properties, offering significant advantages in geothermal energy utilization. New technologies are being explored, such as the use of phase change materials to enhance thermal performance and the adoption of low-carbon concrete to reduce CO_2 emissions.
Pipe configuration	The pipe configurations mainly include single U-shaped, parallel double U-shaped, series double U-shaped (W-shaped), parallel triple U-shaped, series triple U-shaped, and spiral configurations. Overall, the heat exchange performance increases in the following order of pipe configurations: single-U, double-U, W, triple-U, and spiral.
Pile size	The pile length should exceed the ground temperature variation zone to achieve effective system performance. Longer piles can improve the total heat exchange. Larger-diameter piles can improve the thermal performance and allow more energy to be integrated into the foundation. However, once the length-to-diameter ratio exceeds a certain value, the heat exchange performance tends to become saturated.
Fluid flow rate	The heat exchange increases with the increase in fluid flow rate. However, the increase rate diminishes gradually once the flow rate reaches a certain speed. The fluid flow rate should not be too high or too low, and it is generally considered sufficient to ensure that the flow state is turbulent.
Inlet water temperature	The inlet temperature directly affects the temperature difference of the liquid entering and exiting during heat exchange. A larger temperature difference leads to a higher heat exchange rate.
Operating condition	The intermittent operation mode can improve the heat exchange compared with the continuous operation mode, as the former allows for a certain degree of recovery of geothermy in the surrounding ground of underground heat exchange pipes.

2008a, 2008b). Prefabricated piles may have some problems caused by transportation and cause damage to the heat transfer system during installation, leading to relatively fewer applications (Sadeghi & Singh, 2023). The phase change material backfill can improve the thermal performance of prefabricated concrete energy piles (Bao et al., 2022; H. Wang et al., 2025). Steel piles exhibit excellent heat conduction properties, offering significant advantages in geothermal energy utilization (Beragama Jathunge et al., 2024; Morino & Oka, 1994). Steel pipe piles can transfer heat directly through liquid circulation or by using heat-conducting pipelines. However, the high cost of steel pipe piles limits their application in construction projects. Soil-cement mixed piles and slurry solidified gravel piles with embedded heat transfer pipes utilize cement slurry to protect the heat exchange pipes to some extent, but their heat conduction performance is not as efficient as reinforced concrete piles. To enhance the heat conduction performance of these low-strength soil–cement piles, researchers have considered incorporating components such as sand and quartz into the pile body to overcome the poor heat conduction of this pile type. For situations where high bearing capacity is not required, using soil–cement piles for geothermal energy utilization offers significant advantages (Brandl, 2006; Esen & Inalli, 2009; Morino & Oka, 1994; Tamawski et al., 2009). In addition, the use of low-carbon concrete piles, such as alkali-activated concrete energy piles, can improve heat exchange performance while reducing CO_2 emission (Shen et al., 2022).

2.1.3.3 Influence of buried pipe configuration

For the configurations of buried pipes, the existing pile heat exchangers mainly include single U-shaped, parallel double U-shaped, series double U-shaped (W-shaped), parallel triple U-shaped, series triple U-shaped, and spiral configurations (Sani et al., 2019), as shown in Fig. 8. Figure 9 (a) shows the influence of pipe configuration on heat transfer rate per unit pile length. Overall, the heat transfer rate increases in the following order: single U-shaped configuration, double U-shaped configuration, W-shaped configuration, triple U-shaped configuration, and spiral configuration. A single U-shaped configuration has the simplest structure but a limited heat exchange area, result-

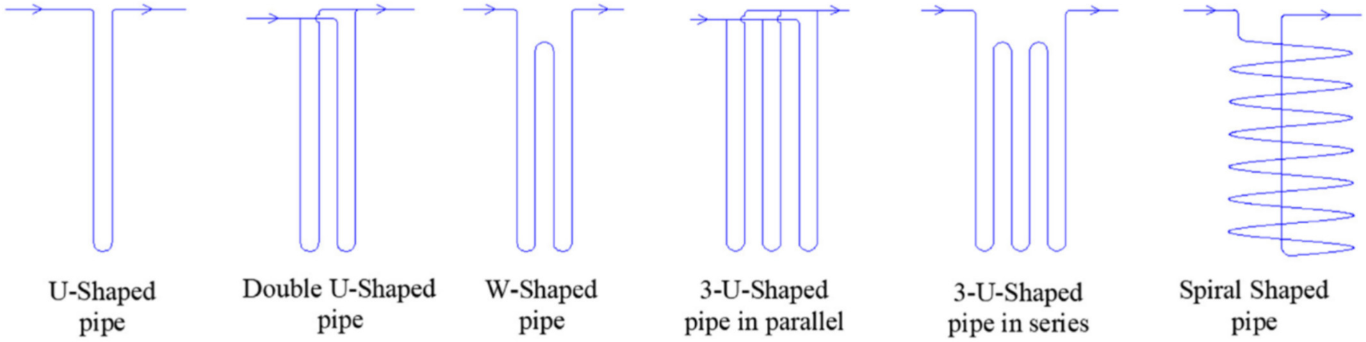


Fig. 8. Main configurations of buried pipes in energy piles (Sani et al., 2019) (Reproduced with permission, courtesy of Elsevier).

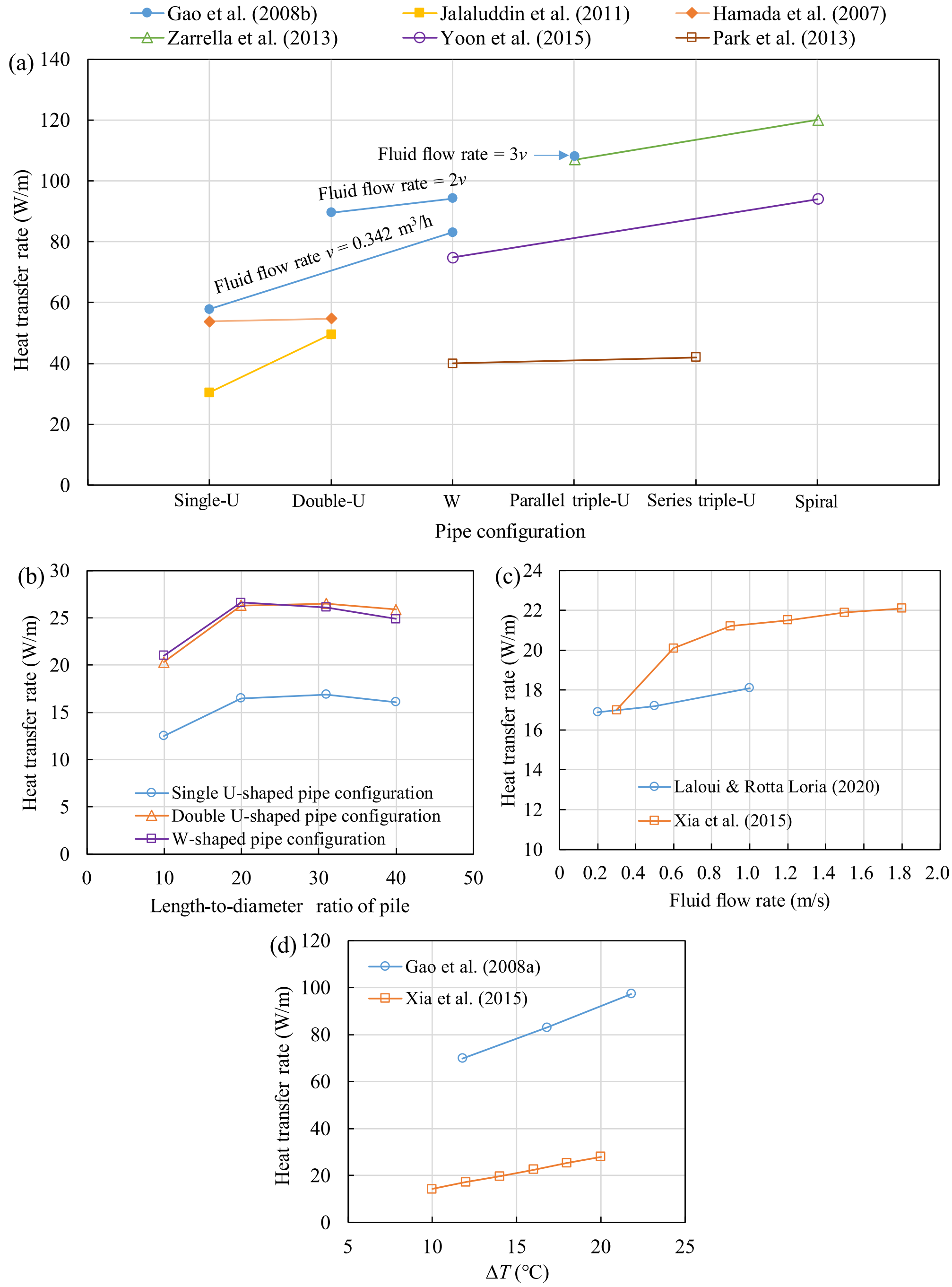


Fig. 9. Influences of some factors on heat transfer rate of energy piles. (a) Pipe configuration, (b) pile length-to-diameter ratio (data from Laloui & Rotta Loria, 2020), (c) fluid flow rate, and (d) temperature difference (ΔT) between the inlet fluid and original ground.

ing in insufficient heat exchange capacity and underutilization of the heat exchange function of energy piles. Parallel double U-shaped and parallel triple U-shaped configurations have more buried pipes, a larger heat exchange area, and relatively stronger heat exchange capacities. However, due to the higher number of buried pipes and smaller pipe spacing, these configurations are prone to “thermal short-circuiting”. The W-shaped buried pipe configuration, also known as the series double U-shaped configuration, increases the number of buried pipes and heat exchange area, enhancing the heat exchange capacity without increasing the number of thermal fusion joints, thus reducing the probability of leakage. Its drawback is that it is difficult to exhaust the gas in the buried pipe at the top of the pile, which is not conducive to the flow of heat transfer fluid, leading to a decrease in heat exchange efficiency. Compared with the W-shaped configuration, the series triple U-shaped configuration further increases the number of buried pipes and the heat exchange area. The spiral pipe configuration increases the heat exchange area within the energy pile significantly, leading to a notable improvement in heat exchange capacity. However, it is mostly in the research stage and uncommon in practical engineering applications due to its complex structure (Fadejev et al., 2017). In addition to the above configurations, there are coaxial pipe configuration (Mohamad et al., 2021), offset pipe configuration (Beragama Jathunge et al., 2024; Guo et al., 2025), triple spiral configuration (Farajollahi et al., 2022), and so on.

2.1.3.4 Influence of pile size

The length and diameter of energy piles largely depend on the mechanical loads imposed by the superstructure rather than the energy requirements of the building. However, the length of piles is crucial due to temperature fluctuations at shallow depths, and the length should exceed the ground temperature variation zone (Suryatriyastuti et al., 2012). Effective system performance can be achieved if the pile length extends beyond the ground temperature fluctuation zone. Once the construction of a building is completed, this effect diminishes (Sani et al., 2019). Research by Xia et al. (2015) indicates that increasing the length of the pile body implies an increase in the total length of buried pipes within the pile. As the length of the pile body increases, the heat exchange per unit length of the buried pipe decreases, but the total heat exchange of a single group of buried pipes increases. Additionally, larger-diameter piles increase the contact area with the ground, significantly affecting the heat transfer and heat storage capacity of energy piles, thereby improving their thermal performance (Loveridge & Powrie, 2013) and allowing more energy to be integrated into the foundation (Loveridge, 2012). Loveridge (2012) reported that the importance of the geometry of energy piles is best indicated by the length-to-diameter ratio, and the length-to-diameter ratios for constructed energy piles are generally in the range of 10 to 50. Figure 9(b) exhibits the influence of pile length-to-diameter ratio on heat transfer rate per unit pile length. It can be found that as the length-to-diameter ratio increases from 10 to 20, the heat transfer rate significantly increases. However, when the length-to-diameter ratio rises from 20 to 40, the change in heat transfer rate becomes less noticeable. This is due to the fact that, with the increase in heat transfer surface area, the heat exchange capacity of the heat exchanger approaches saturation.

2.1.3.5 Influence of flow rate of fluid in the pipe

Researchers have employed various methods to investigate the impact of fluid flow rate inside pipes on heat exchange performance. For instance, Jalaluddin et al. (2011) conducted experimental research on the influence of steel pile heat exchangers with different pipe configurations on the heat transfer characteristics of energy piles under various fluid flow rates. It was found that increasing the flow rate can increase the heat exchange rate in all pipe configurations. Kramer et al. (2015) carried out model trench tests on the heat transfer performance of energy piles in dry sand, revealing that as the circulation liquid flow rate increases, the heat transfer efficiency of the pile increases, while changes in circulation liquid flow rate do not cause significant variations in the soil temperature. Xia et al. (2015) utilized a fluid-thermal coupled numerical calculation method to investigate the heat transfer performance of drilled shaft row piles, finding that the heat exchange increases with the increase in circulating water flow rate. However, the rate of increase in heat exchange diminishes gradually once the flow rate reaches a certain speed. Z. Chen et al. (2023) numerically simulated a deeply buried pipe energy pile group, indicating that increasing the flow rate can improve heat exchange efficiency, but aggravate heat accumulation, resulting in a reduction of the energy efficiency ratio. Figure 9(c) presents the influence of fluid flow rate on heat transfer rate per unit pile length. Summarizing existing research indicates that at lower flow rate levels, the fluid flow state approximates laminar flow, resulting in low heat exchange rates. Increasing the fluid flow rate at this point enhances the convective heat transfer coefficient between the fluid and the pipe wall, leading to an increase in heat exchange amount and significantly improving the heat exchange rate. However, once the flow rate exceeds a certain value, inadequate heat exchange occurs due to reduced heat exchange time inside the pipe, resulting in a decrease in the heat exchange rate (Cecinato & Loveridge, 2015). Therefore, the fluid flow rate inside the pipes should not be too high or too low, and it is generally considered sufficient to ensure that the flow state is turbulent.

2.1.3.6 Influence of inlet water temperature

If there is no external interference, the inlet water temperature is mainly determined by the local air temperature. According to Eq. (17), the inlet temperature directly affects the temperature difference of the liquid entering and exiting during heat exchange. The larger the temperature difference, the stronger the driving force of heat transfer, leading to a higher heat exchange rate. Studies indicate that within a certain range, the heat exchange rate increases approximately linearly with increasing inlet water temperature (Gao et al., 2008a, Xia et al., 2015). Figure 9(d) shows the influence of the temperature difference between the inlet fluid and the original ground on the heat transfer rate per unit pile length. The slopes of the curves with data from Gao et al. (2008a) and Xia et al. (2015) are about 2.7 and 1.4 W/(m·°C), respectively, which indicates that for each degree of temperature difference between the inlet temperature and the original ground temperature, the heat transfer rate can be increased by 2.7 and 1.4 W/m, respectively.

2.1.3.7 Influence of operating condition

Morino and Oka (1994) experimentally studied the heat exchange characteristics of pile foundations under different energy pile system operation modes (intermittent, continuous operation). The results showed that the unit length heat transfer during intermittent operation of energy piles is three times that of long-term continuous operation. Park et al. (2013) conducted thermal response tests (TRTs) and numerical simulation studies on PHC energy piles, with a 72 h temperature response simulation yielding an effective thermal conductivity of energy piles close to the experimental results. In intermittent operation mode, the heat exchange of a triple U-shaped buried pipe energy pile is 15% higher than that of a W-shaped energy pile, while in continuous operation mode, the heat exchange of both is essentially equal. Xia et al. (2015) used a fluid-thermal coupled numerical calculation method to study the impact of daily operating hours (8, 16, 24 h) on heat exchange performance. It was found that adopting an intermittent operation mode allows for a certain degree of recovery of geothermy in the surrounding ground of underground heat exchange pipes. The shorter the daily operating hours, the slower the decay rate of the heat exchange capacity of the underground heat exchange pipes.

2.2 Heat transfer of energy walls

2.2.1 Heat transfer models of energy walls

Due to the large size of underground diaphragm walls (with a width of approximately 0.8 to 1.0 m), their thermal capacity cannot be neglected. When establishing a heat transfer model, it is necessary to consider the two different mediums of the underground diaphragm wall and the soil. Therefore, the heat transfer model for buried pipes within underground diaphragm walls differs significantly from traditional vertical buried pipe models, and buried pipe models of energy piles are also not applicable in this case. Currently, there are not many studies on the heat transfer models of underground diaphragm walls. Xia et al. (2015) and Sun et al. (2013) established heat transfer models for buried pipes within underground diaphragm walls based on the structural form (as shown in Fig. 10) and heat transfer characteristics. Through certain assumptions, they developed analytical solutions for the above and below excavation sections of the underground diaphragm wall with buried pipes using the Green's function method.

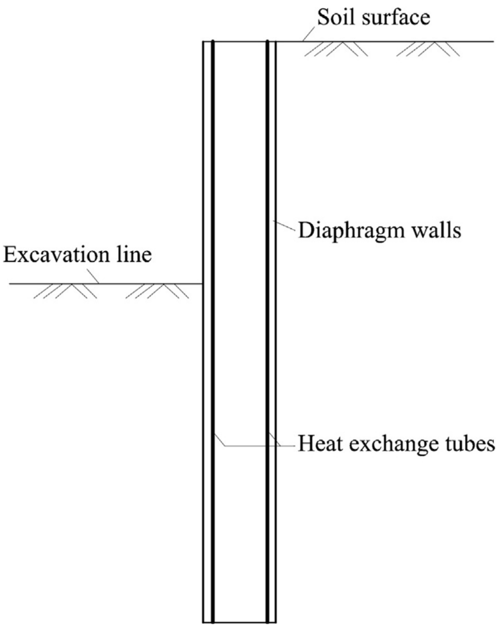


Fig. 10. Section plan drawing of geothermal heat exchangers embedded in diaphragm walls (Sun et al., 2013).

Based on the assumptions (Sun et al., 2013), the heat transfer model for buried pipes within the underground diaphragm wall above the excavation face can be represented by the calculation model shown in Fig. 11(a). The left side of the underground diaphragm wall faces a convective boundary; it is in close contact with the soil on the right side (neglecting contact thermal resistance). The right boundary of the soil is considered far enough to assume that the soil temperature at the right boundary is unaffected by the operation of the heat exchange pipes and is assumed to be a constant temperature boundary. The upper and lower boundaries of the model are assumed to be adiabatic boundaries. The heat transfer model for buried pipes within the underground diaphragm wall below the excavation face can be represented by the calculation model shown in Fig. 11(b). Both sides of the underground diaphragm wall below the excavation face are in close contact with the soil (neglecting contact thermal resistance); the far boundaries of the soil on both sides are considered far enough and assumed to be constant temperature boundaries. The upper and lower boundaries of the model are assumed to be adiabatic boundaries.

The heat transfer differential equation for the buried pipes within the underground diaphragm wall above the excavation face is

$$\begin{aligned} & k_i \frac{\partial^2 T_{\mathrm{o},i}}{\partial x^2} + k_i \frac{\partial^2 T_{\mathrm{o},i}}{\partial y^2} \\ & \quad + q(t)[\delta(x-a_1)\delta(y-b_1) + \delta(x-a_1)\delta(y-b_2)\delta(x-a_2)\delta(y-b_1) \\ & \quad + \delta(x-a_2)\delta(y-b_2)] = \rho_i c_{\mathrm{p},i} \frac{\partial T_{\mathrm{o},i}}{\partial t}. \end{aligned} \tag{19}$$

The initial condition is

$$T_{\mathrm{o},i}(x,y,t) = T_0,\ i=1,2,\ 0 \le x \le L_2,\ 0 \le y \le W,\ t=0. \tag{20}$$

The boundary conditions are

$$-k_1 \frac{\partial T_{\mathrm{o},1}}{\partial x} + h[T_{\mathrm{o},1} - f(t)] = 0,\ x=0,\ 0 \le y \le W,\ t>0, \tag{21}$$

$$T_{\mathrm{o},2} = T_0,\ x=L_2,\ 0 \le y \le W,\ t=0, \tag{22}$$

$$-k_i \frac{\partial T_{\mathrm{o},i}}{\partial y} = 0,\ 0 \le x \le L_2,\ y=0,\ t>0, \tag{23}$$

$$k_i \frac{\partial T_{\mathrm{o},i}}{\partial y} = 0,\ 0 \le x \le L_2,\ y=W,\ t>0. \tag{24}$$

The continuity conditions are

$$T_{\mathrm{o},1} = T_{\mathrm{o},2},\ x=L_1,\ 0 \le y \le W,\ t=0, \tag{25}$$

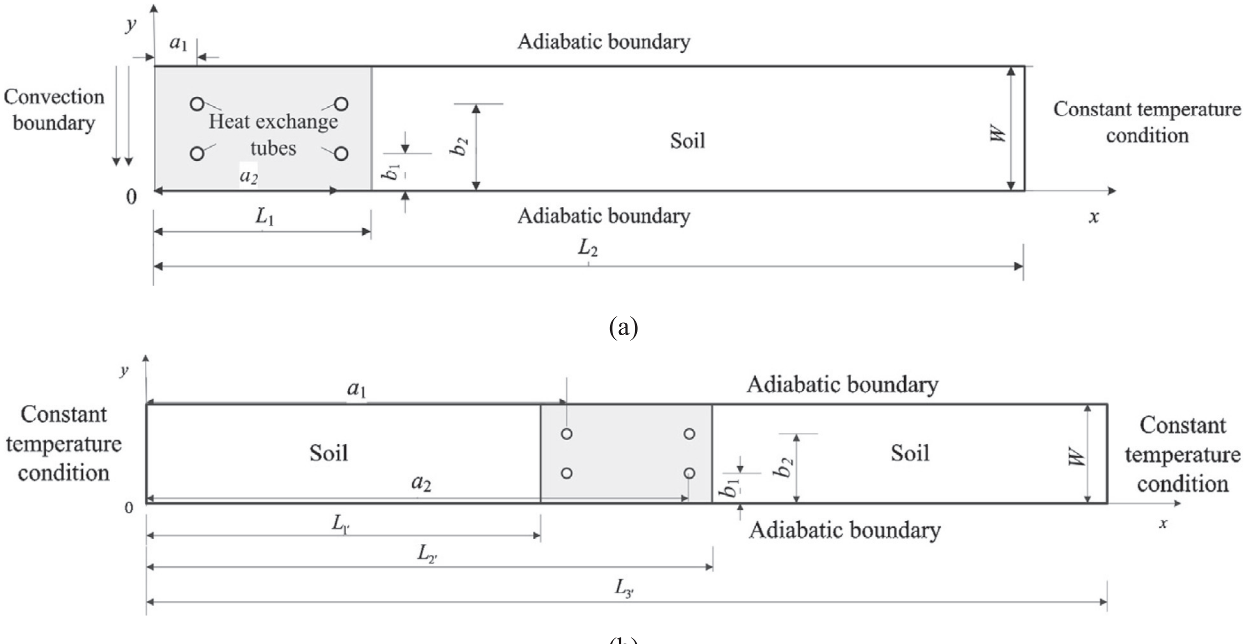


Fig. 11. Plan drawing of the heat transfer model of the energy wall. (a) Above excavation surface, and (b) below excavation surface (Sun et al., 2013).

$$k_1\frac{\partial T_{o,1}}{\partial x}=k_2\frac{\partial T_{o,2}}{\partial x},\ x=L_1,\ 0\le y\le W,\ t=0, \tag{26}$$

where $T_{o,1}$ and $T_{o,2}$ are the temperatures of the diaphragm wall and soil over the excavation line, respectively; k_1 and k_2 are the thermal conductivities of the diaphragm wall and soil, respectively; ρ_1 and ρ_2 are the densities of the diaphragm wall and soil, respectively; $c_{p,1}$ and $c_{p,2}$ are the specific heat capacities of the diaphragm wall and soil, respectively; h is the convective heat transfer coefficient; $f(t)$ is air temperature; δ is Dirac function; a_1 and a_2 are the x-coordinates, and b_1 and b_2 are the y-coordinates of the heat exchange pipes as shown in Fig. 11; L_1 is the x-coordinate of the right boundary of the diaphragm wall in the calculation model above the excavation surface; L_2 is the length of the calculation model above the excavation surface; W is the width of the calculation model.

The heat transfer differential equation for the buried pipes within the underground diaphragm wall below the excavation face is

$$\begin{aligned}&k_{i'}\frac{\partial^2 T_{u,i'}}{\partial x^2}+k_{i'}\frac{\partial^2 T_{u,i'}}{\partial y^2}\\&\quad+q(t)[\delta(x-a_1)\delta(y-b_1)+\delta(x-a_1)\delta(y-b_2)\\&\quad+\delta(x-a_2)\delta(y-b_1)+\delta(x-a_2)\delta(y-b_2)]\\&\quad=\rho_{i'}c_{p,i'}\frac{\partial T_{u,i'}}{\partial t}.\end{aligned} \tag{27}$$

The initial condition is

$$T_{u,i'}(x,y,t)=T_0,\ i'=1,2,3,\ 0\le x\le L_{3'},\ 0\le y\le W,\ t=0. \tag{28}$$

The boundary conditions are

$$T_{u,1'}=T_0,\ x=0,\ 0\le y\le W,\ t=0, \tag{29}$$

$$-k_{i'}\frac{\partial T_{u,i'}}{\partial y}=0,\ 0\le x\le L_{3'},\ y=0,\ t>0, \tag{30}$$

$$k_{i'}\frac{\partial T_{u,i'}}{\partial y}=0,\ 0\le x\le L_{3'},\ y=W,\ t>0, \tag{31}$$

$$T_{u,3'}=T_0,\ x=L_{3'},\ 0\le y\le W,\ t=0. \tag{32}$$

The continuity conditions are

$$T_{u,1'}=T_{u,2'},\ x=L_{1'},\ 0\le y\le W,\ t=0, \tag{33}$$

$$k_{1'}\frac{\partial T_{u,1'}}{\partial x}=k_{2'}\frac{\partial T_{u,2'}}{\partial x},\ x=L_{1'},\ 0\le y\le W,\ t=0, \tag{34}$$

$$T_{u,2'}=T_{u,3'},\ x=L_{2'},\ 0\le y\le W,\ t=0, \tag{35}$$

$$k_{2'}\frac{\partial T_{u,2'}}{\partial x}=k_{3'}\frac{\partial T_{u,3'}}{\partial x},\ x=L_{2'},\ 0\le y\le W,\ t=0, \tag{36}$$

where $T_{u,1'}$, $T_{u,2'}$, and $T_{u,3'}$ are the temperatures of the soil on the left of the diaphragm wall, the diaphragm wall itself, and the soil on the right of the diaphragm wall under the excavation line, respectively; $k_{1'}$, $k_{2'}$, and $k_{3'}$ are the thermal conductivities of the soil on the left of the diaphragm wall, the diaphragm wall itself, and the soil on the right of the diaphragm wall under the excavation line, respectively; $\rho_{1'}$, $\rho_{2'}$, and $\rho_{3'}$ are the densities of the soil on the left of the diaphragm wall, the diaphragm wall itself, and the soil on the right of the diaphragm wall under the excavation line, respectively; $c_{p,1'}$, $c_{p,2'}$, and $c_{p,3'}$ are the specific heat capacities of the soil on the left of the diaphragm wall, the diaphragm wall itself, and the soil on the right of the diaphragm wall under the excavation line, respectively; $L_{1'}$ is the x-coordinate of the left boundary of the diaphragm wall in the calculation model below the excavation surface; $L_{2'}$ is the x-coordinate of the right boundary of the diaphragm wall in the calculation model below the excavation surface; $L_{3'}$ is the length of the calculation model below the excavation surface.

The analytical solutions to the above equations can be found in the derivation by Sun et al. (2013). The calculated results were compared with the measured data, and except for relatively large errors in the first 10 h, the overall agreement was good. This model can solve complex medium heat conduction problems with internal heat sources that vary with time and non-homogeneous boundary conditions. It can be used for analyzing the temperature field within the underground diaphragm wall and surrounding soil, as well as for optimizing the parameters such as the buried pipe configuration, pipe spacing, and intermittent operation times.

Additionally, Xia et al. (2015) and Sun et al. (2013) also established a calculation model for the temperature field of the fluid inside the pipes (as shown in Fig. 12). This model can calculate the dynamic changes in heat exchange. The heat transfer equation for the fluid inside the pipes is

$$M\frac{\mathrm{d}T_{\mathrm{f}}(z,t)}{\mathrm{d}z}=\frac{T_{\mathrm{p}}(t)-T_{\mathrm{f}}(z,t)}{R'}. \tag{37}$$

The boundary condition is

$$T_{\mathrm{f}}(z=0,t)=T_{\mathrm{in}}(t). \tag{38}$$

The temperature of the outer wall of the pipe is calculated based on the analytical solution of the diaphragm wall heat transfer model:

$$T_{\mathrm{p}}(t)=T(a_1,b_1,t). \tag{39}$$

The solution of Eq. (37) can be obtained as

$$\begin{aligned}T_{\mathrm{out}}(t)&=T_{\mathrm{f}}\big(z=H_{\mathrm{p}},t\big)\\&=T_{\mathrm{p}}(t)+\big[T_{\mathrm{in}}(t)-T_{\mathrm{p}}(t)\big]\mathrm{e}^{-\frac{H_{\mathrm{p}}}{MR'}},\end{aligned} \tag{40}$$

$$R'=\frac{1}{\pi d_{\mathrm{p,inner}}h_{\mathrm{ci}}}+\frac{1}{2\pi k_{\mathrm{p}}}\ln\left(\frac{d_{\mathrm{p,outer}}}{d_{\mathrm{p,inner}}}\right), \tag{41}$$

$$h_{\mathrm{ci}}=\frac{0.023{R_{\mathrm{e}}}^{0.8}{P_{\mathrm{r}}}^{0.3}k_{\mathrm{w}}}{d_{\mathrm{p,inner}}}, \tag{42}$$

$$R_{\mathrm{e}}=\frac{\rho_{\mathrm{w}}vd_{\mathrm{p,inner}}}{\mu}, \tag{43}$$

$$P_{\mathrm{r}}=\frac{c_{\mathrm{w}}\mu}{k_{\mathrm{w}}}, \tag{44}$$

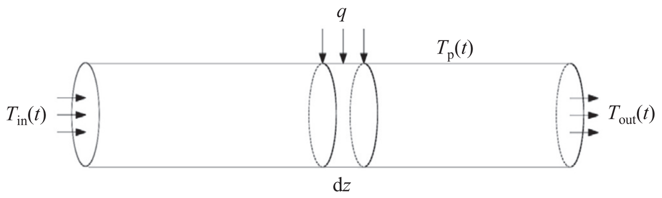


Fig. 12. Schematic diagram of the heat transfer process of fluids in the pipes (Sun et al., 2013).

where v is the flow rate of fluid; μ is the dynamic viscosity coefficient of fluid; ρ_{w} is the density of fluid; c_{w} is the specific heat of fluid; k_{p} is the thermal conductivity of pipe wall; k_{w} is the thermal conductivity of fluid; $d_{\mathrm{p,inner}}$ and $d_{\mathrm{p,outer}}$ are the pipe inner and outer diameters, respectively; R' is the heat transfer resistance of the pipe wall and the fluid; h_{ci} is the convective heat transfer coefficient between the pipe wall and the fluid inside the pipe; R_{e} is the Reynolds number; P_{r} is the Nusselt number; T_{f} is the fluid temperature inside the pipe; T_{p} is the temperature of the outer wall of the pipe.

The summary of advantages, limitations, and application scenarios of the energy wall heat transfer model proposed by Sun et al. (2013) is listed in Table 4.

2.2.2 Factors influencing heat exchange performance of energy walls

Compared to energy pile systems, energy wall systems have larger structural sizes, allowing for greater underground heat transfer capacity (Soga & Rui, 2016). In the design of pipe configuration for energy geostructures with large heat exchange surfaces, such as energy walls, the key to design lies in achieving the maximum heat exchange surface for the selected energy geostructure with minimal pressure drop and investment conditions.

Currently, there is limited practical engineering application and thermal performance testing of energy walls. Xia et al. (2012) implemented the first underground energy wall project in China by burying heat exchange pipes within the underground diaphragm wall at the Shanghai Natural History Museum. They conducted a study on the heat transfer performance of buried pipes within the underground diaphragm wall through field experiments, analyzing the effects of pipe configuration (Fig. 13), circulating water flow rate, inlet water temperature, and operation mode on heat exchange performance. They also analyzed additional factors such as buried pipe spacing, branch pipe spacing, buried pipe length, and diaphragm wall width using theoretical calculations to assess their impact on heat exchange performance. In addition, Baralis and Barla (2021) tested the thermal performance of a novel very shallow energy wall system. Zannin et al. (2022) tested the thermal performance of energy walls and energy slabs installed at the Lancy-Bachet train station in Geneva, Switzerland. Hu et al. (2024) conducted field tests of energy wall thermal performance in a metro station in Nanjing, China. Field testing and theoretical calculations (Sun et al., 2013; Xia et al., 2012, 2015) revealed the following (a brief summary is presented in Table 5):

(1) As shown in Fig. 13, the heat exchange of W-shaped and improved W-shaped pipes is approximately 1.2–1.4 times that of a single U-shaped pipe under the same conditions. The heat exchange of improved W-shaped pipe is greater than that of W-shaped pipe. In the early to mid-testing period, the heat exchange of W-shaped and improved W-shaped

Table 4
Summary of advantages, limitations, and application scenarios of the energy wall heat transfer model proposed by Sun et al. (2013).

Advantages	Limitations	Application scenarios
Both the surrounding soil heat transfer model and circulating fluid heat transfer model were established. It can solve complex medium heat conduction problems with internal heat sources that vary with time and non-homogeneous boundary conditions.	The heat capacity of heat exchange pipes and thermal contact resistance between different materials are ignored. The errors are relatively large in the first 10 h.	It can be used for analyzing the temperature field within the diaphragm wall and surrounding soil, as well as for optimizing the parameters such as the buried pipe configuration, pipe spacing, and intermittent operation times.

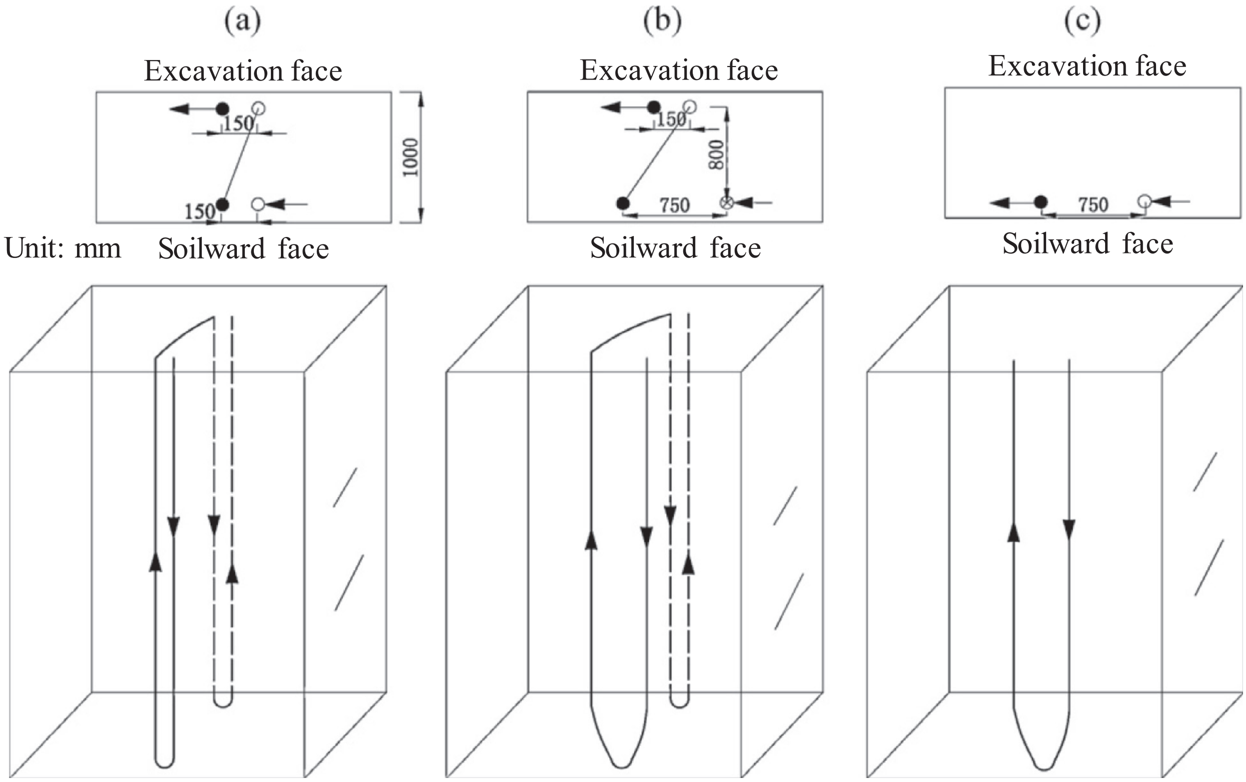


Fig. 13. Three types of underground heat exchangers investigated by Xia et al. (2012). (a) W-shaped pipe, (b) improved W-shaped pipe, and (c) single U-shaped pipe.

pipes is similar. However, with time, the heat exchange of W-shaped pipe decreases significantly faster than that of improved W-shaped pipe, while the heat exchange of single U-shaped pipe remains lower than that of W-shaped and improved W-shaped pipes.

(2) The heat exchange per unit length of pipe significantly increases with increasing pipe spacing, but the increase rate gradually diminishes. This indicates that pipe spacing is a significant factor affecting pipe heat exchange, as increasing the spacing enlarges the heat absorption range of a single group of pipes and reduces mutual interference between adjacent pipes, thereby improving heat exchange efficiency. However, since the length of the underground diaphragm wall available for pipe arrangement is finite, excessively large pipe spacing reduces the number of pipes that can be arranged, resulting in a decrease in total heat exchange. Therefore, an optimization analysis is recommended to determine the appropriate pipe spacing.

(3) The branch pipe spacing is the distance between the inlet and outlet branch pipes of a single U-shaped pipe. The heat exchange increases significantly with increasing branch pipe spacing, but the heat exchange essentially plateaus with further increases in branch pipe spacing. Moreover, increasing branch pipe spacing has a relatively better effect on enhancing heat exchange in the early stages of operation.

(4) In the initial stage of operation, the heat exchange per unit length of pipe decreases gradually with increasing total pipe length. However, as the operation time extends, the decreasing trend in heat exchange per unit length diminishes. The total heat exchange of a single group of pipes increases with pipe length, particularly noticeable in the early stage of operation.

Table 5
Influences of some factors on heat exchange performance of energy walls.

Factor	Influences on heat exchange performance
Heat exchange pipe	The heat exchange of the W-shaped pipe configuration is greater than that of the single U-shaped pipe configuration. The heat exchange per unit length of pipe significantly increases with increasing pipe spacing, but the increase rate gradually diminishes. The heat exchange increases significantly with increasing branch pipe spacing, but essentially plateaus with further increases in branch pipe spacing. The total heat exchange of pipes increases with pipe length.
Circulating fluid	Increasing the circulating water flow rate enhances heat exchange efficiency, but once a certain flow rate is reached, the rate of increase in heat exchange becomes very slow. The heat exchange exhibits a linear increasing trend with rising inlet water temperature.
Diaphragm wall width	The heat exchange per unit length of pipe increases to a certain extent with the increase in the width of the diaphragm wall.
Operating condition	The intermittent operation mode can improve the heat exchange compared with the continuous operation mode.

(5) Increasing the circulating water flow rate enhances heat exchange efficiency, but once a certain flow rate is reached, the rate of increase in heat exchange becomes very slow (Fig. 14(a)). Additionally, higher flow rates result in increased resistance along the path, necessitating higher requirements for the circulating water pump and system. Therefore, for optimal heat exchange efficiency and economic considerations, it is recommended to maintain the circulating water flow rate below 0.9 m/s and not lower than 0.6 m/s.

(6) The heat exchange exhibits a linear increasing trend with rising inlet water temperature, and the inlet water temperature has a significant effect on the heat exchange efficiency (Fig. 14(b)). On average, it is improved by 15% every 1 °C increase in inlet water temperature.

(7) The heat exchange per unit length of pipe increases to a certain extent with the increase in the width of the underground diaphragm wall, with a relatively small increase in the early stage of operation that gradually amplifies over time.

(8) Over time, both intermittent operation (a total of 96 h, with each heat exchange cycle lasting 12 h) and continuous operation (48 h) show a decreasing trend in average heat exchange rate with time going on (Fig. 14(c)), but the decrease rate is slower when using intermittent operation (Fig. 14(d)). A comparison shows that adopting an intermittent operation mode with a 1:1 run-stop ratio can increase heat exchange rate by 14.7% compared to the continuous operation mode.

In addition, some numerical simulations were carried out to investigate the complex problems of energy walls

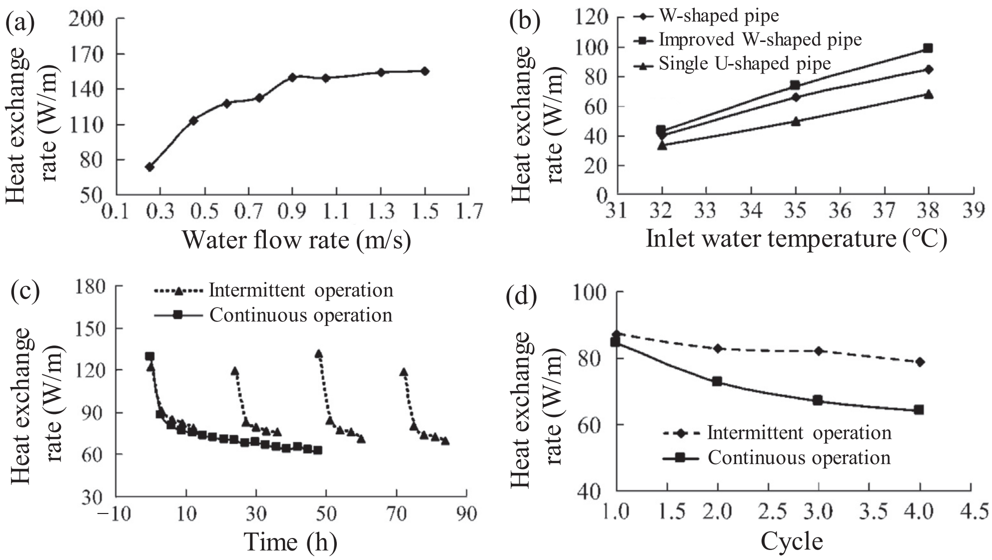


Fig. 14. Influences of (a) water flow rate, (b) inlet water temperature, and (c) and (d) operation mode on heat exchange rate of energy walls.

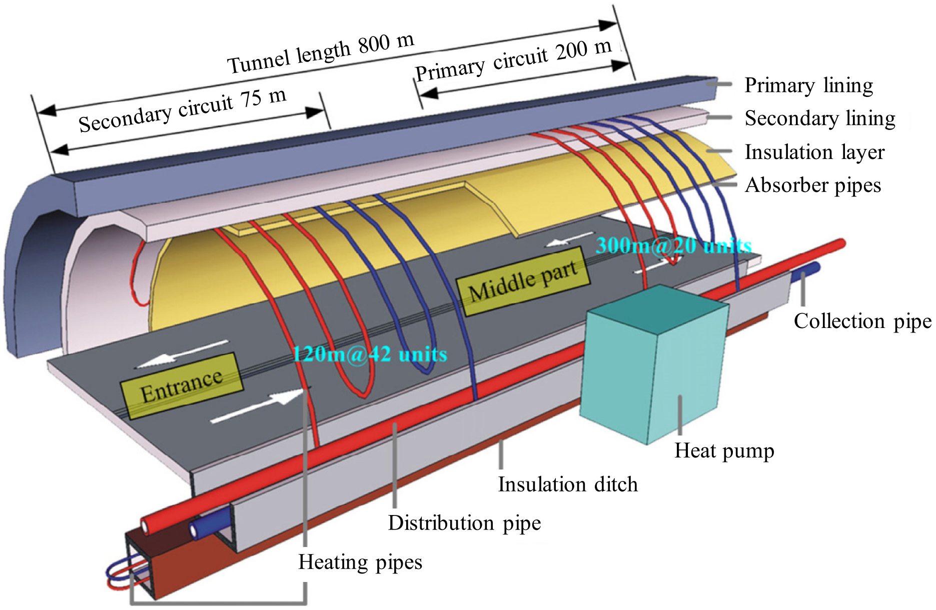


Fig. 15. Schematic view of the tunnel heating system using geothermal energy (Zhang et al., 2013).

considering the influence factors other than those mentioned above, such as ground conditions (Di Donna et al., 2021; Mi et al., 2024; Zannin et al., 2021; Zhong et al., 2023), ground surface thermal boundary conditions (Xu et al., 2023; Zhu et al., 2024), airflow conditions (Dai et al., 2022), climatic conditions (Peterson & Shafagh, 2022), and the heat interaction between energy wall and adjacent air-conditioned space (Zeng et al., 2021).

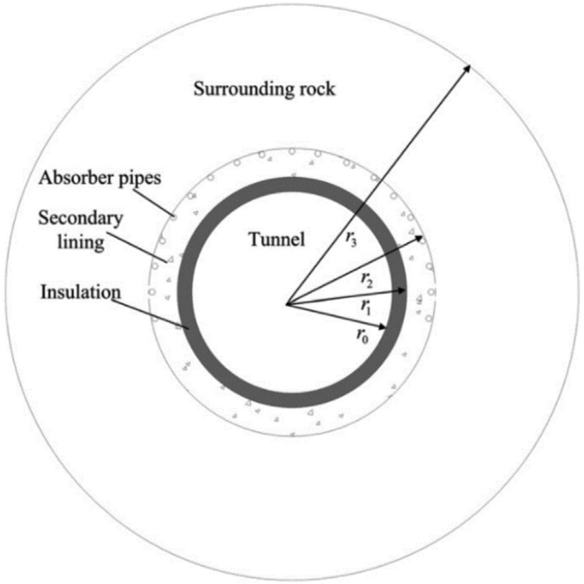


Fig. 16. Schematic view of two-dimensional analyses of energy tunnels (Zhang et al., 2013).

2.3 Heat transfer of energy tunnels

2.3.1 Heat transfer models of energy tunnels

Currently, there are few heat transfer models for energy tunnels. To address frost damage issues in cold region tunnels, Xia et al. (2015) and Zhang et al. (2013) first applied a ground source heat pump heating system in a highway tunnel in Inner Mongolia, China (Fig. 15). The heating system consists of a heat extraction section, a heating section, a heat pump, and distribution and collection pipes, which can be used for heating the tunnel entrance lining and drainage system. The heat extraction section is located in the middle of the tunnel to extract geothermal energy from the surrounding rock. The temperature field of the heat extraction section of the tunnel is composed of the temperature field of the surrounding rock outside the heat exchange pipes and the temperature field of the fluid inside the heat exchange pipes, for which heat transfer models have been established separately.

The heat transfer model of the surrounding rock outside the heat exchange pipes in the heat extraction section of the tunnel considers the lining structure and the heat source (Fig. 16). The basic assumptions are: (1) The tunnel cross-section is circular. (2) The secondary lining has good contact with the thermal insulation layer, with no contact thermal resistance. (3) The tunnel surrounding rock, secondary lining, and insulation layer are all constant thermal properties that do not vary with temperature. (4) The heat exchange pipe diameter is only 2.5 cm, and it is considered as a line heat source in calculations.

Based on circular composite media heat conduction theory, the heat conduction equation for the surrounding rock around the heat exchange pipe is

$$\frac{1}{\alpha_i}\frac{\partial T_i}{\partial t}(r,\theta,t)=\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial T_i}{\partial r}(r,\theta,t)\right]+\frac{1}{r^2}\frac{\partial^2 T_i}{\partial \theta^2}(r,\theta,t)+\frac{g_i(r,\theta,t)}{k_i},\ i=1,2,3. \tag{45}$$

The boundary condition at the inner surface of the secondary lining is

$$-k_1\frac{\partial T_1}{\partial r}(r_0,\theta,t)+hT_1(r_0,\theta,t)=hf(t). \tag{46}$$

The boundary condition at the outer surface of the surrounding rock is

$$T_3(r_3,\theta,t)=T_0. \tag{47}$$

The periodic boundary conditions are

$$T_i(r,0,t)=T_i(r,2\pi,t), \tag{48}$$

$$\frac{\partial T_i}{\partial \theta}(r,0,t)=\frac{\partial T_i}{\partial \theta}(r,2\pi,t). \tag{49}$$

The continuity conditions (boundary conditions at the ith layer interface) are

$$T_i(r_{\mathrm{i}},\theta,t)=T_{i+1}(r_{\mathrm{i}},\theta,t),\ i=1,2, \tag{50}$$

$$k_i\frac{\partial T_i}{\partial r}(r_{\mathrm{i}},\theta,t)=k_{i+1}\frac{\partial T_{i+1}}{\partial r}(r_{\mathrm{i}},\theta,t),\ i=1,2. \tag{51}$$

The initial condition is

$$T_i(r,\theta,0)=f_i(r,\theta),\ i=1,2,3,4,\ r_0\le r\le r_3, \tag{52}$$

where T_1 is the temperature of the insulation layer; T_2 is the temperature of the secondary lining; T_3 is the temperature of the surrounding rock; α_i is the thermal diffusivity; k_i is the thermal conductivity; h is the convective heat transfer coefficient; and $g_i(r,\theta,t)$ is the extracted geothermal energy from the surrounding rock. The determination of $g_i(r,\theta,t)$ and air temperature $f(t)$ is detailed in Zhang et al. (2013).

The above heat transfer mathematical equations are solved by using a combination of the superposition principle, Laplace transform, and integral transform to obtain the analytical solution of the temperature field in the heat extraction section, as detailed in Zhang et al. (2013).

The fluid heat transfer model inside the heat exchange pipe is similar to Fig. 12. The basic assumptions are: (1) steady-state heat conduction between the fluid inside the heat exchange pipe and the surrounding rock wall; (2) constant thermal properties for the heat exchange pipe wall, surrounding rock, lining, and insulation layer that do not change with temperature; (3) the temperature of the outer wall of the heat exchange pipe only changes with the operating time of the heat pump; (4) the heat transferred between the fluid inside the heat exchange pipe due to heat conduction is negligible.

By utilizing the analytical solution of the surrounding rock temperature field around the heat exchange pipe in the tunnel heat extraction section, the temperature field of the heat exchange pipe wall is calculated as

$$T_{\mathrm{p}}(t)=T_2(r_2,\theta,t). \tag{53}$$

The heat transfer equation for the fluid inside the heat exchange pipe is shown in Eq. (37). The outlet temperature of the heat exchange pipe can be obtained using an iterative method (Zhang et al., 2013). Comparing theoretical solutions with field experimental data shows that the accuracy meets engineering requirements. The summary of advantages, limitations, and application scenarios of the energy tunnel heat transfer model proposed by Zhang et al. (2013) is listed in Table 6.

2.3.2 Factors influencing heat exchange performance of energy tunnels

Researchers have conducted research on the influencing factors of the heat exchange performance of energy tunnels using different methods. For example, Lee et al. (2012, 2016) found through field thermal response tests and numerical simulation analysis that the configuration of heat exchange pipes, the thermal conductivity of shotcrete and lining, tunnel air temperature, heat circulation, cold circulation, and drainage layers all have varying degrees of impact on the thermal performance of energy geotechnical fabrics. Cousin et al. (2019) demonstrated that the configuration of heat exchange pipes, pipe diameter, pipe spacing, flow rate of circulating fluid (indicated by the Reynolds number), and burial depth of pipes (the ratio of the distance from the tunnel lining inner arch to the pipe position to the lining thickness) all have certain effects on the thermal performance of energy tunnels. Ogunleye et al. (2020, 2021) explored the influences of circulating fluid diffusivity, concrete diffusivity, pipe thermal conductivity, pipe diameter, pipe length, pipe spacing, pipe location, operation mode, and tunnel air temperature on the thermal efficiency of energy tunnels. Zhang et al. (2013, 2014, 2016, 2017) studied the influences of different factors (such as inlet temperature of circulating fluid, flow rate, pipe spacing, ventilation conditions, and groundwater seepage) on the heat exchange performance of energy tunnels through

Table 6
Summary of advantages, limitations, and application scenarios of the energy tunnel heat transfer model proposed by Zhang et al. (2013).

Advantages	Limitations	Application scenarios
Both the surrounding rock heat transfer model and the circulating fluid heat transfer model were established. Considering both composite medium and time-dependent boundary conditions. It was validated by the full-scale thermal response tests in a short term.	Only the case of the heat exchange pipe being arranged along the tunnel axis is considered. The long-term applicability needs to be further verified.	Suitable for, but not limited to, cold area tunnel heat extraction and frost prevention.

Table 7
Influences of some factors on heat exchange performance of energy tunnels.

Factor	Influences on heat exchange performance
Heat exchange pipe	Heat exchangers installed near the tunnel wall have significantly higher thermal efficiency compared to those installed at the center of the tunnel concrete lining. Reducing the pipe diameter and spacing increases the heat extraction per square meter of surrounding rock.
Circulating fluid	As the flow rate of circulating fluid increases, the heat exchange increases, but increases slowly after exceeding a certain flow rate value. An increase in the inlet temperature of circulating fluid can increase the heat exchange.
Tunnel air	The average heat exchange of energy tunnels shows a decreasing trend with the decrease in tunnel air temperature. Increased ventilation and convective heat transfer coefficients can enhance the heat exchange capacity.
Groundwater	Groundwater flow can effectively increase heat extraction and dissipation. The thermal performance is significantly enhanced when the direction of groundwater flow changes from 0° (tunnel axial direction) to 45°.
Operating condition	The intermittent operation mode can improve the heat exchange compared with the continuous operation mode.

field tests, indoor model tests, numerical simulations, and theoretical analyses. Li et al. (2022) presented a design method for pipe length in energy tunnel linings based on the energy efficiency of a heat pump. Dornberger et al. (2022) investigated the influence of energy tunnel airflow on heat exchange performance. Ma et al. (2021a, 2021b) suggested that it is necessary to undertake assessments on the groundwater, tunnel environment, and concrete lining thermal properties when evaluating the geothermal potential of an energy tunnel.

The summary of the influences of various factors on the heat exchange performance of energy tunnels is as follows (a brief summary is presented in Table 7):

(1) Different configurations of spiral, transverse, and longitudinal heat exchange pipes have similar thermal efficiency. Heat exchangers installed near the tunnel wall have significantly higher thermal efficiency compared to those installed at the center of the tunnel concrete lining (Lee et al., 2012).

(2) Field tests by Zhang et al. (2014) showed that the heat exchange capacity of heat exchange pipes with a spacing of 50 cm is superior to that with a spacing of 100 cm (Fig. 17(a)). Cousin et al. (2019) demonstrated that reducing the pipe diameter and spacing increases the heat extraction per square meter of surrounding rock; decreasing the burial depth of pipes increases the heat extraction per square meter of surrounding rock.

(3) An increase in the flow rate of circulating fluid (increase in Reynolds number) leads to an increase in heat flow (Insana & Barla, 2020) and the heat extraction per square meter of surrounding rock by the heat exchanger (Cousin et al., 2019). The research by Zhang et al. (2013) indicates that when the flow rate is over 0.8 m/s, the heat exchange grows slowly (Fig. 17(b)). Therefore, selecting the appropriate flow rate is crucial for improving the heat exchange performance of energy tunnel heat exchangers. From the economic point of view, it is advised that the flow rate is no more than 0.8 m/s.

(4) An increase in the inlet temperature of circulating fluid can increase the heat extraction per square meter of surrounding rock as shown in Fig. 17(c) (Zhang et al., 2014).

(5) Tunnel air temperature affects the thermal performance of energy geotechnical fabrics and should be considered in the design of energy tunnels (Lee et al., 2016). The average heat exchange of energy tunnels shows a decreasing trend with the decrease in tunnel air temperature (Ogunleye et al., 2020).

(6) Increased ventilation and convective heat transfer coefficients can enhance the heat exchange capacity of energy tunnels as shown in Fig. 17(d) (Zhang et al., 2016).

(7) Groundwater flow can effectively increase heat extraction and dissipation (Barla et al., 2016). The thermal performance of energy tunnels is significantly enhanced when the direction of groundwater flow changes from 0° (tunnel axial direction) to 45° (Insana & Barla, 2020). The appropriate installation position for tunnel heat exchangers is in the upstream area of the groundwater flow field, which allows for more geothermal energy to be obtained (Zhang et al., 2017).

(8) The heat exchange of energy tunnels reaches its highest level under cooling conditions and its lowest level under heating conditions (Lee et al., 2016). Intermittent operation mode can increase the average heat exchange compared to continuous operation mode (Ogunleye et al., 2020).

3 Research on thermo-mechanical behaviour

3.1 Thermo-mechanical behaviour of energy piles

3.1.1 Research methods

3.1.1.1 Theoretical analytical method

In theory, when energy piles are heated or cooled, they will expand or contract, resulting in tensile or compressive stresses within the piles. While the stress, strain, and dis-

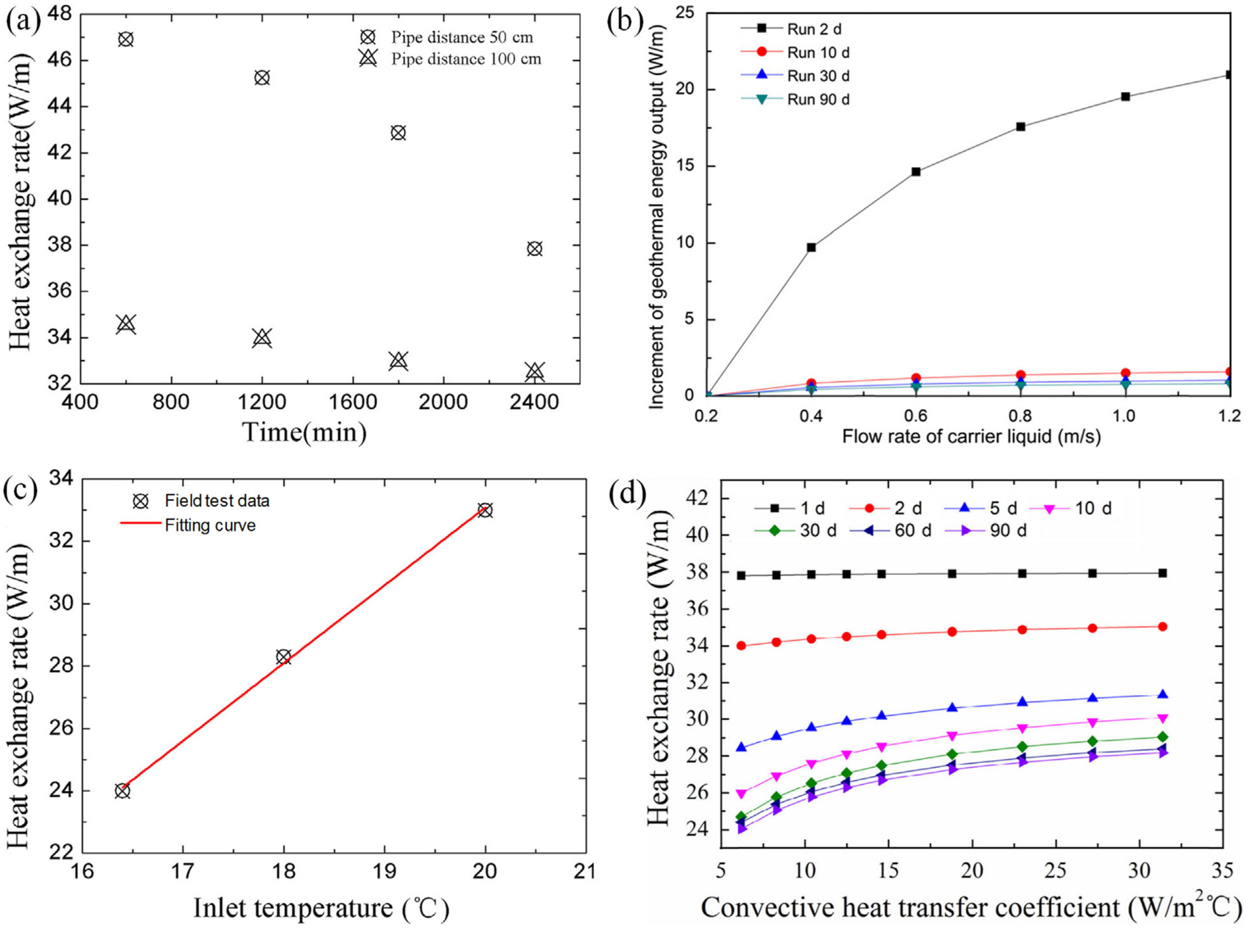


Fig. 17. Influences of (a) pipe spacing (Zhang et al., 2014), (b) fluid flow rate (Zhang et al., 2013), (c) inlet fluid temperature (Zhang et al., 2014), and (d) convective heat transfer coefficient (Zhang et al., 2016) on heat exchange rate of energy tunnels.

placement in soils depend on the competitive relationships between thermal and mechanical loading patterns (Yang et al., 2024a). The stresses generated by heating are constrained by the soil at the pile tip and around the pile, affecting the bearing capacity of the pile foundation. Therefore, studying the thermo-mechanical behaviour of energy piles is necessary. Bourne-Webb et al. (2013) conducted a systematic study on the thermo-mechanical behaviour of energy piles early on. Currently, theoretical analyses of the thermo-mechanical effects of energy piles are mainly based on the load transfer method. Knellwolf et al. (2011) first introduced the thermal influence factor into the load transfer method, proposing a theoretical approach for calculating the load transfer of energy piles. This method assumes the pile body is elastic, neglects radial deformation, and considers the influence of thermal stresses on pile-soil load transfer. Based on this theory, the results of field tests of energy piles are validated, and the thermo-mechanical effects of friction piles, end-bearing piles, and end-bearing friction piles are compared and analyzed. Subsequently, based on the load transfer method, researchers have carried out numerous studies (Chen & McCartney, 2016; Feng et al., 2024; Mimouni & Laloui, 2014; Pasten & Santamarina, 2014; Shi et al., 2024; Suryatriyastuti et al., 2014). The load transfer method is mainly used for the study of the thermo-mechanical effect of a single pile and has certain limitations. For the study of energy pile groups, Rotta Loria and Laloui (2016a, 2017) proposed the interaction factor method and the equivalent pier method. Using the interaction factor method, a parameter analysis of the vertical displacement under the interaction of adjacent energy piles was conducted, and further analysis of the influencing factors on the displacement of energy pile groups under different design conditions was carried out.

3.1.1.2 Experimental method

Conducting experimental tests to analyze the thermo-mechanical behaviour of energy piles is crucial and serves as validation for theoretical analysis and numerical simulations. Experimental methods for studying the thermo-mechanical response of energy piles mainly include field tests and indoor tests. Field tests involve piles with different loading characteristics, such as friction-type energy piles (Bourne-Webb et al., 2009; Brandl, 2006; Kong et al., 2023), end-bearing energy piles (Murphy & McCartney, 2015), semi-floating energy piles (Laloui et al., 2006), and pile group effects (Bandeira Neto et al., 2023; Mimouni & Laloui, 2015). Indoor tests primarily consist of model tests (Yang et al., 2023a, 2023b) and centrifuge tests (McCartney et al., 2011; Ng et al., 2015). Through tests, it is possible to investigate the effects of temperature on pile shaft resistance, pile bearing capacity, internal stress and strain of the pile body, thermo-mechanical response of the soil around the pile and the effect of pore water pressure, as well as the thermo-mechanical effects and long-term deformation characteristics of the pile body under intermittent and continuous temperature loading (Chang et al., 2023; Faizal et al., 2016a; Goode & McCartney, 2015; Kalantidou et al., 2012; Singh et al., 2015; Stewart & McCartney, 2012; Wang et al., 2015; Yavari et al., 2014).

3.1.1.3 Numerical modelling method

The application of theoretical analysis methods is relatively expedient, but the results of analytical calculations are generally not as rigorous as numerical modelling. Field tests suffer from challenges in implementation, limited consideration of working conditions, and the inherent discreteness of test results, while indoor model tests face discrepancies in materials and scales compared to actual engineering projects. Therefore, when dealing with complex issues, the use of numerical modelling methods is essential. This involves employing the thermo-hydro-mechanical numerical modelling method to analyze coupled heat transfer, mass transfer, deformation, and the resulting material thermo-hydro-mechanical behaviour. This rigorously coupled numerical modelling method may be considered the most accurate approach for addressing phenomena within the scope of energy geostructures, enabling the simulation of various coupling scenarios such as thermo-hydro coupling and thermo-mechanical coupling (Laloui & Rotta Loria, 2020). The finite element method is the most commonly used numerical simulation method by researchers for studying the thermo-hydro-mechanical coupled response of energy piles (Laloui et al., 2006; Rotta Loria et al., 2015; Wang et al., 2014). Many researchers used the COMSOL Multiphysics software for finite element numerical simulations. However, numerical simulations based on the COMSOL Multiphysics software often assume complete contact between the pile and soil, which is overly simplistic. Olgun et al. (2015) and Ozudogru et al. (2015) simulated pile-soil contact by introducing thin layer elements between the pile and soil, considering the influence of the displacement field on pile-soil contact. Simulation studies of a single energy pile can be compared and validated with experimental results. However, for energy pile group foundations, the thermo-mechanical response of the piles under temperature loading is more complex, and due to limitations such as site conditions and test constraints, experiments are challenging to conduct and are primarily studied through numerical simulations (Dupray et al., 2014; Jeong et al., 2014; Salciarini et al., 2015; Suryatriyastuti et al., 2016). Thermo-hydro-mechanical coupled numerical simulation represents the most advanced method in the study of energy geostructures, typically addressing the actual time-dependence involved with the operation of energy geostructures and the three-dimensional characteristics of such problems, serving analytical and design purposes. Any comprehensive analysis or design of energy geostructures should include numerical simulations encompassing energy, structural, and geotechnical aspects (Rotta Loria, 2020).

3.1.2 Thermo-mechanical behaviour of pile body

During the actual operation of energy piles, the alternating heating and cooling cycles induce a cyclic thermo-mechanical response within the pile body (Kalantidou et al., 2012; Yavari et al., 2014). The thermo-mechanical effects of energy piles with different constraint conditions and load characteristics vary significantly. Brandl (2006) conducted field experimental research on frictional energy piles in Bad Schallerbach, Austria. The test results indicate that thermal loading causes changes in stress and strain within the pile body, but the changes are not significant. The thermal loading induces smaller displacements in the pile body compared to external loading. Laloui et al. (2006) further conducted field experimental research on semi-floating energy pile thermo-mechanical effects at the Swiss Federal Institute of Technology in Lausanne (EPFL). The experimental results show that the thermal strain in the pile body exhibits thermal elasticity. Under temperature loading, significant thermal stresses occur within the pile body, especially near the bottom of the pile, with values greater than the internal stresses when only external loading is applied. Stewart and McCartney (2012) conducted centrifuge model tests on end-bearing energy piles in silty soil. The test results show that under thermal loading, the pile body experiences significant compressive strain, with the thermal strain values larger than those under only external loading. Along the depth of the pile body, there are significant variations in thermal strain values. After thermal cycling, residual thermal strain remains within the pile body; however, the displacement changes at the pile top can be neglected after heating. Goode and McCartney (2015) investigated the influence of pile end constraints on the thermo-mechanical effects of energy piles through centrifuge model tests in sandy and silty soil. By altering the distance from the pile base to the model slot base, a comparative analysis of the thermo-mechanical effects of end-bearing piles and end-bearing friction piles was conducted. The test results show that after heating, the thermal stresses in the pile body are greater in silty soil than in sandy soil for end-bearing friction piles. Due to the stiffness constraints at the pile base, the thermal stresses within end-bearing piles are greater than those in end-bearing friction piles. For end-bearing friction piles, there is minimal variation in the position of the zero displacement point. In dry sandy soil, compared to stiffness constraints, the displacement at the pile top of end-bearing piles under load constraints is larger, while the thermal stresses in the pile body near the soil surface are smaller. The model experiment results by Yang et al. (2024c) display that the strain of end bearing pile increases gradually along pile depth, while the strain distribution of friction pile is large at both ends and small in the middle. The end bearing pile has a larger pile tip soil pressure and smaller side friction compared with the friction pile. Chang et al. (2023) established model tests to investigate the thermo-mechanical behaviour of a static drill-rooted energy pile under long-term temperature cycles, finding that it had better heat transfer performance and bearing capacity than the conventional pile. In addition, Nouri et al. (2023) carried out small-scale energy pile tests under inclined mechanical loads and found an irreversible settlement and horizontal displacement of the pile head, which would gradually accumulate over thermal cycles.

In summary, the energy piles will experience thermal stresses that superimpose with the stresses induced by mechanical loads. The magnitude of the thermal stresses and their potential impact on the pile are primarily influenced by the constraint conditions of the pile and the mechanical loads it is subjected to. This necessitates a reevaluation of the design of the energy piles. If the movement of the pile is restricted, the thermal stresses will increase; therefore, the maximum thermal stress of a fully constrained pile can serve as a conservative limit for assessing the thermal stresses in energy piles.

3.1.3 Thermo-mechanical behaviour of soil around pile

Energy piles undergo heat conduction with the surrounding soil, causing changes in soil temperature and subsequently altering the mechanical properties of the soil (Kramer et al., 2015; Lupattelli et al., 2024; Yazdani et al., 2019). For normally consolidated soil, the plastic compression deformation induced by temperature increase is much larger than the thermal elastic expansion deformation of the soil skeleton, resulting in an overall volume reduction. Heating leads to soil consolidation during the process of pore water expulsion, where soil particles are compacted, leading to an increase in shear strength (Di Donna et al., 2016). The thermal expansion effect of highly consolidated soil is more pronounced, with the plastic compression deformation insufficient to counteract the thermal expansion effect, ultimately resulting in volume expansion. The influence of pore water expulsion is minimal, and the increase in temperature leads to a slow dissipation of excess pore water pressure, potentially causing a decrease in shear strength due to heating. Furthermore, different types of soils may exhibit varying mechanical behaviours under temperature loading. For instance, in normally consolidated clay, the volume shrinkage deformation induced by temperature increases with the plasticity index (Abuel-Naga et al., 2007). Under the same temperature loading, sands and clayey soils may exhibit different deformation characteristics, with normally consolidated clay experiencing volume shrinkage when heated, while the volume of sand remains largely unchanged during heating (Demars & Charles, 1982). The variation in pore water pressure experienced by energy piles in saturated normally consolidated clay under cyclic temperature loading is primarily determined by the heating and cooling rates of the clay, as well as its permeability and compressibility (Yazdani et al., 2019). Reducing the ratio of heating and cooling load can effectively alleviate the water loss of unsaturated soil, making the properties of the soil more stable (Zeng et al., 2024).

In summary, the changes in deformation and shear strength of the soil around the energy pile, caused by thermal disturbance, can vary significantly based on the soil's properties and degree of consolidation, sometimes even exhibiting opposite behaviour. Whether the overall thermal deformation of the soil increases or decreases primarily depends on the competing relationship between the thermal compressibility of the soil's pores and the thermal expansion of the soil particle skeleton. Normally consolidated soil tends to experience contraction upon heating, which can lead to increased shear strength, while highly consolidated soil tends to undergo expansion when heated, resulting in decreased shear strength.

3.1.4 Shaft resistance and bearing capacity of piles

The shaft resistance of the pile significantly contributes to the bearing capacity of the pile. As shown in Fig. 18, energy piles can be assumed as rods that undergo linear deformation under thermal loads, with stress divided into thermal stress caused by thermal loads and mechanical stress caused by conventional loads (Amatya et al., 2012). When the temperature of the pile body increases, the pile expands, causing the upper part of the pile to move upward relative to the soil, resulting in downward negative shaft resistance. The lower part of the pile moves downward relative to the soil, leading to upward shaft resistance (see Fig. 18(b)). When the temperature decreases, the pile contracts, causing the upper part to move downward relative to the soil, resulting in upward shaft resistance, while the lower part moves upward relative to the soil, leading to downward shaft resistance (see Fig. 18(d)). The shaft resistances under simultaneous temperature and load for temperature increase and decrease are depicted in Fig. 18(c) and (e), respectively.

Researchers have conducted numerous studies on the shaft resistance and bearing capacity of energy piles. McCartney and Rosenberg (2011) demonstrated through centrifuge model tests that as the temperature rises, the pile expands, leading to enhanced shear strength after soil drainage and strengthening of the shaft resistance. Wang et al. (2015) studied the variation trend of the pile bearing capacity under temperature loading in a sandy soil foundation through field tests, indicating an increase in the ultimate shaft resistance of the pile after heating, which

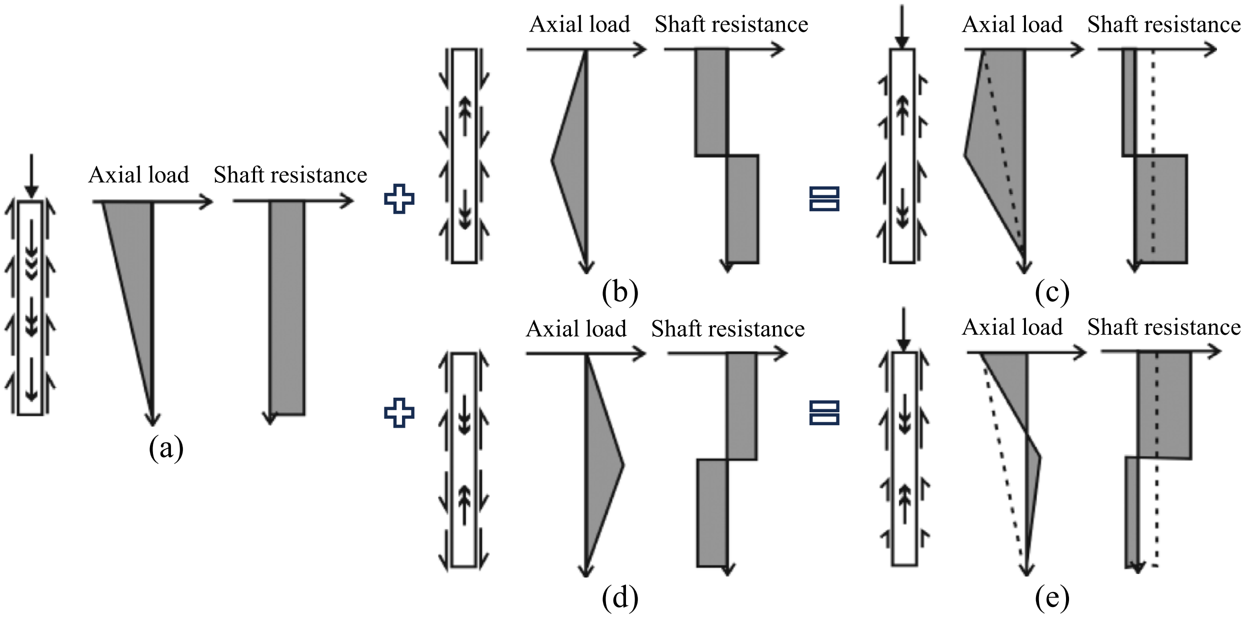


Fig. 18. Thermo-mechanical response mechanism of energy piles (with no end restraint). (a) Load only, (b) heating only, (c) combined load and heating, (d) cooling only, and (e) combined load and cooling (after Amatya et al., 2012; reproduced with permission, courtesy of Elsevier).

mostly returns to its initial value upon natural recovery. Kramer et al. (2015) found that the ultimate bearing capacity of energy piles operated in dry sand conditions increases with pile expansion under heating conditions. However, during cooling, the shaft resistance decreases slightly due to the lateral contraction of the pile, leading to a minor reduction in pile bearing capacity. Goode and McCartney (2015) revealed from centrifuge model test results that after heating the end-bearing friction pile, the ultimate bearing capacity of the pile in dry sand shows minimal changes, while in compacted silty soil, there is a significant increase in the ultimate bearing capacity of the pile. Theoretical studies by Zhou et al. (2024) indicated that increasing temperature will mobilise more friction at both the upper and lower sides of the pile, and will decrease the foundation settlement but increase the load sharing ratio of the piles. The above studies suggest that heating may enhance or not reduce the shaft resistance/bearing capacity of energy piles, while cooling may slightly decrease these values. However, considering the cyclic effect of temperature, some studies indicate a weakening effect on the long-term bearing performance of the pile. Kalantidou et al. (2012) found that after temperature cycling, the curvature of the load-settlement curve of the pile increases, indicating a weakening of the bearing performance of the pile, leading to a decrease in the ultimate bearing capacity and unfavorable long-term bearing performance. Ng et al. (2016) considered the temperature-induced periodic uplift-shrinkage changes in the pile as equivalent to cyclic shear action on the soil around the pile, revealing a gradual attenuation of the pile-soil contact stress with temperature cycling, resulting in a decrease in shaft resistance and continuous weakening of the bearing performance of the pile foundation.

In summary, due to the differing conditions considered, it is not possible to draw a definitive conclusion regarding whether heating can increase or decrease the shaft resistance or bearing capacity of energy piles. Although some studies indicate that thermal expansion of the pile can enhance shaft resistance by displacing the surrounding soil, others suggest that the cyclic effect of temperature may weaken the long-term bearing performance of the pile. Therefore, quantitatively assessing this impact is crucial for the safe operation of energy piles.

3.1.5 Pile group effect

The energy pile group exhibits different structural response characteristics compared to the individual pile. The existence of energy piles and conventional piles in the asymmetric thermally loaded energy pile group will cause the load redistribution between piles, which will affect the serviceability of the energy pile group (Farivar et al., 2023). Therefore, the pile group effect should be fully considered in the design and application (Yin et al., 2022). Mimouni and Laloui (2015) conducted field experimental research on the thermo-mechanical effects of an energy pile group at EPFL. The experimental results indicate that stress redistribution occurs between conventional piles and energy piles due to settlement differences. Compared to heating a single pile, when four piles are heated simultaneously, the displacement at the pile top increases, but the displacement differences between each pile decrease. In stiffer soil layers, radial strain in the pile body may have a significant impact on the axial thermo-mechanical response. During the heat transfer process, pore water pressure in the soil remains largely unchanged. Rotta Loria and Laloui (2016b) and Peng et al. (2018) investigated the influence of the position of energy piles within a pile group. The results suggest that the interaction between energy piles and raft foundations alters the mechanical properties of energy piles, and even non-heated piles are affected. Pile group effect can reduce the heat exchange efficiency of energy piles. When subjected to a constant temperature load, the main reason for the mutual influence between energy piles and conventional piles is the mismatch in deformation between the two. Murphy and McCartney (2015) and Salciarini et al. (2015) conducted research on the long-term bearing capacity of energy pile groups, revealing that the load redistribution effect reaches its peak in the early stage of the thermal conduction process (at which point the temperature difference between the heat exchange piles and conventional piles is maximal), gradually decreasing over time until reaching a steady state. Yang et al. (2024b) carried out experimental and numerical investigations on thermo-mechanical behaviours of an energy pile group under different operational strategies, indicating that raising the start-stop time ratio can lead to the rise of pile deformation degree as the soil temperature cannot recover well. Ding et al. (2024) examined the impact of heating or cooling a single pile within the energy pile group subjected to a horizontal load, showing that the bending moment is significantly larger on a single pile than that of the other piles, with the majority of this variation occurring in its upper part.

In summary, the deformation differences between energy piles and conventional piles within a pile group can lead to a redistribution of loads between the piles, potentially affecting the serviceability of the pile group. The response of the pile group depends on various factors influencing the interactions between the piles, such as pile spacing, the ratio of thermal expansion coefficients of the pile and soil, and pile stiffness. Therefore, determining the optimal position and number of energy piles within the group should be a key objective in engineering design to ensure both heat exchange efficiency and bearing capacity.

3.2 Thermo-mechanical behaviour of energy walls

In recent decades, numerical simulations of thermo-mechanical and thermo-hydro-mechanical coupling have dominated the research on energy walls, with a predominant focus on thermal performance rather than mechanical properties. Mechanical analysis involves thermal stress/strain changes, wall movements, and ground settlements (Barla et al., 2020; Bourne-Webb et al., 2016a; Dai et al., 2022; Sailer et al., 2020; Sterpi et al., 2017; Zhou et al., 2023). There has been limited experimental research on the thermo-mechanical response of energy walls. Dong et al. (2019) conducted indoor model tests on energy underground diaphragm walls, studying the influence of different heat exchange conditions and boundary constraints on the thermo-mechanical behaviour of the wall and the wall-soil interface. Through analysis of temperature, stress, and strain data collected during the experiments, they explored the temperature field during heat exchange, vertical strain within the wall, and variation in normal stress at the interface. Li et al. (2019, 2020) simulated the heat exchange process of underground diaphragm walls in sandy soil using a centrifuge model, investigating the variation in temperature-induced stress and its impact on structural elements. They simulated the heat transfer and temperature rise of underground diaphragm walls in sandy soil under a 50*g* centrifugal acceleration field, monitoring the temperature field in the soil, soil pressure, and the strain of the underground diaphragm wall, ultimately calculating the temperature-induced stress in the wall. Baralis and Barla (2021) carried out field monitoring of the stress and strain of a novel energy wall.

Several key conclusions can be drawn from these studies:

(1) Temperature rise variation can induce significant temperature-induced stress within the wall of energy underground diaphragm walls. The generation of temperature-induced stress is attributed to both the increase in lateral frictional resistance caused by temperature rise (Dong et al., 2019) and the differential deformation resulting from the non-uniform distribution of temperature within the wall (Dong et al., 2019; Li et al., 2020).

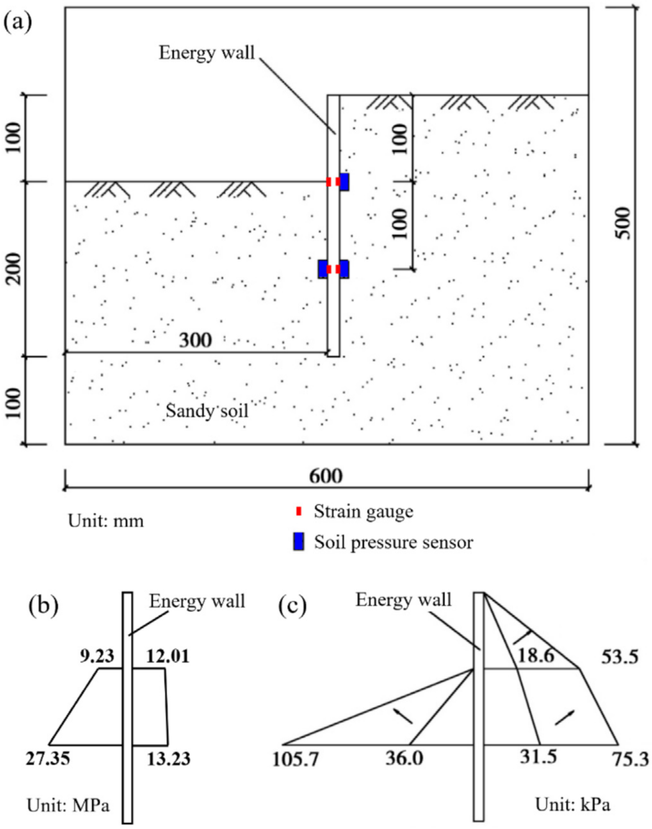


Fig. 19. Centrifugal acceleration model experiment of an energy wall. (a) Experimental model, (b) temperature-induced stress of the energy wall, and (c) temperature-induced soil pressure.

(2) Deeper buried underground diaphragm walls experience greater temperature-induced stress, with the temperature-induced stress on the excavation side increasing significantly along the depth compared to the unexcavated side (Fig. 19(a)). Therefore, in the design of energy underground diaphragm walls and energy underground projects, the influence of burial depth on temperature-induced stress on the wall, especially on the excavation side, should be carefully considered (Li et al., 2020).

(3) As shown in Fig. 19(b), as the temperature rises, the soil pressure significantly increases, and the increment of passive soil pressure is significantly greater than that of active soil pressure. The increment of soil pressure increases along the depth direction (Li et al., 2019).

(4) Bending moment and horizontal displacement at the top of the diaphragm wall increase due to thermal activation. However, stress variations are largely compatible with strength limits (Barla et al., 2020).

(5) In general, thermal effects within energy walls are unlikely to cause severe damage to structural stability. However, specific evaluation of the bending moments related to wall deflection at connections between floor slabs and walls is warranted, as thermal-induced mechanical movements/bending moments may lead to adverse operational issues (such as cracks) that could affect the long-term durability of the structure. Therefore, in the design of energy walls, careful attention should be paid to the selection of thermal functionality and operational modes (Q. Dai et al., 2023).

In summary, the increase in lateral frictional resistance and the differential deformation resulting from the non-uniform distribution of temperature within the energy wall due to heating can induce additional stresses, particularly more pronounced on the excavation side, leading to increased bending moment and horizontal displacement at the top of the energy wall. Generally, thermal effects within energy walls are unlikely to cause severe damage to structural stability. However, it is still essential to conduct a specific evaluation of the bending moments related to wall deflection at connections between floor slabs and walls to prevent the formation of cracks.

3.3 Thermo-mechanical behaviour of energy tunnels

Currently, there is limited research on the thermo-mechanical response of energy tunnels. Barla et al. (2019) realized an experimental real-scale energy tunnel prototype in the tunnel under construction of the Turin Metro Line 1 South Extension. They measured the stresses and strains in the lining caused by the thermal activation, which are of the same order of magnitude as those experienced during normal seasonal temperature changes and can be fully accommodated within the elastic material behaviour. Y. Wang et al. (2025) constructed a scaled-down model with the similarity ratio of 1:5 and the thermal stress of the segment lining was measured. Other researchers conduct research mainly through numerical simulations (Barla & Di Donna, 2018; Gawecka et al., 2021; Insana et al., 2020; Liu & Zhou, 2022, 2023; Liu et al., 2024; Ma & Cheng, 2017; Ma et al., 2022; Nicholson et al., 2014; Rotta Loria, 2021; Rotta Loria et al., 2022; Yang et al., 2014; S. Zhang et al., 2021). Yang et al. (2014) established a finite element analysis model based on the actual size of the Zhadun River Tunnel in Inner Mongolia, China, to calculate the temperatures and stresses induced by heat exchange. The research findings indicate that after system operation, there are noticeable temperature and stress concentrations around the pipes in the concrete, but the impact area is small (Fig. 20). During operation, the concrete tem-

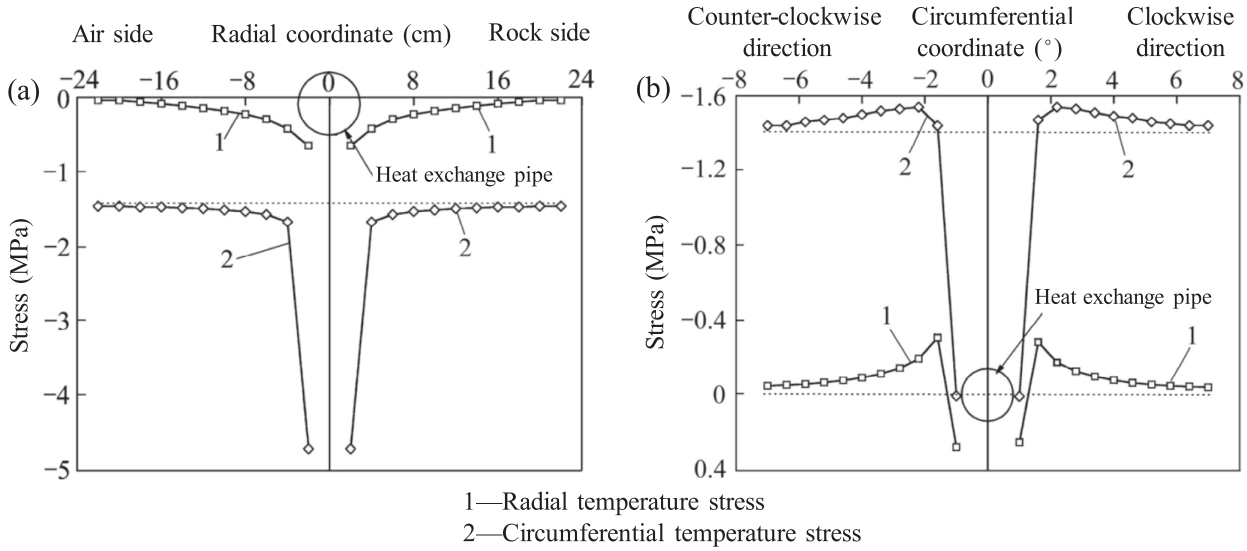


Fig. 20. Temperature stress concentrations around the pipes in the concrete of the energy tunnel. (a) Radial, and (b) circumferential temperature stresses.

perature decreases exponentially with some fluctuation range. Tensile stress dominates the temperature-induced stress, with radial temperature stress being less than tangential temperature stress. The rate of change in radial temperature stress during operation is low, while the rate of change in tangential temperature stress is significant. However, after long-term operation, tangential temperature stress tends to stabilize. Ma and Cheng (2017) analyzed the temperature-induced stress generated during the heat exchange process in energy tunnels using the ABAQUS general finite element software and the Tsinghua Thermo-Soil model finite element program (TTS-FEP). The results show that there are significant variations in tangential stress, and radial stress exhibits noticeable stress concentration at the interface between the lining and surrounding rock. Some studies (Barla & Di Donna, 2018; Insana et al., 2020; Ma et al., 2022; Rotta Loria, 2021) suggested that thermal-induced stress and deformation can be neglected and will not affect the safety of tunnel structures. In addition, some researchers (Gawecka et al., 2021; Liu & Zhou, 2022; Rotta Loria et al., 2022; S. Zhang et al., 2021) investigated thermal-induced ground deformation, which is more critical than tunnel structure deformation.

In summary, the limited existing research on the thermo-mechanical behaviour of energy tunnels tends to suggest that the impact of thermal stress on tunnel structure deformation is small. Instead, issues related to thermal-induced ground deformation are considered more critical than those concerning the tunnel structure deformation.

A comprehensive summary of the key conclusions regarding the thermo-mechanical behaviour of energy piles, energy walls, and energy tunnels is presented in Table 8.

4 Future perspectives

4.1 Aspects that require strengthening in the research

Research on energy geostructure technology has achieved significant results, particularly in the study of energy piles. However, based on the literature review in this paper, in order to further develop and apply this energy-

Table 8
Summary of thermo-mechanical behaviour of energy geostructures.

Energy geostructure	Key conclusions	
Energy pile	Pile body	The energy piles will experience thermal stresses that superimpose with the stresses induced by mechanical loads. The magnitude of the thermal stresses and their potential impact on the pile are primarily influenced by the constraint conditions of the pile and the mechanical loads it is subjected to. This necessitates a reevaluation of the design of the energy piles. If the movement of the pile is restricted, the thermal stresses will increase; therefore, the maximum thermal stress of a fully constrained pile can serve as a conservative limit for assessing the thermal stresses in energy piles.
	Soil around the pile	The changes in deformation and shear strength of the soil around the energy pile, caused by thermal disturbance, can vary significantly based on the soil's properties and degree of consolidation, sometimes even exhibiting opposite behaviour. Whether the overall thermal deformation of the soil increases or decreases primarily depends on the competing relationship between the thermal compressibility of the soil's pores and the thermal expansion of the soil particle skeleton. Normally consolidated soil tends to experience contraction upon heating, which can lead to increased shear strength, while highly consolidated soil tends to undergo expansion when heated, resulting in decreased shear strength.
	Shaft resistance and bearing capacity	Due to the differing conditions considered, it is not possible to draw a definitive conclusion regarding whether heating can increase or decrease the shaft resistance or bearing capacity of energy piles. Although some studies indicate that thermal expansion of the pile can enhance shaft resistance by displacing the surrounding soil, others suggest that the cyclic effect of temperature may weaken the long-term bearing performance of the pile. Therefore, quantitatively assessing this impact is crucial for the safe operation of energy piles.
	Pile group effect	The deformation differences between energy piles and conventional piles within a pile group can lead to a redistribution of loads between the piles, potentially affecting the serviceability of the pile group. The response of the pile group depends on various factors influencing the interactions between the piles, such as pile spacing, the ratio of thermal expansion coefficients of the pile and soil, and pile stiffness. Therefore, determining the optimal position and number of energy piles within the group should be a key objective in engineering design to ensure both heat exchange efficiency and bearing capacity.
Energy wall	The increase in lateral frictional resistance and the differential deformation resulting from the non-uniform distribution of temperature within the energy wall due to heating can induce additional stresses, particularly more pronounced on the excavation side, leading to increased bending moment and horizontal displacement at the top of the energy wall. Generally, thermal effects within energy walls are unlikely to cause severe damage to structural stability. However, it is still essential to conduct a specific evaluation of the bending moments related to wall deflection at connections between floor slabs and walls to prevent the formation of cracks.	
Energy tunnel	The existing research on the thermo-mechanical behaviour of energy tunnels tends to suggest that the impact of thermal stress on tunnel structure deformation is small. Instead, issues related to thermal-induced ground deformation are considered more critical than those concerning the tunnel structure deformation.	

saving and emission-reducing technology, the following aspects about heat transfer and thermo-mechanical behaviour still warrant further research.

4.1.1 Enhance the heat transfer models for energy geostructures

Currently, there are several heat transfer models for energy piles, each with its own applicability and limitations. However, the heat transfer models for energy walls and energy tunnels are more complicated, and there are few relevant analytical models. The heat transfer models of energy geostructures considering the temporal and spatial changes of soil thermal properties, groundwater seepage, and its uncertainty, and concrete structure characteristics are yet to be improved. In addition, current heat transfer models have limitations on the time scale, and effective heat transfer models need to be established to calculate the temperature response on the scale of less than one hour to several decades.

4.1.2 Strengthen the analysis of influencing factors on heat exchange performance of energy geostructures

In addition to considering the conventional design parameters, it is necessary to strengthen the analysis of ground structure, soil particle structure, soil-structure contact state and contact thermal resistance, soil saturation condition, and other factors, so as to fully understand the influences of each factor on the heat exchange performance of energy geostructures. It is necessary to conduct relevant laboratory tests, field monitoring, and theoretical research to explore the interaction between different factors, quantify the impact of each factor, and seek collaborative optimization of different factors.

4.1.3 Deepen the research on the multi-field coupling performance of energy geostructures

Energy geostructure technology involves multiple disciplines such as heat transfer, mechanics, fluid mechanics, and geomechanics, and may also involve chemistry for high-temperature underground engineering. The thermo-hydro-mechanical-chemical (THMC) coupling performance and mechanisms of energy geostructures under complex conditions (such as considering the thermal interference of groundwater flow, characteristics of ground structure, and the change of thermal physical properties, air convection, high-temperature chemical reaction) remain a key focus of research.

4.1.4 Develop multi-field coupling numerical simulation technologies for complex energy geostructure systems

Current numerical simulations often use simplified models, assuming soil as a homogeneous material with thermal properties, pore water density, viscosity, and pressure remaining constant with temperature changes. This approach may lead to errors in the design calculations of energy geostructures. In addition, most of the existing numerical simulations only focus on the underground part, and there is a lack of overall evaluation of the thermal efficiency of the whole system. Therefore, it is necessary to develop multi-field coupling numerical simulation technologies considering the complex energy geostructure system to realize the purpose of simulation and optimal control of the whole system. At the same time, further experimental studies are needed to accurately verify the validity of the numerical models.

4.1.5 Evaluate the long-term operational effects of existing energy geostructures

In the process of long-term thermal cycle operation and long-term unbalanced thermal demand, the changes of soil and structure and the interface between them, and how they affect the system performance, are still lacking in-depth understanding and quantitative evaluation. Due to limited studies on the practical application effects under long-term operation, further advancement and development of energy geostructure technology are hindered. In addition to analyzing economic advantages, a comprehensive long-term evaluation should be conducted from various aspects, including changes in heat transfer characteristics, thermo-mechanical performance, bearing capacity, as well as potential issues such as thermal pollution and biochemical effects on the geological environment, to provide a basis for the improvement of energy geostructure technology.

4.2 New methods for evaluating thermal performance and thermo-mechanical behaviour

Numerical simulation is usually the most commonly used and accurate method for energy geostructure evaluation, but the complex multi-physics field coupling problems make the simulation difficult and time-consuming. On the other hand, analytical solutions usually require some simplifications and assumptions, and have limitations in terms of accuracy and flexibility. Therefore, researchers have explored new effective evaluation methods to save evaluation time and resources.

4.2.1 Machine learning technology

Previous analyses of energy geostructures mainly relied on physical model-based analysis methods. However, in recent years, with the rapid development of artificial intelligence, some researchers have attempted to use machine learning technology to evaluate the thermal performance and thermo-mechanical behaviour of energy geostructures. Machine learning technology was first applied to energy piles by Makasis et al. (2018), who used multiple linear regression to predict the inlet and outlet pipe temperatures under any thermal load and pointed out that this method is effective for any type of energy geostructure. W. Zhang et al. (2023) established a new hybrid deep learning model, namely a convolutional neural network (CNN) and long short-term memory (LSTM) hybrid model (CNN-LSTM), for efficiently and accurately predicting the outlet pipe temperature of energy piles. The CNN layer can extract the spatial features of the dataset, while the LSTM layer can handle the time series features of the dataset. This model still has a good effect on evaluating energy piles affected by groundwater. Pei et al. (2022) provided a high precision and computational efficiency model to predict the long-term thermal-induced displacement development of energy piles by the artificial neural network (ANN). This model also has a high prediction accuracy for group piles. Hu et al. (2023) established a regression tree model for predicting the thermal-induced stress of energy piles based on measured water temperature, pile body temperature, and thermal-induced stress of the previous stage. Y. Chen et al. (2023) compared the coefficient of performance (COP) prediction performance of six algorithms for the energy pile heat pump system. Hu et al. (2024) established a thermal performance support vector regression (SVR) prediction model of an energy wall based on 227 field-measured samples. Cross-validation and prediction results show that the optimized SVR model has good universality and prediction performance. Ma et al. (2024) explored the possibility of applying machine learning technology in the energy tunnel field and used a neural network model to predict the outlet pipe temperature. The mutual verification among different thermal operation modes indicates the applicability and flexibility of this method. Hu and Kong (2024) established five machine learning prediction models for energy tunnel heat flux. These machine learning models can accurately capture the variation trends of heat flux under unknown conditions, among which the random forest model has the best prediction performance, generalization ability, and accuracy. In conclusion, machine learning technology, as an effective prediction and optimization method, reduces the computing time and resources. Compared with the computing time of several hours to several days required by numerical simulation, the total time required by machine learning technology, including training time, is on the order of seconds to minutes (Ma et al., 2024). Therefore, it is reasonable to believe that machine learning technology can promote the development and utilization of energy geostructures and is an advanced method that can reduce the evaluation time.

4.2.2 Simulated annealing algorithm

The heat extraction section design of energy tunnels in cold regions often relies on engineering analogy and lacks convenient and reliable auxiliary methods. To solve this problem, Liu and Han (2023) proposed an optimization design method for the heat extraction section based on numerical simulation and a simulated annealing algorithm. This method can automatically select the position of the tunnel heat extraction section according to the on-site geological and meteorological conditions. Simulated annealing is a metaheuristic global optimization algorithm based on the Metropolis principle. Different from traditional optimization methods based on gradients, it doesn't require derivatives and also avoids being trapped at a local optimum by accepting poor solutions. This method is preferable to other artificial intelligence algorithms for this problem because of its simplicity and clear physical meaning. One of the limitations of this method is its excessive reliance on numerical solutions. However, this can be replaced by in-situ measurement data. As long as there are data such as heat load, heat extraction power, and the initial ground temperature along the tunnel axis, this method can significantly reduce costs and optimize benefits. Overall, this is an intelligent and efficient method for designing the heat extraction section of energy tunnels, and it has the ability to guide practical applications.

4.2.3 Taguchi statistical approach

Recently, Ogunleye et al. (2021) evaluated the thermal efficiency of energy tunnels by combining a numerical method and a Taguchi statistical approach. The Taguchi optimization design method is a trial optimization approach that uses standard orthogonal matrices to form trial matrices and obtain the optimal levels of each parameter with the least number of trials. This method can achieve more accurate analysis results with fewer trials, and can reduce the number of simulations when conducting a large number of influence factor analyses using numerical simulation, thereby saving the evaluation time and resources of energy geostructures.

4.3 New methods and technologies for improving thermal performance

In order to improve the thermal performance of the energy geostructures, in addition to the conventional factors that affect the heat transfer performance as discussed previously, some new methods and technologies have also been explored.

4.3.1 Phase change materials

Phase change materials (PCMs) are substances with high latent heat of fusion, which can melt or solidify at nearly constant temperatures, providing the potential to store and release large amounts of thermal energy. PCMs can be classified into organic, inorganic, and eutectic. Among them, organic PCMs, such as paraffins, fatty acids, and sugar alcohols, are favoured for their high latent heat storage, chemical stability, and low corrosivity (Onaizi et al., 2025). PCMs have been widely applied in the building components, pavements, cold chain logistics, etc. In recent years, to reduce the thermal stress of energy piles and improve their thermal performance, PCMs have been incorporated into energy piles. For example, Cao et al. (2022) carried out the thermal performance analysis and evaluation of PCM backfilled PHC energy pile under building heating and cooling modes. Shahidi et al. (2023)

conducted the experimental investigation on the efficiency of the PCMs for improving the thermal performance of energy piles in sandy soils. Chang et al. (2025) investigated the thermo-mechanical behaviour of steel pipe energy pile groups with and without PCM. The incorporation of PCMs in energy piles holds significant potential for revolutionising thermal management in construction, making them a crucial component in the development of next-generation systems; however, research in this area is still in its infancy (Onaizi et al., 2025).

4.3.2 Steel fiber-reinforced concrete

Good thermal conductivity of concrete is important for efficient operation of energy geostructures. Extensive research has been conducted in recent years to improve the thermal conductivity of concrete. Steel fiber-reinforced concrete has significant advantages over ordinary concrete in terms of crack resistance, toughness, impact resistance, and durability (Cui et al., 2022). Different amounts and types of steel fibers added to concrete can improve its thermal performance in varying degrees. Cui et al. (2022) proposed an approach for improving the thermal performance of subway tunnels by using steel fiber-reinforced concrete segments to obtain shallow geothermal energy. The heat exchange performance is noticeably better than that of the ordinary concrete segment. If designed properly, fiber-reinforced segment lining is a breakthrough technology for efficient geothermal energy use.

4.3.3 Novel energy segment

Politecnico di Torino developed a novel precast energy segment called Enertun (Barla et al., 2019; Barla & Insana, 2023). As shown in Fig. 21, there are three different configurations of the segment, according to the pipes mesh positioning, that is close to the extrados (Ground, Fig. 21 (a)), close to the intrados (Air, Fig. 21(b)) or it can include two circuits, one per each of the previous locations (Ground & Air, Fig. 21(c)). In the first case, the heat exchange with the ground is predominant, while it mainly involves air in the second case. In the third case, heat exchange can occur in both directions. Thanks to an innovative layout of the heat exchange pipes, the Enertun energy segment reduces head losses by 20%–30% in each ring and increases its energy efficiency up to 10%.

4.3.4 Enhanced circulation fluid and heat exchange pipe

Apart from the concrete materials of the energy geostructures, the materials of the heat exchange pipes and the circulating liquid inside them are also potential targets for improving the heat exchange performance. Faizal et al. (2016b) conducted relevant research on energy piles. The results indicate that nanofluids have shown great potential in enhancing the heat exchange performance. By adding extremely low concentrations of nanoparticles (such as multi-walled carbon nanotubes, graphene, alumina, titanium dioxide, silver, aluminium oxide, and copper oxide), the thermal conductivity of the circulating fluid can be enhanced. Therefore, nanofluids can be used as thermal conductive fluids to enhance the thermal conductivity and convective heat transfer coefficient. Highly thermal conductive fillers (such as metallic oxides, graphite, silver-coated polyamide particles, single-walled carbon nanotubes, multi-walled carbon nanotubes, and carbon nanofibers) can also be used to enhance the thermal conductivity of high-density polyethylene (HDPE) material. These enhanced HDPE materials can be used for manufacturing pipes for use in energy piles, which in turn will reduce the total thermal resistance by increasing heat transfer between the primary circuit fluid and the ground.

4.3.5 Two-phase closed thermosyphon

The tunnel lining ground heat exchangers will encounter the issue of a rapid decline in heat exchange rate with time. This is because the huge heat accumulation around the tunnel lining ground heat exchangers obstructs the heat trans-

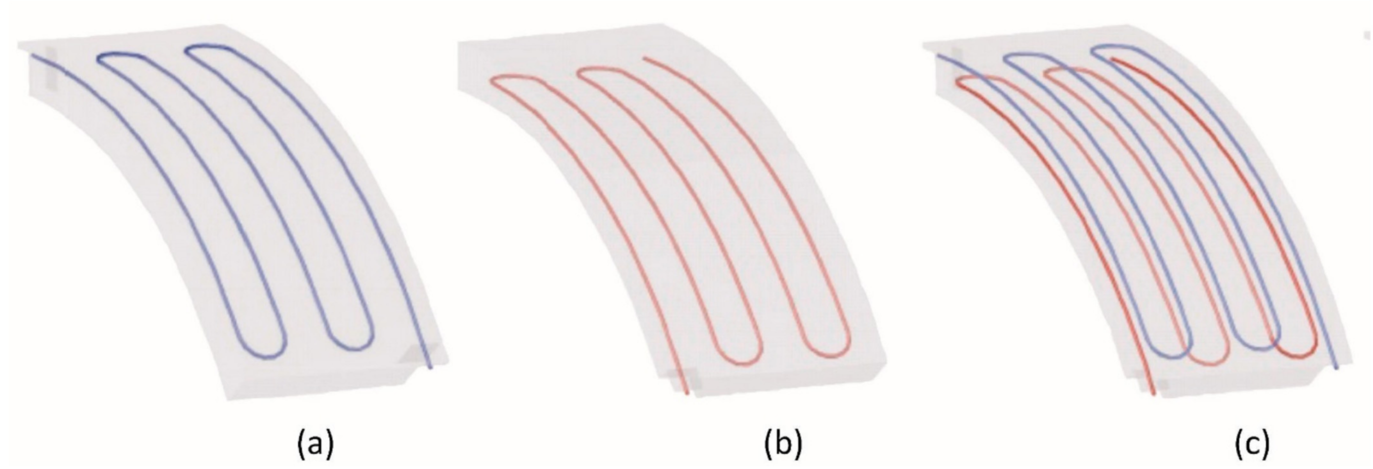


Fig. 21. Possible configurations of the Enertun energy segment. (a) Ground, (b) air, and (c) ground & air (Barla et al., 2019; reproduced with permission, courtesy of Elsevier).

fer between the absorber pipes and the surrounding rock during the heat exchanger operation. Hence, to improve the heat accumulation and enhance the heat exchange rate, the two-phase closed thermosyphon (Li et al., 2023), an efficient device for long-distance heat transfer, was employed in the tunnel lining ground heat exchangers to build a thermally induced channel between the absorber pipes and the surrounding rock, accelerating heat transfer between them. As shown in Fig. 22, heat in absorber pipes could be transferred outside of the heat-resisting ring using two-phase closed thermosyphons, which can greatly enhance the heat injection rate of tunnel lining ground heat exchangers, implying that it is a promising technology.

4.4 New application scenarios

In addition to being used for traditional building heating and cooling, the energy geostructures have also been explored for applications in other scenarios, demonstrating their significant potential for use.

4.4.1 Road anti-freezing and snow melting

During the cold season, the freezing or accumulation of snow on roads may hinder normal driving and even cause traffic accidents. The application of energy geostructures in road anti-freezing and snow melting has also been explored. For example, Islam et al. (2006) introduced the horizontal U-Tube road heating system in the Nanaori-Toge tunnel in Japan (Fig. 23(a)). The horizontal U-Tube was buried 1.2 m deep in the middle of the tunnel, and the extracted geothermal energy was injected into the tunnel entrance to prevent freezing of the road surface. X. Cao et al. (2024) conducted the feasibility evaluation of implementing an energy pile-based snowmelt system on a practical bridge deck in diverse climate conditions across China. As shown in Fig. 23(b), the energy pile-based bridge deck snowmelt system consists of a geothermal heat exchanger pile, a heat pump, a bridge deck water circulation heating system, water pumps, and related control sensors. The study provides valuable insights into the practical application of energy pile-based snowmelt systems in different climate conditions and highlights the critical role of climate considerations in the successful implementation of such innovative technologies.

4.4.2 Anti-freezing of tunnel drainage systems in cold regions

Y. Zhang et al. (2022) proposed a new anti-freezing method for tunnel drainage system based on ground heat exchangers to remove the cumulative freezing effect and solve frost damage problems of tunnels in cold regions. As shown in Fig. 24, the system extracts the renewable thermal energy deep in the surrounding rock that has a certain distance from the tunnel entrance. The surrounding rock is used as a heat source to heat the tunnel drainage system in the entrance section after being raised to a high-quality heat source by the heat pump. This research is a preliminary attempt. Further studies are needed to improve the theoretical and applied aspects of ground heat exchangers in tunnel drainage systems.

4.4.3 High-temperature tunnel cooling

An increasing number of tunnels pass through the anomaly geothermal zones and inevitably encounter thermal engineering geological problems during tunnel operation. Y. Zhang et al. (2023) proposed an efficient and energy-saving cooling system composed of borehole heat

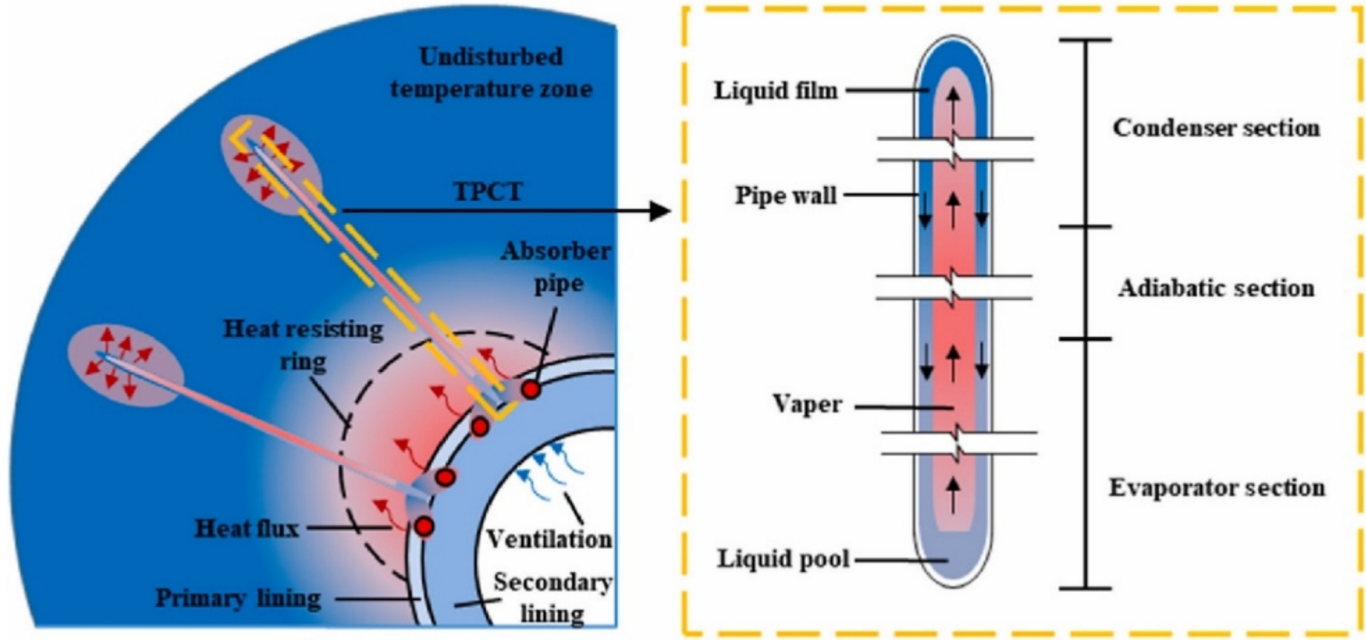


Fig. 22. Heat transfer schematic of tunnel lining ground heat exchangers with two-phase closed thermosyphons for building cooling (Li et al., 2023; reproduced with permission, courtesy of Elsevier).

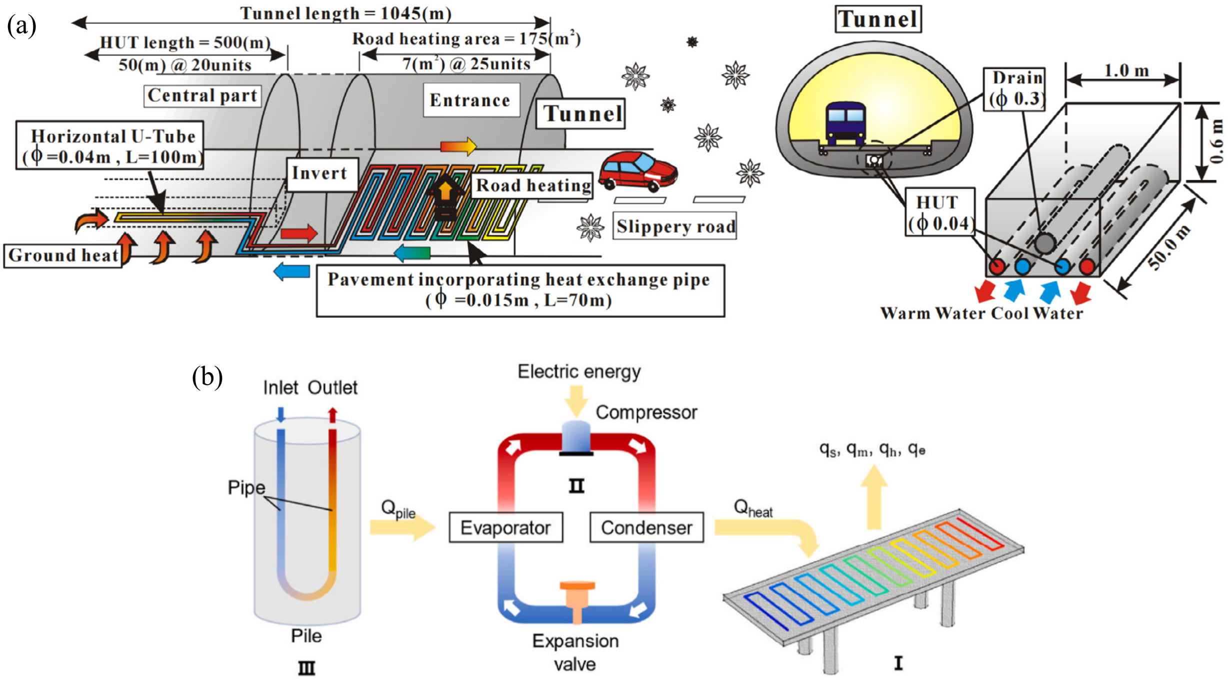


Fig. 23. (a) Schematic of horizontal U-Tube road heating system in the Nanaori-Toge tunnel in Japan (Islam et al., 2006), and (b) schematic of energy exchange between energy pile, heat pump, and bridge deck heating system (X. Cao et al., 2024; reproduced with permission, courtesy of Elsevier).

exchangers and a thermal insulation layer in a high geotemperature tunnel. As shown in Fig. 25, boreholes are radially arranged in the surrounding rock and buried at depths of around 10–50 m. The heat exchange pipes are installed in the tunnel boreholes and surrounded by backfill materials. The inlet and outlet of each heat exchange pipe are connected to the annular main pipe near the inner wall of the tunnel, where cold water is circulated, and heat is exchanged with the surrounding rock with high geotemperature. The heat is then taken away to avoid heat transfer to the tunnel environment. In addition, the thermal insulation layer is placed on the surface of the secondary lining to prevent the high temperature of the surrounding rock from diffusing into the tunnel air. The research results show that the cooling effect of the cooling system in the high-geotemperature tunnels is proved to be remarkable in comparison with the tunnel having a thermal insulation layer.

Cao et al. (2023) and Z. Cao et al. (2024) proposed a novel cold energy storage method for phase change plates (PCPs) based on tunnel lining ground heat exchangers to cool high-temperature tunnels. The continuous cold energy charging operation of PCPs within the tunnel is illustrated in Fig. 26. In actual application, different groups of PCPs can be placed inside the tunnel chamber to conduct the cold energy charging operation. The cold energy source of PCPs comes from the surrounding rock at the low geotemperature area of the tunnel. The low-geotemperature geothermal energy can be extracted from the surrounding rock by utilizing tunnel lining ground heat exchangers and stored in the PCPs. Then, PCPs can be transported to the designated locations to cool the high ambient temperature within the tunnel. Combining tunnel lining ground heat exchangers and PCPs to extract and store the geothermal energy is an environment-friendly energy utilization method.

4.4.4 Improvement of the thermal environment in subway tunnels

With the operation of the subway system, heat accumulation may occur around the tunnels. Recently, the authors have proposed a new idea to improve the thermal environment of subway tunnels by using the energy tunnel technology. As shown in Fig. 27, in the cold season, the segment heat exchanger is used to actively extract heat from the ground around the tunnel and store it for cooling. The geothermal energy of the ground is extracted and enhanced by a heat pump, which is then used for heating or providing hot water for nearby buildings. At the same time, the low-temperature heat from the buildings is injected into the ground, causing the ground temperature to be lower than the original temperature, equivalent to storing cold energy in the ground. Then, the operation of the segment heat exchanger is stopped. Owing to the delayed ground heat dissipation, a portion of the stored cold energy is retained even during hot seasons, resulting in a reduction in the ground temperature around the tunnel compared

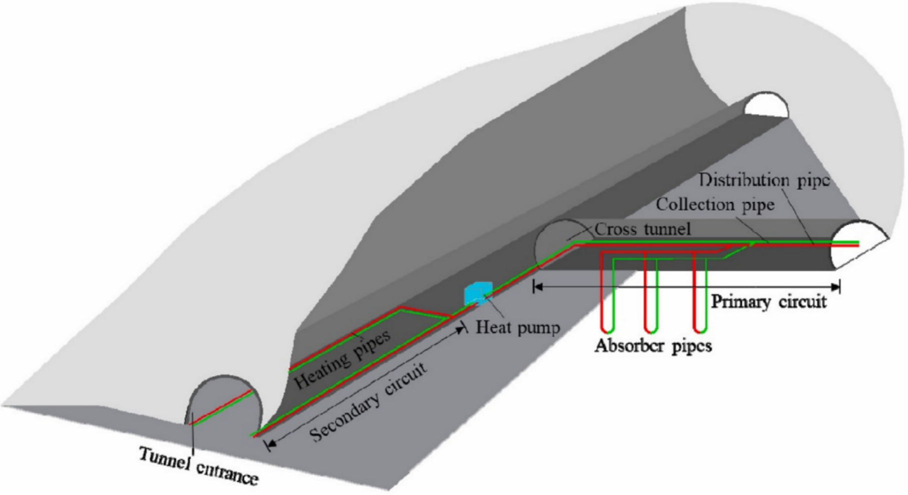


Fig. 24. Schematic of tunnel drainage system based on ground heat exchangers (Y. Zhang et al., 2022).

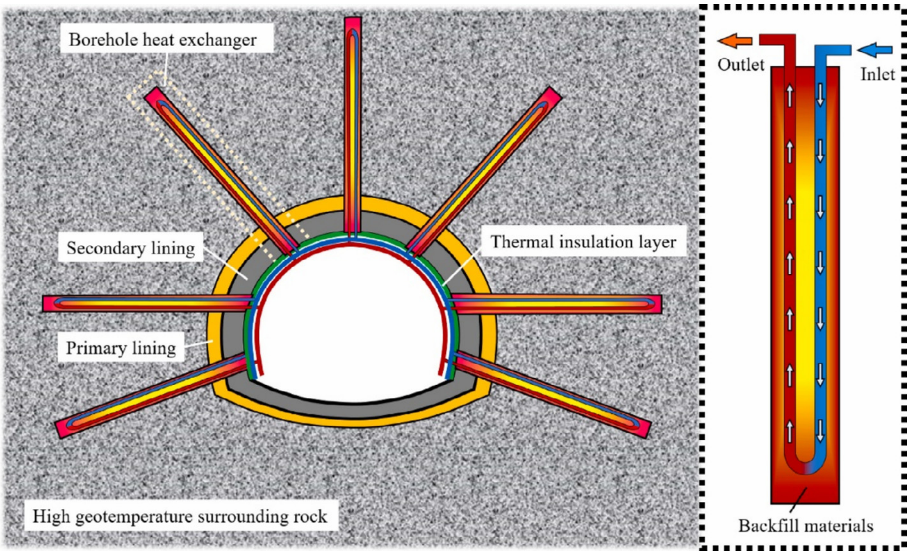


Fig. 25. Schematic of a novel cooling system for high geotemperature tunnels (Y. Zhang et al., 2023).

to the situation without cold storage, thereby improving the ground thermal accumulation. Additionally, the cold energy stored in the ground can help absorb a portion of the high-temperature heat generated within the tunnel. This method is based on the concept of cross-seasonal heat storage and utilization of underground rock and soil bodies. It provides a new solution for the thermal environment control of subway tunnels in summer. Compared with traditional air conditioning and ventilation environmental control systems, it can significantly reduce the energy consumption of environmental control, thus having great application potential.

4.4.5 Thermal activation retrofitting of existing underground structures

Since the heat exchange pipes need to be installed inside the structure, the previous energy geostructures were all applied to new construction projects. However, in recent years, attempts have been made for thermal activation retrofitting of existing underground structures. For example, Baralis and Barla (2021) proposed a novel energy wall system to overcome the limitations of conventional geothermal applications in urban areas. The system is characterized by ease of installation, low initial costs, and applicability to existing buildings undergoing energy retrofitting. De Feudis et al. (2024) proposed some approaches of tunnel thermal activation retrofitting, including the extrados energy mats (Fig. 28(a)), intrados energy mats (Fig. 28(b)), and radial borehole heat exchangers (Fig. 28 (c)). These approaches fit various existing tunnel decay contexts and diverse levels of refurbishment necessity. The thermal activation retrofitting of existing tunnels during rehabilitation would allow their thermal activation during interventions involving the partial or integral demolition and subsequent reconstruction of the vault. In such circumstances, the extrados energy mats are applica-

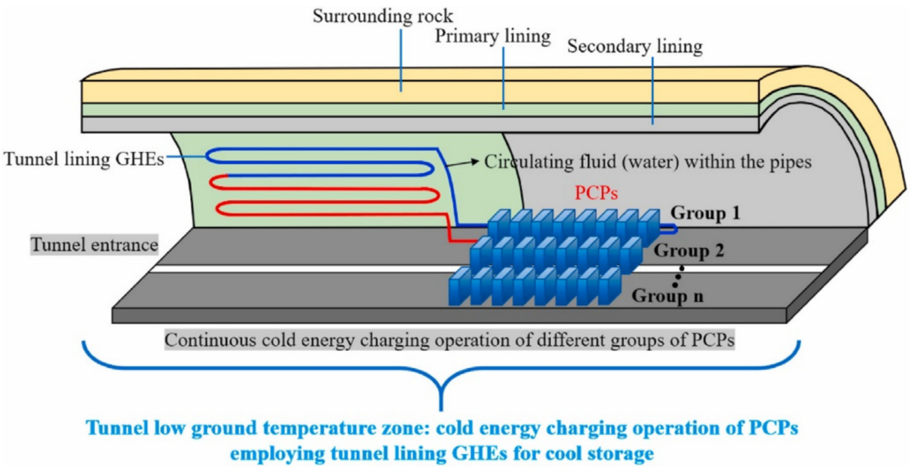


Fig. 26. Schematic of continuous cold energy charging operation of PCPs employing tunnel lining ground heat exchangers for cool storage (Z. Cao et al., 2024; reproduced with permission, courtesy of Elsevier).

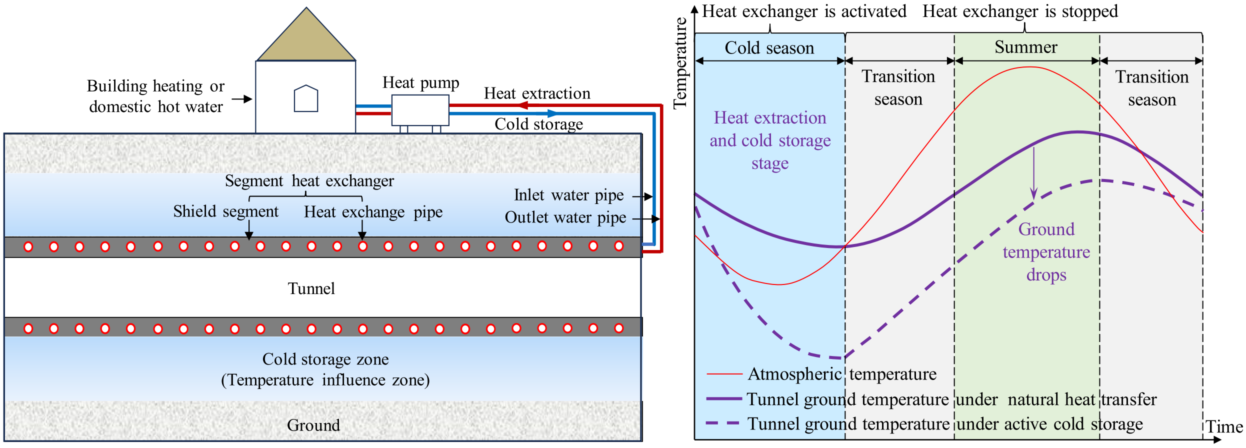


Fig. 27. Schematic of thermal environment improvement in subway tunnels by energy tunnel technology.

ble. For thermal activation retrofitting of existing tunnels after repurposing or during serviceability, the intrados energy mats and radial borehole heat exchangers are applicable. The thermal activation retrofitting of existing underground structures is an innovative method for energy utilization, significantly expanding the application scenarios of energy geostructures. Especially for tunnels, due to long-term operation, the lining structure may need renovation due to diseases, providing an opportunity for thermal activation retrofitting, which has great prospects.

4.5 Future development trends

Since developing renewable energy sources is an inevitable trend for global sustainable energy utilization, the development potential of energy geostructures is enormous, and related research and projects are constantly increasing. Combining the energy geostructures with other renewable energy utilization methods (such as solar energy, wind energy, and deep geothermal energy) can further reduce carbon emissions. Therefore, it is reasonable to believe that the comprehensive utilization of different forms of renewable energy sources is an important development direction in the future. Some researchers have already begun to explore this aspect. For example, Ma et al. (2023) proposed and designed a ground source heat pump system based on energy piles and combined with seasonal solar energy storage to meet the heating and cooling demands of high-rise buildings. Zhang et al. (2025) proposed a solar seasonal thermal storage heating system in a cold-region tunnel based on ground heat exchangers, which was applied in Tianshan Shengli Tunnel in Xinjiang, China. The employment of underground structures and infrastructures as thermal energy storage means appears promising to establish resilient and sustainable energy systems that can serve urban areas from the building to the district scales (Rotta Loria, 2021). The incorporation of energy geostructures in fifth generation district heating and cooling networks (Fig. 29) can enhance the sustainability, flexibility, and resilience of the network (Meibodi & Loveridge, 2022). There is the potential to exploit a greater share of cost-effective geothermal energy, and the ability to act as both thermal energy sources and stores for efficiently supplying both heating and cooling demands. However,

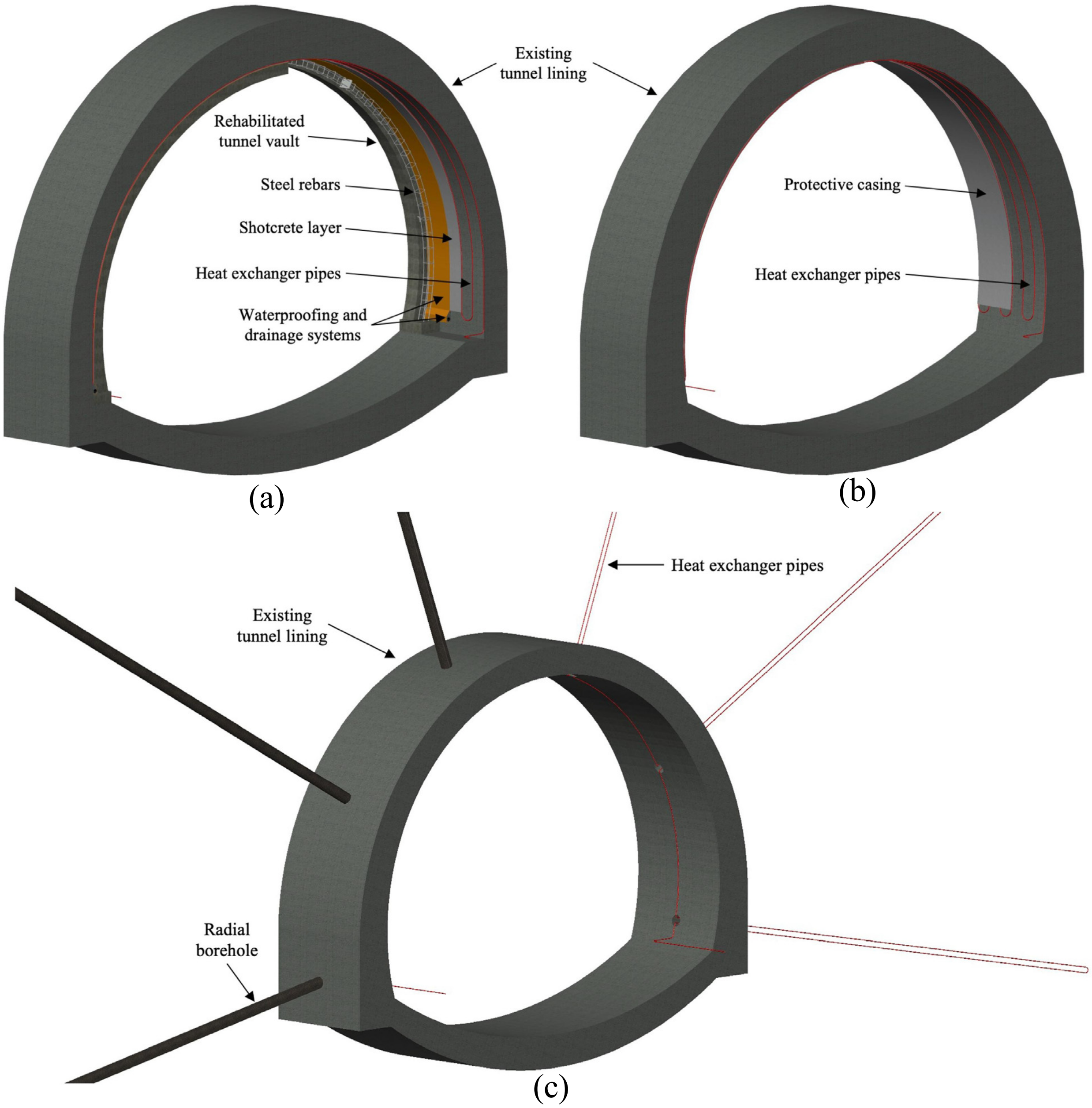


Fig. 28. Schematic of (a) an extrados energy mat applied to a partial rehabilitation of a tunnel vault, (b) an intrados energy mat, and (c) radial borehole heat exchangers (De Feudis et al., 2024; reproduced with permission, courtesy of Elsevier).

since the development of fifth generation thermal networks and energy geostructures, particularly energy walls and energy tunnels, is still in its infancy, further research is required to assess the magnitude of the opportunities and quantify the advantages of integrating energy geostructures into the fifth generation district heating and cooling networks (Meibodi & Loveridge, 2022).

5 Conclusions

Detailed summaries of heat transfer models, factors influencing heat exchange performance, and thermo-mechanical behaviour of energy geostructures are presented in Tables 2–8. The following are some key conclusions regarding these aspects and future perspectives.

5.1 Energy pile aspects

Four types consisting of ten basic heat transfer models for energy piles were summarized. Infinite heat source models are only suitable for energy piles with a large length-to-diameter ratio. The finite line heat source model and the hollow cylinder heat source model ignore the influence of pile size and heat capacity, respectively, which will cause some errors in the short-term temperature and the temperature near the pile. The solid cylinder heat source

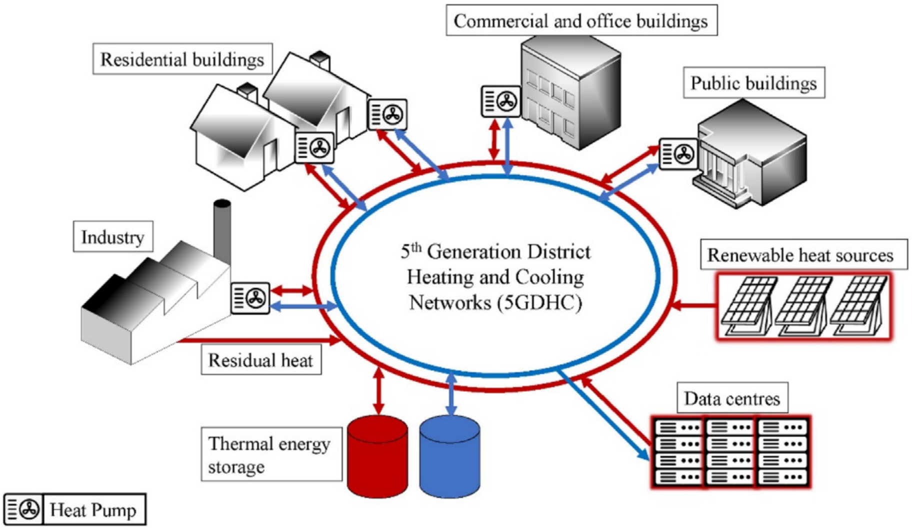


Fig. 29. Schematic of a typical fifth generation district heating and cooling network (Meibodi & Loveridge, 2022).

model is more appropriate for energy piles, while for energy piles with spiral pipe configurations, more accurate ring heat source and spiral heat source models should be employed to inform the optimization of parameters such as spiral pitch.

Overall, the heat exchange performance increases in the following order of pipe configurations: single U-shaped, double U-shaped, W-shaped, triple U-shaped, and spiral. The heat exchange performance increases as the length-to-diameter ratio increases; however, it tends to become saturated once the ratio exceeds a certain value. The fluid flow rate should not be too high or too low, and it is generally considered sufficient to ensure that the flow state is turbulent. The intermittent operation mode can improve the heat exchange compared with the continuous operation mode, as the former allows for a certain degree of recovery of geothermy.

The magnitude of the thermal stresses and their potential impact on the pile are primarily influenced by the constraint conditions of the pile and the mechanical loads it is subjected to. The changes in deformation and shear strength of the soil around the energy pile, caused by thermal disturbance, can vary significantly based on the soil's properties and degree of consolidation, sometimes even exhibiting opposite behaviour. Due to the differing conditions considered, it is not possible to draw a definitive conclusion regarding whether heating can increase or decrease the shaft resistance or bearing capacity of energy piles. The deformation differences between energy piles and conventional piles within a pile group can lead to a redistribution of loads between the piles, potentially affecting the serviceability of the pile group.

5.2 Energy wall aspects

The heat transfer model for underground diaphragm walls established by the team of the authors can solve complex medium heat conduction problems with internal heat sources that vary with time and non-homogeneous boundary conditions. It can be used for analyzing the temperature field within the diaphragm wall and surrounding soil, as well as for optimizing the parameters such as the buried pipe configuration, pipe spacing, and intermittent operation times.

The heat exchange per unit length of pipe significantly increases with increasing pipe spacing, but the increase rate gradually diminishes. Increasing the circulating water flow rate can enhance heat exchange efficiency, but once a certain flow rate is reached, the rate of increase in heat exchange becomes very slow. The heat exchange per unit length of pipe increases to a certain extent with the increase in the width of the diaphragm wall. The intermittent operation mode can improve the heat exchange compared with the continuous operation mode.

The increase in lateral frictional resistance and the differential deformation resulting from the non-uniform distribution of temperature within the energy wall due to heating can induce additional stresses, particularly more pronounced on the excavation side, leading to increased bending moment and horizontal displacement at the top of the energy wall. Generally, thermal effects within energy walls are unlikely to cause severe damage to structural stability. However, it is still essential to conduct a specific evaluation of the bending moments related to wall deflection at connections between floor slabs and walls to prevent the formation of cracks.

5.3 Energy tunnel aspects

Compared to energy piles and walls, energy tunnels have a larger heat exchange area with the ground; however, their relatively complex structure makes the development of heat transfer models more challenging. The team of the authors established a heat transfer model for energy tunnels in cold regions, considering both composite medium and time-dependent boundary conditions. However, only the case of the heat exchange pipe being arranged along the tunnel axis is considered.

As the fluid flow rate increases, the heat exchange increases. Increasing ventilation and convective heat transfer coefficients can enhance the heat exchange capacity. Groundwater flow can effectively increase heat extraction and dissipation. The thermal performance is significantly enhanced when the direction of groundwater flow changes from 0° (tunnel axial direction) to 45°. The intermittent operation mode can improve the heat exchange compared with the continuous operation mode.

The existing research on the thermo-mechanical behaviour of energy tunnels tends to suggest that the impact of thermal stress on tunnel structure deformation is small. Instead, issues related to thermal-induced ground deformation are considered more critical than those concerning the tunnel structure deformation.

5.4 Future perspective aspects

The following aspects require strengthening in the future research on heat transfer and thermo-mechanical behaviour: (1) refinement of heat transfer models; (2) strengthening the analysis of factors influencing heat exchange performance; (3) deepening the understanding of the mechanisms governing multi-field coupling performance; (4) development of multi-field coupled numerical modelling technologies for complex energy geostructure systems; (5) evaluation of the long-term operational effects of existing energy geostructure projects.

New effective evaluation methods of energy geostructures can be further explored to save evaluation time and resources, such as machine learning technology, simulated annealing algorithm, and Taguchi statistical approach. Among them, machine learning technology has received particular attention due to the rapid development of artificial intelligence. It is reasonable to believe that machine learning technology can promote the development and utilization of energy geostructures and is an advanced method that can reduce the evaluation time.

New methods and technologies for improving the thermal performance of energy geostructures can be explored, such as the application of PCMs, steel fiber-reinforced concrete, Enertun energy segment, enhanced circulation fluid, heat exchange pipe, and two-phase closed thermosyphon. Among them, PCMs and fiber-reinforced concrete are applicable to all three types of energy geostructures. The incorporation of PCMs in energy geostructures holds significant potential for revolutionizing thermal management in construction, making them a crucial component in the development of next-generation systems. If designed properly, the application of fiber-reinforced concrete to the energy geostructures is a breakthrough technology for efficient geothermal energy use.

In addition to being used for traditional building heating and cooling, the energy geostructures have also been explored for applications in other scenarios, demonstrating their significant potential for use. The new application scenarios include road anti-freezing and snow melting, anti-freezing of tunnel drainage systems in cold regions, high-temperature tunnel cooling, improvement of the thermal environment in subway tunnels, thermal activation retrofitting of existing underground structures, etc.

Combining the energy geostructures with other possible renewable energy utilization methods (such as solar energy, wind energy, and deep geothermal energy) is an important development direction in the future. The employment of underground structures and infrastructures as thermal energy storage means appears promising to establish resilient and sustainable energy systems that can serve urban areas from the building to the district scales. The incorporation of energy geostructures in fifth generation district heating and cooling networks can enhance the sustainability, flexibility, and resilience of the network.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Duofeng Cen: Writing – original draft, Visualization, Methodology. **Caichu Xia:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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