

## Review Article

# A New Environmentally Friendly Utilization of Energy Piles into Geotechnical Engineering in Northern China

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In the past 30 years, because of built-in advantages, energy saving, pollution control, and sustainability, the energy pile system has had a rapid development around the world. Many scholars did numerous researches on the parameters' optimization, heat exchange efficiency, and structure-soil response. Also, the researches of evolutional GSHP system using high temperature in deep mine and lager collection surface of tunnel lining were learned. At present, most of researchers are discussing the geothermal collection for the heating or cooling the building, and plenteous and significant research achievements have been obtained. It is a novel attempt to apply energy pile to geotechnical engineering, and good results have been achieved in engineering practice in Northern China. The area of northern China is a typical seasonal frozen region: the high temperature in summer and the cold weather and accumulated snow in winter will result in huge challenge and resource consumption of maintainance on highway tunnel, pavement, and other geotechnical engineering facilities. In this paper, taking example of using the geothermal heat exchanger to melt snow, the novel idea of using energy piles to prevent track in summer and crack in winter of pavement, and guaranteeing the safety of frost crack on tunnel lining were discussed. Also, through simulation research, we propose a buried pipe form with good heat transfer uniformity-spiral buried pipe, which has better engineering applicability. This shows us that the application of energy pile in geotechnical engineering will provide solutions to geotechnical problems, which will have a brilliant future.

## 1. Introduction

In the background of the global energy crisis, energy pile is a form of green and sustainable energy utilization, or one of the solutions to energy problems. At present, a large number of scholars have conducted scientific research on energy piles and formed a large number of research results.

*1.1. The Development of Energy Pile.* At present, the coal, petroleum, natural gas, and other nonrenewable energy forms are consumed rapidly, and energy crisis has become a worldwide problem. Due to the more unreasonable energy structure, this problem is more serious in China. Meanwhile, in order to realize the social sustainable development, harmonious development between the energy exploitation and environmental protection and ecological balance are

required. So far, the clean energy system and energy-saving system are becoming the direction of the world's energy development strategy. And as everyone knows, comparing with the air temperature, the soil temperature is more stable the whole year, and the changing of soil temperature with depth in Beijing area is shown in Figure 1. As it can be seen, when the soil temperature is within 6 m, the monthly temperature dispersion of soil is very large. When the soil depth exceeds 6 m, the monthly temperature of the soil tends to be close to 18°C. In the 1980s, considering the stable temperature characteristic of soil, geotechnical engineers in Austria and Switzerland creatively utilized building foundations (concrete pile [1], CFG pile [2], and underground diaphragm [3–5]) placed by the heat exchanger, to process the heat exchange between fundamental components and its host soil. This new geotechnical structure, which can achieve the function of heat complementation between summer and

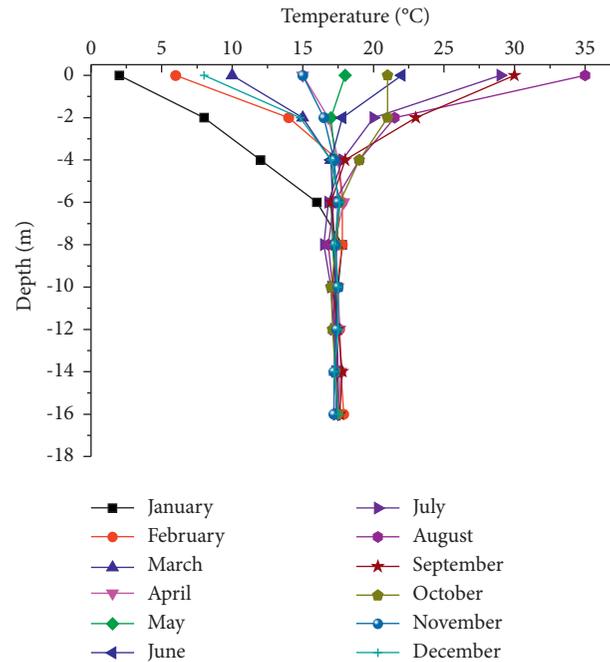


FIGURE 1: Change rule of soil temperature along with the depth.

winter, is the energy pile system. It is due to the preferable heat conduction properties of concrete and larger heat exchange surface of foundation structure that the energy pile has the better heat exchange efficiency than the traditional geothermal heat exchanger. Research results showed that the energy pile system could save more than 30% energy than air conditioning system. Meanwhile, the heat exchanger pipe is surrounded closely by pile foundation, the stability and durability could be guaranteed, and the cost of energy pile is also much lower than the traditional geothermal heat exchange system. Because of the built-in advantages, the energy pile system has achieved fast development around the world.

*1.2. Research Status of Energy Pile System.* In the interest of improving the heat exchange efficiency, many scholars did numerous researches on the parameters' optimization. Bozis et al. evaluated the effects of design parameters on the heat transfer efficiency and developed a methodology for comparative estimation of design alternatives of cast-in-place of energy piles [6]. Bandos et al. presented a finite cylinder-source model for simulating the energy pile heat exchangers and studied the effects of thermal storage and vertical temperature variations [7]. Moon and Choi contrastively analyzed the heating performance characteristics of the ground-source heat pump system with energy piles and energy slabs [8]. In addition, there are also many other scholars who did the parameters' optimization to improve the heat exchange efficiency [9–12]. Meanwhile, a number of scholars have already did research on the thermal performance of different coil types, and the research achievements were listed in Table 1.

As shown in Table 1, the latest studies show that spiral coil with the largest heat exchange surface of the fluid tube is the optimal type of heat exchanger cast-in-place energy pile. For the thermal efficiency analysis results, the spiral coils type has the best heating and cooling performance, accounting for near 150% thermal efficiency compared to double U type [25].

Usually, concrete energy pile systems are comprised of exchange fluid, metal pipe, concrete, and host soil, and the structural diagram is exhibited in Figure 2 [27]. It is easy to know that the thermal parameters of heat exchange medium (mainly concrete and soil) would be the important impact factor of thermal efficiency. So, many scholars begin to research the backfill material with high thermal parameters for replacing the soils with lower thermal parameters. Delaleux et al. adopted the bentonite-graphite composites as the backfill material to enhance the geothermal borehole heat exchangers performances [28]. Coccia et al. considered municipal solid waste landfills as a potential source of heat for GSHP (Ground-Source Heat Pumps) [29]. Indacoechea-Vega et al. analyzed the different behaviors of different grouting materials (bentonite-based grouts and cement-based grouts) for GSHP, by contrastively proceeding the thermal conductivity, water/solid ratios, permeability, mechanical strength, and other tests [30]. Ocloń et al. simulated the heat dissipation processes in underground power cable system situated in thermal backfill and buried in a multi-layered soil [31]. Li et al. researched the heat transfer performance of the U-tube heat exchangers with different backfill materials (shape-stabilized phase change materials and crushed stone concrete) [32]. To achieve improvement of the heat exchange efficiency, scholars have discussed the parameters' optimization, types of heat exchangers cast-in-place energy piles, and the backfill material with high

TABLE 1: Research achievements on different types of heat exchangers cast-in-place energy piles.

Reference	U-shaped	Double U-shaped	Triple U-shaped	W-shaped	Double W-shaped	Spiral type
Park et al. [13]						★
Zarrella et al. [14]			▼			★
Go et al. [15]						★
Zhang et al. [16]						★
Xiang et al. [17]						★
Go et al. [18]						★
Lee et al. [19]						★
Yoon et al. [20]				◆		★
Wang et al. [21]						★
Wang et al. [22]						★
Park et al. [23]						★
Zhao et al. [24]	■			◆		★
Luo et al. [25]		▲	▼		●	★
Zarrella et al. [26]	■					★

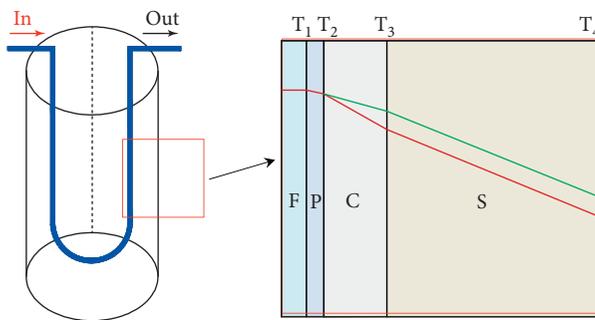


FIGURE 2: Energy pile with U tube and its heat transfer medium diagram.

thermal parameters. A series of mature and applicable achievements were obtained.

For the energy pile, it is not only a heat-exchanging system, but also a foundation structure, so it should meet the double requirement of heat exchanging and supporting. The research on different mechanical property of pile under the cyclic action of cooling and heating is necessary. Suryatriyastuti et al. studied the the temperature-induced mechanical behavior of energy pile foundations [33]. Park et al. evaluated the thermal response and performance of precast-high strength concrete energy pile by taking results of field experiments and numerical simulation [34]. Besides, there are also abundant researches on structural response between pile and soil [35–44]. For the group of energy piles, scholars and professionals in many countries also did the corresponding research on the multiple interaction [45–47] and mechanical response [48–51]. By studying the above references, plenteous and significant achievements on the research of energy pile system were realized, and it has been widely used in green energy-saving buildings in China, European countries, Canada, Japan, and other countries.

## 2. Evolutional GSHP System Use with Geotechnical Engineering Structure

*2.1. Geothermal Heat Extraction from Mines.* With the development of mining depth, the high temperature problem is

becoming more and more serious. In China, the temperature in working faces at more than 700 m mining depth are mostly larger than 35°C, the highest temperature is near 50°C, and the typical rock temperatures of deep mine are listed in Table 2.

It is easy to know that the working environment under high temperature not only has an effect on the mechanical property of host rock but also inflicts harm to the body health of worker. The high temperature environment would reduce their ability of attention and reaction; sometimes, these effects may lead to real accidents. According to the surveyed data by the former Soviet Union and Germany, the labor productivity will decline by 6%~8% when the working temperature is 1°C out of limit [52]. Based on the surveyed data of 7 mines in Hokkaido, Japan, the results show that the accident rate at working face under 37°C is 2.13 times that under 30°C [53]. So it is very important to research the technique of high temperature control and cooling. And many scholars have done some research on how to cool deep mine heat. He et al. adopted a high temperature exchange machinery system (HEMS) to cool the high temperature and control heat hazard in deep coal mines [54]. Plessis et al. analyzed the variable speed drives for cost-effective energy savings in South African mine cooling systems and found that an annual cost saving of USD 6,938,148 and CO<sub>2</sub> emissions reduction of 132 M ton are possible [55], and they further researched the development and integrated simulation of a variable water flow energy-saving strategy for deep mine cooling systems at 2015 [56]. Apel et al. simulated the effects of thermal insulating shotcrete on the energy consumption of ventilation and cooling systems at deep underground mines [57]. Chen et al. proposed a split-type vapor compression refrigerator for heat hazard control in deep mines [58]. With the developing and improving of the studying about heat hazard in deep mines, some people have realized that the high temperature is also an energy source and also can be utilized. Guo et al. used the HEMS technique to control the heat harm in Jiahe coal mine (Hunan province, China) and extracted the deep geothermal energy to replace the ground fired boiler for heating [59]. Ghoreishi-Madiseh and Abbasy did the numerical and experimental study of geothermal heat extraction from backfilled mine

TABLE 2: Rock temperatures of deep mine in Northern China.

Mines	Geographical location	Measuring depth (m)	Rock temperature (°C)
Dataigou iron mine	Liaoning province	1250	41.4~43.0
Linglong Gold mine	Shandong province	1095	42.0~44.0
Lingnan Gold mine	Shandong province	975	40.0
Xiadian Gold mine	Shandong province	850	35.2
Sanshandao Gold mine	Shandong province	825	38.5
Xincheng Gold mine	Shandong province	760	37.0~38.0

stopes [60]. Furthermore, Ramos et al. discussed the feasibility of using abandoned mines for geothermal heat recovery [61]. Guo et al. present a geothermal recycling system for parallel mine, where the collected heat can be used to supply heat for buildings and domestic hot water [62]. The schematic diagram of geothermal heat extraction from mines is shown in Figure 3. Driven by the circulation system, the heat exchange fluid circulates inside the mine, fully contacts the surrounding high temperature rock and soil, and extracts the heat for ground buildings.

### 2.2. Geothermal Heat Collection from Tunnel (Energy Tunnel).

To extract the heat from mine is utilization of deeper geothermal resource, and for the shallow geothermal resource utilization, the researchers have noticed the tunnel. Mimouni and Laloui estimated the geothermal potential of heat exchanger anchors on a cut-and-cover tunnel, and the numerical simulation results showed that the extractable heat from the ground through the anchors ranges from 0.4 to 0.8 GWh per year and per kilometer of tunnel [63]. Barla et al. discussed the application of energy tunnels to an urban environment and investigated the possibility of thermal activation of a new section underground construction of the Metro Torino line 1 (Italy) to heat and cool adjacent buildings [64]. Lee et al. introduced development of energy textile to use geothermal energy in tunnels and conducted a test bed of six pilot energy textile modules with various configurations in an abandoned railroad tunnel in South Korea [65]. Buhmann et al. summarized the German experience with renewable energy concepts in tunnel projects [66]. López et al. evaluated energy consumption and sustainability of road tunnels [67]. The typical tunnel lining was equipped as ground heat exchanger as shown in Figure 4. Through the pipeline buried on the lining surface, the heat on the tunnel surface is collected to the heat collecting pipe to realize the efficient utilization of geothermal energy.

## 3. Geothermal Energy Resources in Northern China

China has rich geothermal resources accounting for 8% of total global geothermal energy reserve [68]. The distribution of geothermal resources in China was consulted as shown in Figure 5.

As shown in Figure 5, the main distribution of geothermal resources is in Northern China, including the Songliao Basin, Erlian Basin, North Basin, Ordos Basin,

Qaidam Basin, and Tarim Basin. The shallow geothermal resource, which can be utilized by the energy piles, is also very abundant. According to the shallow depth data (within 200 m) provided by China Geological Survey, an evaluation on the shallow geothermal resources of 16 provinces in Northern China was performed [70, 71]. The shallow geothermal energy data in Northern China are listed in Table 3. It is easy to learn that the shallow geothermal resources in Northern China (16 calculated provinces) are about  $31.32 \times 10^{12}$  kWh, equal to 3752 million tons of standard coal. Considering the available shallow geothermal resource, the value is more than  $1.17 \times 10^{12}$  kWh, equal to 145 million tons of standard coal.

## 4. Energy Piles Utilized in Geotechnical Engineering

When solving geotechnical engineering problems, the traditional engineering technical measures have the characteristics of high pollution and high energy consumption. Under the background of carbon peak, carbon neutralization and green industrial revolution, huge green and clean geothermal energy reserves, and the great development of energy pile technology in the world, energy pile has been vigorously promoted and applied in Northern China. Combined with the geographical characteristics of seasonal freezing area in Northern China, specific application forms have been developed, such as snow melting and deicing, realization of wide temperature range of asphalt concrete pavement, and prevention and control of frost heave and frost crack of tunnel inlet and outlet lining.

In the northern China, there is a huge distance of air temperature between winter and summer; the daily variation of four seasons' temperature in Beijing area is shown in Figure 6. According to the Köppen classification, the climate types in Northern China are mainly Dwb (cold dry winter, warm summer) and Bsk (arid steppe, cold). In the past 30 years, the climate types in North China have changed significantly [72–74], which is of great value in the utilization of geothermal energy.

As shown in Figure 6, Beijing area is a typical seasonal frozen region in China, where the lowest air temperature in winter is about  $-15^{\circ}\text{C}$ , the highest temperature in summer can reach more than  $35^{\circ}\text{C}$ , and the cold weather and accumulated snow in winter and the high temperature in summer will result in huge challenge and resource consumption of maintenance on highway tunnels, pavements, and other geotechnical engineering facilities.

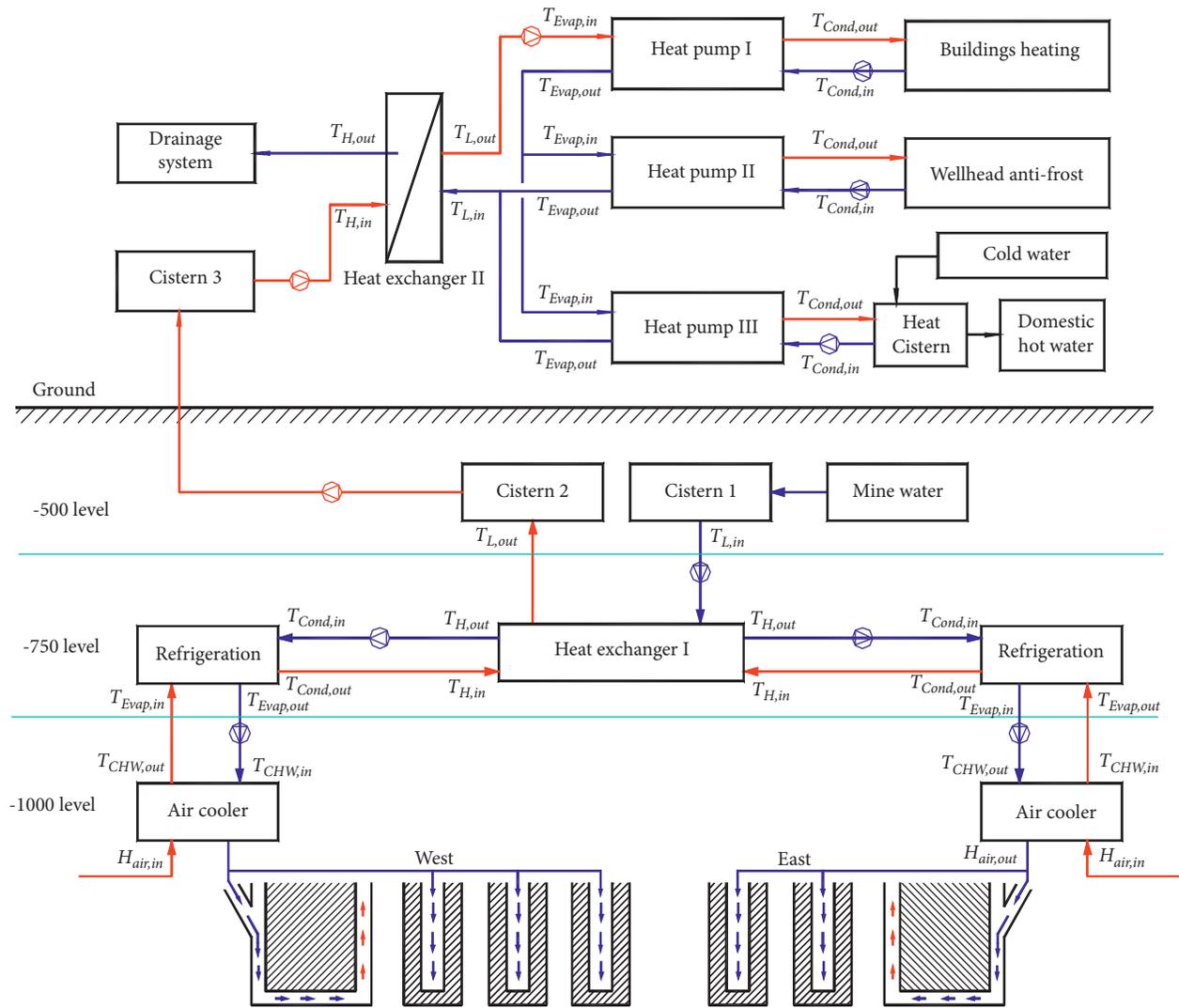


FIGURE 3: The schematic diagram of geothermal heat extraction in the Zhang Shuang-lou Mine [62].

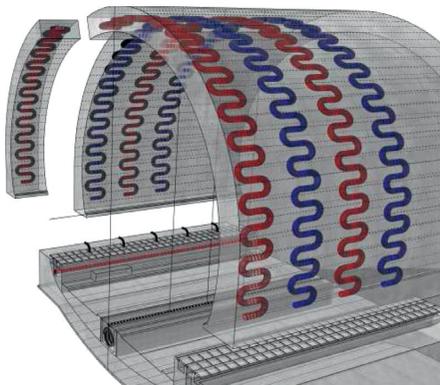


FIGURE 4: Schematic representation of a segmental tunnel lining equipped as heat exchanger [64].

4.1. GSHP System Used for Melting Snow. In Northern China, the continuous low temperature may bring about the accumulated snow for several months; usually, the pavement is icy. This accumulated snow and ice would cause the huge

hidden danger for the motion of the vehicle safety. Now, for the snow and ice melting, numerous methods were proposed by scholars. All the common methods could be classified as chemical snow melting method and physical snow melting method. The chemical method uses salt-storage aggregates [75], sodium chloride [76], and other chemicals to melt the snow and ice on pavement; however, chemicals usually have a negative impact on the surrounding environment, and it is corrosive to vehicles and roadside structures. The physical method is utilization of natural heat or generated heat by employing a conductive asphalt solar collector [77], carbon fiber grille [78], copper plates [79], heating films [80], and electric heating pipes [81, 82], to remove the accumulated snow and ice. Although the above introduced methods could melt snow effectively, the low efficiency or huge electric energy consumption always restricts their wide application. With the development of GSHP system, some scholars have begun to study its practicability in melting of accumulated snow on pavement. Pan et al. summarized a review on hydronic asphalt pavement for energy harvesting and snow melting [83]. Yildirim and Hepbasli analyzed the

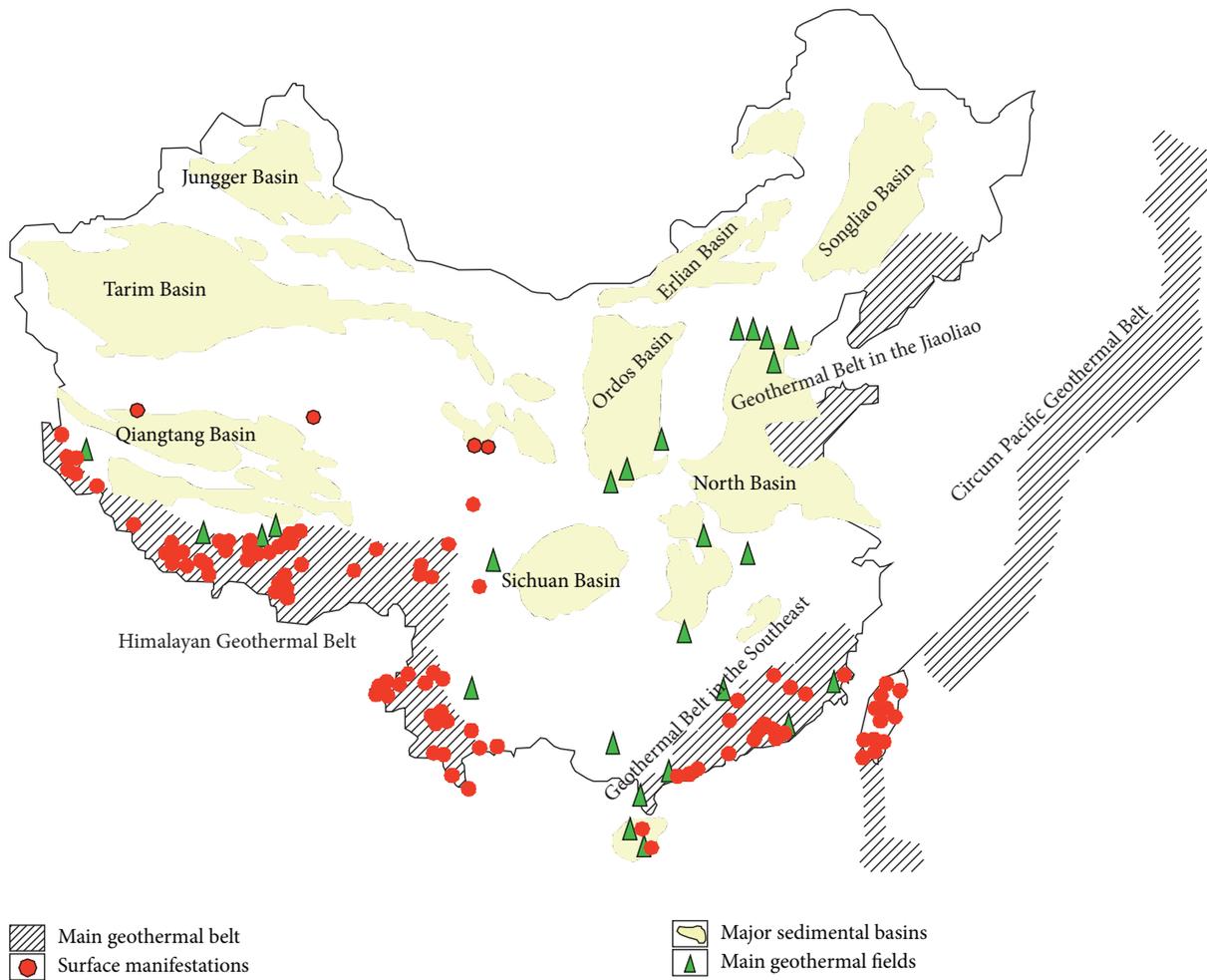


FIGURE 5: The geothermal resources distribution in China [69].

TABLE 3: Evaluation of the shallow geothermal resources in Northern China [71].

No.	Province or city	Total resource capacity		Available resource capacity		Benefit Reduction of CO <sub>2</sub> (Mt)
		×10 <sup>12</sup> kWh	Standard coal (Mt)	×10 <sup>9</sup> kWh	Standard coal (Mt)	
1	Heilongjiang	3.31	407	124	15	0.40
2	Jilin	1.84	226	69.1	9	0.22
3	Liaoning	3.30	406	124	15	0.40
4	Hebei	2.32	285	87.0	11	0.28
5	Beijing	3.01	270	113	14	0.36
6	Tianjin	1.75	215	65.6	8	0.21
7	Inner Mongolia	1.80	221	67.7	8	0.22
8	Shanxi	1.67	205	62.7	8	0.20
9	Shandong	3.47	427	130	16	0.42
10	Henan	3.45	424	129	16	0.42
11	Shanxi	2.24	276	84.2	10	0.27
12	Ningxia	0.974	120	36.5	4	0.12
13	Gansu	1.21	149	45.5	6	0.15
14	Qinghai	0.16	20	6.00	1	0.02
15	Xinjiang	0.486	60	18.2	2	0.06
16	Tibet	0.330	41	12.4	2	0.04
Total in Northern China		31.32	3752	1174.9	145	3.79

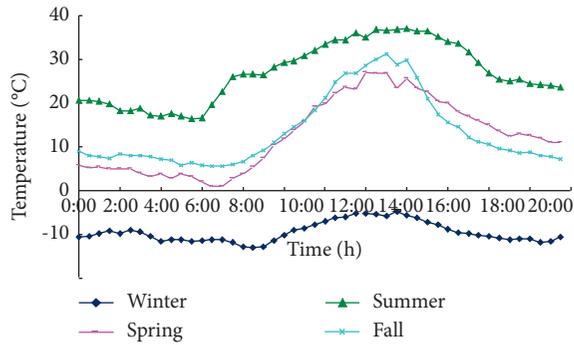


FIGURE 6: Daily variation of four seasons' temperature in Beijing area.

performance of snow melting using a GSHP system [84]. Xu and Tan simulated the pavement snow melting systems utilizing low temperature heating fluids [85]. Han and Yu discussed the feasibility of geothermal heat exchanger pile-based bridge deck snow melting system [86]. Wang et al. performed the thermal analysis and optimization of an ice and snow melting system using geothermal energy by superlong flexible heat pipes [87].

#### 4.2. Guaranteeing Pavement Safety Using Energy Piles.

The pavement asphalt is one of temperature sensitive materials; it will have different mechanical properties under different outer circumstance temperatures. In some regions of Northern China, due to the heat-trapping property of asphalt, the surface temperature of pavement can reach 50°C in summer, but this value is only -15°C in winter, and the temperature difference can reach 65°C. Researches show that dynamic modulus will reduce from 12,000 MPa to 100 MPa under 0.01 frequency when the environment temperature rises from -20°C to 54°C [88], as it can be seen in Figure 7. Hence, the contradictory issues between track in summer and crack of pavement asphalt in winter are especially serious, as shown in Figures 8 and 9, respectively.

For the purpose of dealing with the above contradictory problems, the traditional solving method is striving to develop wide temperature range asphalt material [89–92]. Although many efforts have been done, most of researches could solve the low temperature crack [93] and high temperature track [94] very well separately. It is really difficult to solve these contradictory problems uniformly. In the face of this bottleneck, the other new approach could be explored. Proceeding from that, taking example of GSHP system used for melting snow, and comprehensively considering mature and practical technique and higher thermal efficiency of energy pile and rich shallow geothermal resource in Northern China area, it is possible to implement the energy pile into roadbed structure, to solve the seasonal temperature-induced contradictory problems on pavement. The working schematic diagram of energy piles roadbed is shown in Figure 10. The temperature of the circulating liquid is increased through the vertical solenoid and then flows through the horizontal buried pipe to heat the road surface, so as to improve the road temperature and melt the snow in the road area.

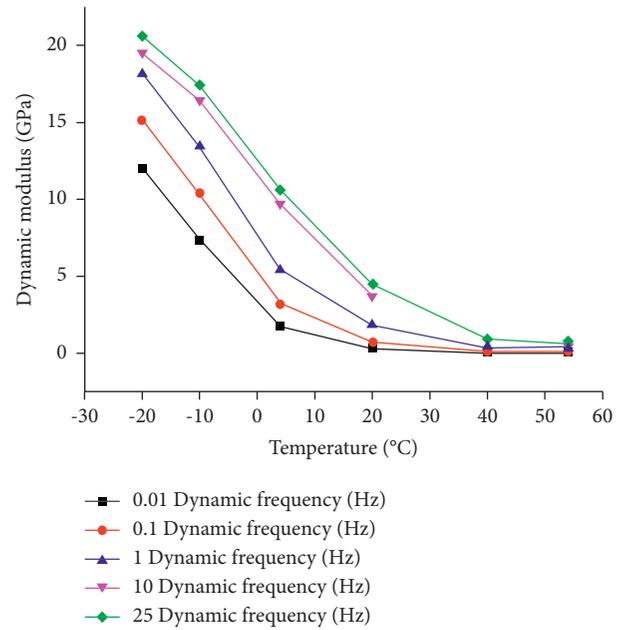


FIGURE 7: Relationships between dynamic modulus and temperature under different frequencies [85].

As shown in Figure 10, by using piles in composite road foundation, the spiral coil with the largest heat exchange surface of the fluid tube is the selected type of heat exchanger cast-in-place energy piles. And taking advantage of good thermal performance and protective layer, the pipes with multi-U type were installed in concrete roadbed. The dynamic modulus of asphalt material (as shown in Figure 7) has strong correlation with the environment temperature. And the soil temperature changing law (as shown in Figure 1) indicates that the soil temperature is stable at 18°C under more than 6 m depth. With utilizing the existing piles in roadbed, the energy pile system can be installed. If the energy piles system can change 30% of temperature differences, the pavement temperature will be about 40°C in summer and about -2°C in winter. So, under this situation, most of the existing asphalt material can meet the temperature requirements, which also means the energy pile system could solve the contradictory problem of track in summer and crack in winter on pavement.

#### 4.3. Preventing Frost Crack Induced by Seepage Using Energy Piles.

Such as Chengde area in Northern China, there is rich underground water in mountains, the low temperature will freeze the underground water around open surface in winter, and the lining at exit and entrance of tunnel will suffer the frost heave force continually with supply underground water. As time passes, a lot of tunnels' linings at position of exit and entrance are facing the water leakage problems. The more serious problem is that the leaked water will be freezing as the ice rapidly. A big block of ice will be hung and accumulated at the roof and road surface, respectively (as shown in Figure 11). It will be a huge potential safety hazard for traffic safety.



FIGURE 8: Pavement crack in winter.



FIGURE 9: Pavement track in summer.

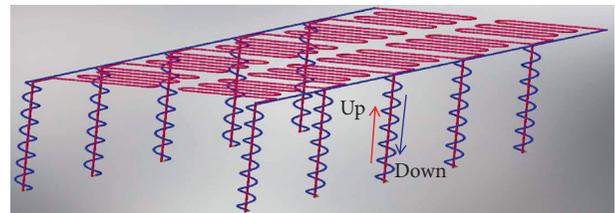
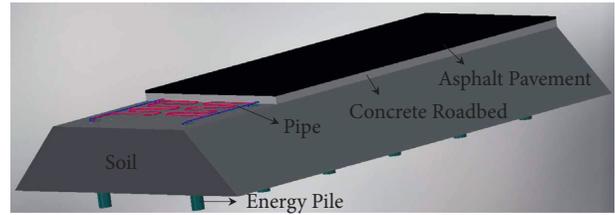


FIGURE 10: The working schematic diagram of energy piles roadbed and laying pipes.

Also, using the energy piles system to collect the heat from ground for heating the lining at both ends of tunnel, the frost heave phenomenon could be avoided. And then, the hanging and accumulating ice problem will be nonexistent. This system is the reverse utilization of energy tunnel, as shown in Figure 4: the heat collection structures are changed as the heat sink structure, and the schematic diagram is shown in Figure 12.

As shown in Figure 12, by using piles in tunnel lining, the spiral coil with the largest heat exchange surface of the fluid tube is the selected type of heat exchanger cast-in-place energy piles. And taking advantage of good thermal performance, the pipes with multi-U type were installed in concrete tunnel lining; also these multi-U type pipes could replace the steel in concrete tunnel lining. The soil temperature changing law (as shown in Figure 1) indicates that the soil temperature is stable at 18°C under more than 6 m depth. If the energy piles system can keep temperature above 0°C, the problem of frost crack induced by seepage could be avoided.

**4.4. Simulation Study on Buried Pipe Form.** Usually, we adopt the form of several shaped buried pipes. However, in engineering practice, we found that the heat transfer uniformity of several shaped buried pipes is poor. When the pipe spacing is large, the temperature at the center between pipes is low. When it is applied to road snow melting and deicing, it will cause uneven melting of ice and snow; when the pipe spacing is small, the temperature near



(a)



(b)

FIGURE 11: The hanging and accumulating ice at the roof and road surface.

the buried pipe is high, which wastes resources. After considering the above factors, the spiral buried pipe and zigzag buried pipe form are designed to discuss better heat transfer effect. The solid heat transfer and pipe heat transfer module in COMSOL is used for simulation, and the results are shown in Figure 13. The results show that the spiral buried pipe has better heat transfer uniformity and better engineering applicability compared with the zigzag buried pipe.

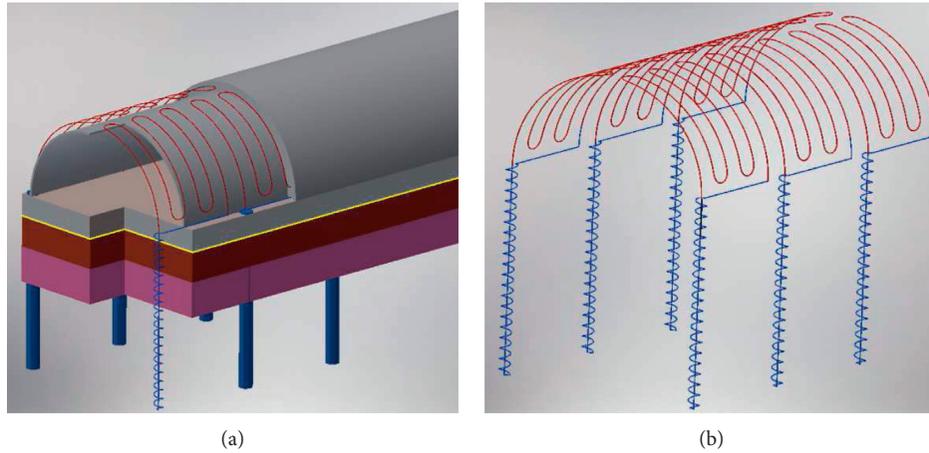


FIGURE 12: The working schematic diagram of energy piles tunnel lining and laying pipes.

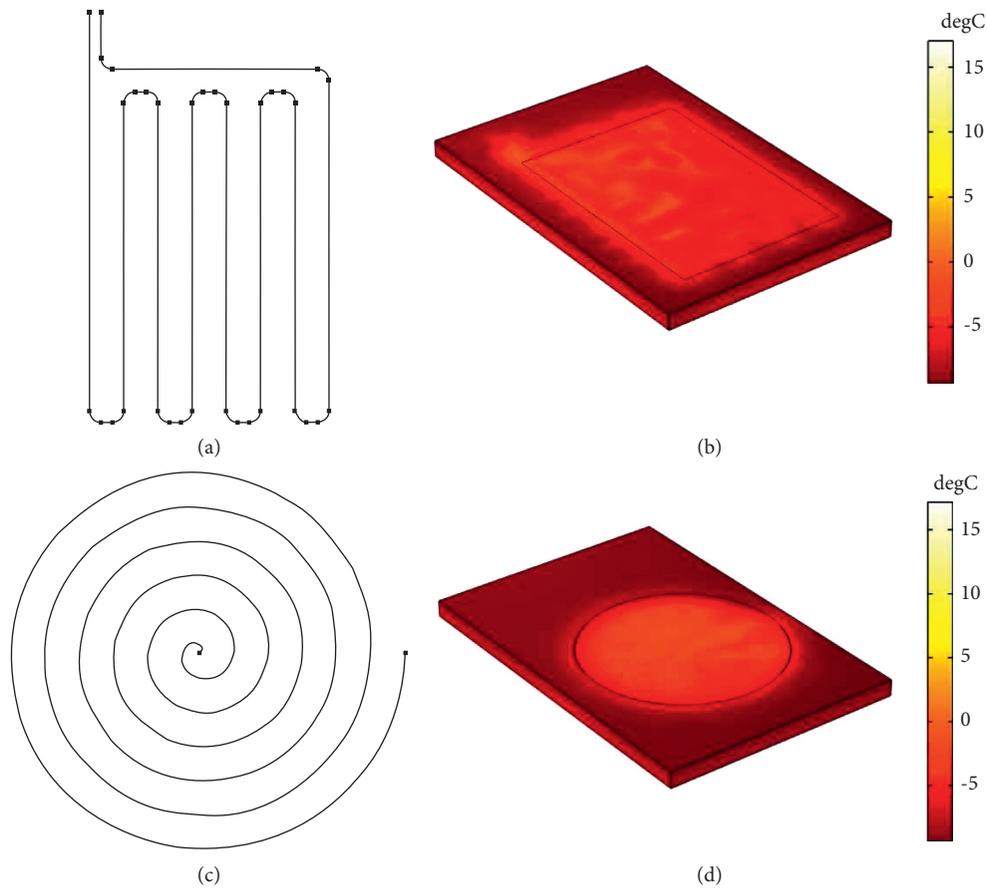


FIGURE 13: Pavement temperature distribution after 10 days of operation with buried depth of 0.5 m. (a) Zigzag buried pipe. (b) Heat exchange of zigzag buried pipe. (c) Spiral buried pipe. (d) Heat exchange of spiral buried pipe.

### 5. Conclusion and Discussion

In the recent 30 years, a large number of scholars have conducted extensive and in-depth research on the energy pile system. Through experimental research and numerical simulation, from parameter optimization and heat transfer

efficiency to structure-soil response, they continuously promote the application of energy pile system from theory to engineering practice.

With the continuous development of ground-source heat pump system, researchers introduced it into geotechnical engineering from the field of building energy

conservation and applied it to deep mine geothermal collection and tunnel lining surface heat collection, which expanded the utilization forms of ground-source heat pump system.

The area of Northern China has abundant shallow geothermal resources. As a typical seasonal frozen soil area, it is high in summer and cold in winter. The application of ground-source heat pump system in geotechnical engineering has obvious popularization and application value. Hence, taking example of using the geothermal heat exchanger to melt snow, the novel idea of using energy piles to prevent track in summer and crack in winter of pavement and guarantee the safety of frost crack on tunnel lining was discussed, to develop implementation of the energy pile into geotechnical engineering. And through the simulation study, compared with the zigzag buried pipe, it is found that the arrangement form of spiral buried pipe has better heat transfer uniformity and engineering applicability.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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