Prospect of comprehensive utilization of geothermal resources during the construction and operation of railway

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Abstract

Purpose – This study is dedicated to systematically collating the distribution and utilization circumstances of geothermal resources in China. Moreover, it endeavors to formulate a comprehensive utilization scheme for geothermal resources during the construction and operation phases of the railway, thereby furnishing robust support and valuable reference for the holistic utilization of geothermal resources along the railway corridor.

Design/methodology/approach – Through an in-depth analysis of the extant utilization of geothermal resources in China, it is discerned that the current utilization modalities are relatively rudimentary, bereft of rational planning and characterized by a low utilization rate. Concurrently, by integrating the practical requisites of railway construction and operation and conducting theoretical dissections, a comprehensive utilization plan for the construction and operation periods of railway is proffered.

Findings – In light of the railway's construction and operation characteristics, geothermal utilization models are categorized. During construction, comprehensive modalities include tunnel illumination power generation, construction area heating, tunnel antifreeze using shallow geothermal energy, tunnel pavement antifreeze and construction concrete maintenance. During operation, they comprise operation tunnel antifreeze, railway roadbed antifreeze, railway switch snow melting and deicing, geothermal power station establishment and railway hot spring health tourism planning.

Originality/value – According to the characteristics and actual needs of railway construction and operation, it is of great significance to rationally utilize geothermal resources to promote the construction and operation of green railways.

Keywords Railways, Construction and operation, Geothermal resources, Comprehensive utilization

Paper type Research paper

1. Introduction

Geothermal resources pertain to energy sources that are derived from the thermonuclear and crustal regions of the Earth's interior, prevalently manifested in the guise of geothermal fluids or heat that is directly harbored within rocks. Geothermal energy is a renewable resource that is

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both environmentally friendly and characterized by low carbon emissions (Chen *et al.*, 2022). In juxtaposition with traditional energy sources like coal and petroleum, geothermal energy demonstrates a reduced extent of environmental pollution and exerts a less detrimental influence on climate change and air quality degradation. Concurrently, its reserves are plentiful, its distribution is wide-ranging, its performance is steady and trustworthy, and it is not susceptible to exogenous factors such as seasonal variations, climatic oscillations, and diurnal alternations. Ergo, geothermal resources possess crucial value in terms of development and utilization and harbor extensive application potentials within the arenas of energy transition and environmental preservation (Zhao & Wan, 2014).

By September 2024, China's railway operating mileage has attained 160,000 kilometers. In recent years, as the construction of railway projects has been continuously advanced, the demand for employing clean geothermal resources to erect a green railway has been escalating on a daily basis. The profuse geothermal resources in China furnish a material foundation for the diversified utilization of geothermal resources during the process of railway construction and operation (Chen *et al.*, 2022).

The construction and operation of the railway encounter the dual predicaments of energy provision and environmental conservation. During the construction phase, the particular geological circumstances, such as the low-temperature milieu and permafrost, render the energy requisites in the construction process complex and multifarious (Wang *et al.*, 2023). In the operational stage, the energy consumption of the facilities and tunnels along the railway line persists, and the traditional energy supply modalities entail high costs and exert a significant impact on the ecological environment. Hence, it is of both substantial practical import and exigency to probe into the cascade utilization paradigm of geothermal resources within the railway domain.

In the railway field, notwithstanding the existence of certain investigations regarding energy utilization, the systematic research on the cascade utilization of inland heat resources throughout the entire life cycle of the railway remains imperfect. The preponderant majority of the extant studies concentrate on the utilization of a solitary link or a localized area, and there is a dearth of in-depth exploration into the comprehensive cascade utilization scheme of geothermal resources in diverse stages and scenarios of railway construction and operation from a holistic vantage point. This lacuna affords an extensive exploration scope and a lucid research orientation for the present study (Zhu *et al.*, 2015). Within this context, it is of momentous significance for the construction and operation of a green and environmentally amicable railway to devise a rational cascade utilization plan and vigorously explore the comprehensive utilization pathway of the geothermal resources of railway in accordance with the local conditions.

This research conducts a systematic consolidation of the distribution pattern of geothermal resources within the China and presents an overview of the current utilization status of such resources. In light of the practical traits exhibited by the railway during both its construction and operation phases, a methodical classification of the geothermal utilization models applicable to the railway is carried out. It is anticipated that the relevant findings will offer robust support and valuable reference for the comprehensive exploitation of geothermal resources along the railway line.

2. Distribution characteristics of geothermal resources in China

The distribution of geothermal resources in China exhibits pronounced regularity and zonation. These resources are predominantly distributed in the eastern part of China, the southeastern coast, Taiwan, the Ordos fault basin, southern Tibet, western Sichuan, and western Yunnan. To date, 103 geothermal fields have been explored, with recoverable geothermal resources amounting to 33,283 $\times$ 10^4 m^3 per year, and 214 hot fields have been preliminarily evaluated, having approximately 5 $\times$ 10^8 m^3 of recoverable hot water resources per year. The heat flow is relatively high (ranging from 91 to 364 MW/m^2) along the suture zone of the Yarlung Zangbo River in southwest China, and it decreases in a stepped fashion towards the north, reaching only 33–44 MW/m^2 in the Junggar Basin. The heat flow value in the eastern Taiwan plate is relatively high, spanning from 80–120 MW/m^2. It decreases to 60–100 MW/m^2 across the Taiwan Strait to the Yanshan orogenic belt along the southeastern coast, and further reduces to 57–69 MW/m^2 in the Jianghan Basin. Geothermal resources are primarily concentrated in eastern China, the Qionglei Basin, the Songliao Basin, and the Ordos fault basin, and they are mainly of medium and low temperature. Upland convective geothermal resources are chiefly found in the southeastern coast of China, Taiwan, western Sichuan, western Yunnan, and the Jiaoliao Peninsula, with high-temperature geothermal resources predominantly located in South Tibet, western Sichuan, and western Yunnan.

Tibet represents the region with the most intense geothermal activity in China, ranking first in terms of geothermal reserve quantity (Guo, Zhou, Wan, Xiao, & Zhou, 2022; Wang, Lu, Nan, Hu, & Shao, 2017). Geothermal manifestations are widespread throughout the region, with over 700 locations, among which 342 geothermal display areas are available for development. The temperature of the majority of surface springs exceeds 80 °C, and the geothermal resource power generation potential surpasses 1 million kilowatts (Bertani, 2009). Geothermal resources in this area are mainly distributed in the Nimu-Yangbajing-Naqu-Cuona Lake area. Additionally, the central basin areas of the Yarlung Zangbo River and Nianchu River region, as well as the uninhabited regions, are also rich in geothermal resources. Generally speaking, geothermal activities are more intense in the south than in the north and more pronounced in the east than in the west (Zhang *et al.*, 2021).

The geothermal resources in Sichuan Province are mainly concentrated in the western Sichuan area (Zhao *et al.*, 2021). The high heat flow in this area anomaly is conspicuous, and the distribution of geothermal hot spots is clearly controlled by plate tectonic movements. High-temperature geothermal areas are concentrated at the edges of plate collisions where the Curie surface is shallowly buried. There are three major fault zones, namely the north - south trending Jinsha River, Ganzi-Litang, and Xianshui River fault zones, which serve as favorable conduits for groundwater hydrothermal activities. This area is abundantly endowed with geothermal resources, with 196 natural hot springs exposed. The hydrothermal types are diverse, encompassing ordinary hot springs, boiling springs, fountains, boiling fountains, and intermittent fountains.

The geothermal resources in Yunnan Province can be classified into wet steam type and hot water type based on temperature and the morphology of the geothermal carrier (Zhang, Tan, Zhang, Wei, & Dong, 2016). Different types of geothermal resources possess distinct distribution characteristics. According to incomplete statistics, there are 124 counties in Yunnan Province with hot springs, with a total of over 700 hot springs and more than 100 hot water boreholes. Among them, low-temperature hot springs account for 51%, medium-temperature hot springs for 33%, high-temperature hot springs for 15%, and ultra-high-temperature hot springs for 10%.

Evidently, the temperature range of geothermal resources across various regions within China is extensive, spanning from low to high temperatures, and the reserves are plentiful. This characteristic furnishes a substantial material foundation for the diversified and cascaded utilization of such resources during railway construction and operation.

3. Utilization status of geothermal resources in China

The development and utilization modalities of geothermal resources are generally bifurcated into two approaches, namely geothermal power generation and direct utilization, contingent upon their disparate temperature gradients. Geothermal resources with a temperature exceeding 150 °C, classified as high-temperature geothermal, are predominantly harnessed for geothermal power generation. Medium-temperature geothermal resources, ranging from 90 °C to 150 °C, and low-temperature geothermal resources, spanning from 25 °C to 90 °C, are primarily utilized directly (as detailed in Figure 1). Low-temperature geothermal finds

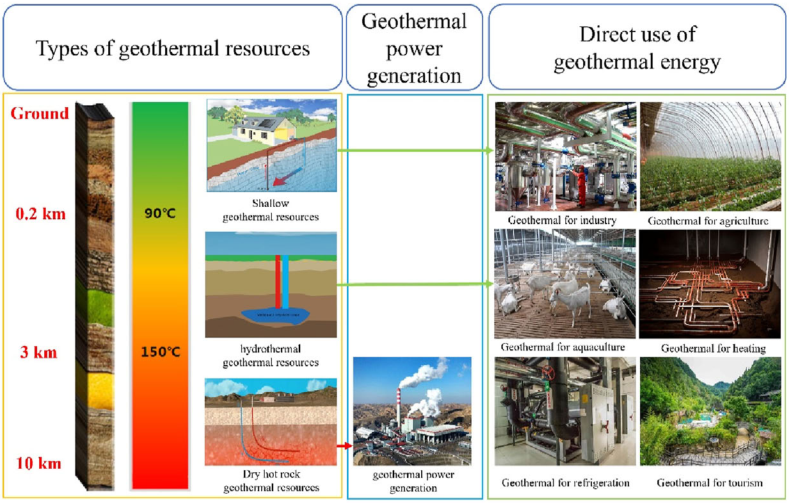

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Figure 1. Comprehensive utilization model of geothermal resources in China

extensive application in numerous domains such as industry, agriculture, aquaculture, heating, refrigeration, tourism, and recuperation. Shallow geothermal resources with a temperature below 25 °C can be exploited for heating and cooling purposes via ground source heat pumps and water source heat pumps. In the subsequent sections, an overview of the current state of geothermal power generation and direct geothermal utilization in China will be presented.

3.1 Present situation of geothermal power generation in China

In the realm of renewable energy utilization, geothermal power generation, as a pivotal application modality of geothermal energy, primarily hinges on medium and high temperature geothermal resources. The utilization of geothermal resources for power generation in China has a history of half a century. In 1970, the 86 kW geothermal power station in Fengshun Tangkeng, Guangdong Province, was put into use, making China the eighth country in the world to successfully use geothermal power generation.

China boasts abundant geothermal resources, with 11 high-temperature geothermal resources having been identified (as detailed in Table 1). Geothermal power stations have played a significant role in the progression of geothermal power generation in China. As early as the 1970s, the relevant test group embarked on power generation exploration in Yangbajing geothermal filed. In 1977, the 1MW test unit achieved successful trial operation, and subsequently, a number of generator sets were installed. By December 2019, the cumulative power generation of the Yangbajing Thermal Power Plant was substantial, which has vigorously propelled local economic development and energy conservation and emission reduction efforts. However, the deep geothermal resources in Yangbajing have yet to be fully exploited.

The Yangyi Thermal Power Plant, which was connected to the grid in 2018, had a load of 13MW during the initial stage of operation, and its power generation capacity could ascend to 18MW in the low temperatures of winter. By the end of 2021, remarkable achievements had been made in its power generation. The Longjiudi Thermal Power Plant installed two 1MW turbogenerator units in 1987. Nevertheless, due to issues such as low steam pressure, wellhead scaling, and backward technology, the actual power generation fell short of expectations, and it ceased operations in 1994, having generated a total of 2.884 million KWH. In 1993, with the

Table 1. The proved high-temperature geothermal resources in China

Geothermal field name	Geothermal temperature (°C)	Uses of planning
Longjiu geothermal field	>150	Geothermal power generation and geothermal comprehensive utilization
Kawudi geothermal field	>150	Geothermal power generation and geothermal comprehensive utilization
Qupu geothermal field	>150	Geothermal power generation and geothermal comprehensive utilization
Jialong geothermal field	>150	Geothermal power generation
Kuma geothermal field	>150	Geothermal power generation
Chabu geothermal field	>180	Geothermal power generation
Bardi geothermal field	>200	Geothermal power generation
Gulu geothermal field	>200	Geothermal power generation and geothermal comprehensive utilization
Gudui geothermal field	>200	Geothermal power generation and geothermal comprehensive utilization
Yangyi geothermal field	>200	Geothermal power generation and geothermal comprehensive utilization
Yangbajing geothermal field	>275	Geothermal power generation and geothermal comprehensive utilization

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support of the United Nations, the Naqu Thermal Power Plant introduced a 1MW double-cycle dual-mass generator set and connected it to the grid for power generation. Its geothermal field is of a medium and low temperature type, with a temperature ranging between 95–114 °C, and it ceased power generation in 1999 due to various factors. The Kangding and Suining areas in Sichuan Province have conducted small-scale geothermal power generation experiments by utilizing high-temperature geothermal water and waste hot water from oil and gas wells.

Although geothermal power generation in China has a certain foundation, the scale of this industry remains small, which is starkly at odds with the abundant reserves of geothermal resources (Hu, Qu, & Xu, 2023). It still confronts numerous challenges and opportunities. It is imperative to further tap its potential, foster the sustainable development of the geothermal power generation industry, enable it to assume a more prominent position in China's energy structure, and contribute to the green and sustainable development of economy and society.

3.2 The current situation of geothermal direct utilization in China

For many years, China's direct utilization of geothermal energy has ranked first in the world. By the end of 2022, the geothermal heating (cooling) area of the country is roughly 1.4 billion square meters, of which the hydrothermal medium and deep heating area is 580 million square meters, and the shallow heating area is 810 million square meters, and China's direct utilization capacity of geothermal energy is equivalent to 100.2 GW. By 2025, the heating area is expected to reach 2.1 billion square meters; By 2035, it will reach 4.2 billion square meters. The geothermal resources within the China assume a crucial role across numerous domains and possess diversified approaches for direct utilization (He, Feng, Luo, & Zeng, 2023).

In the aspect of hot spring recuperation and tourism, the hot spring resources in Qinghai have undergone in-depth development and have emerged as a significant impetus for local economic growth. For instance, the development of the hot spring spa and tourism sectors has not only yielded substantial economic benefits but has also spurred improvements in infrastructure construction. This has enhanced the quality of life for local residents, attracted a large influx of tourists, and generated considerable tourism revenue.

The field of livelihood heating has also witnessed a new milestone in the utilization of geothermal resources. For example, Gna County and Dangxiong County have implemented geothermal heating projects. Following the launch of the first phase of the pilot project in 2016, the second phase was initiated in 2017, which significantly expanded the heating area. In Dangxiong County, construction commenced in 2017, with the first phase providing heating in 2018 and the second phase being completed in 2019. This has brought warmth to numerous units and residents, thereby enhancing the living and working environment (Guo *et al.*, 2022). Similarly, the Golmud district in Qinghai Province has also implemented geothermal heating projects, which have been favorably received by both residents and enterprises.

In the domains of agriculture and aquaculture, low-temperature geothermal resources have been effectively harnessed, offering solutions to production challenges within the unique natural environment. Some farms and greenhouses utilize geothermal heating to overcome the limitations of agricultural production during winter, enabling year-round production. In certain areas, geothermal resources have also been applied to greenhouse breeding, which has boosted the productivity of livestock and enhanced breeding efficiency. This has injected new vitality into the development of local agriculture and aquaculture, promoted the diversified expansion of the regional economy, and contributed to the improvement of people's livelihood.

Although there are particular instances of comprehensive geothermal utilization, there is a lack of precedents for geothermal utilization during the construction and operation railway. It must be clearly recognized that the rational development of geothermal resources is beneficial for promoting the comprehensive utilization of clean energy along the railway. Based on the actual requirements of the railway construction and operation periods, the plans and recommendations for the cascade utilization of geothermal energy for railway are proposed in the following content.

4. Geothermal cascade utilization scheme in railway construction period and operation period

4.1 Comprehensive utilization scheme of geothermal in railway construction period

To achieve the efficient coordination and maximal utilization of geothermal resources within tunnels and construction areas during the construction phase of railways, the layout and extraction scheme of geothermal wells can be optimized by integrating the overall planning of railway construction with the characteristics of energy demand. Through the employment of advanced intelligent control systems, the transmission, distribution, and utilization of geothermal fluids can be precisely regulated.

For instance, the geothermal fluid extracted from high-temperature geothermal wells can be initially introduced into tunnel power generation devices for power generation purposes. Subsequently, the medium-temperature tail water remaining after power generation can be utilized to supply heating in the construction area, for tunnel insulation and anti-freeze measures, as well as for pavement anti-freeze and concrete maintenance. Finally, the low-temperature tail water can be recharged back into the ground, thereby forming a closed-cycle, efficient, and stable cascade utilization system (as detailed in Figure 2).

4.1.1 Power generation for tunnel lighting. Tunnel lighting is reliant on a power supply. Underground hot water, being a widely available and renewable energy resource, has the potential to offer an alternative power supply option for tunnel lighting, on the condition that its potential energy and kinetic energy can be effectively transformed into electrical energy.

As depicted in Figure 3, the flash evaporation electricity generation process entails introducing the local hot water into a low-pressure container. In this process, a part of the hot water promptly flashes into steam. The turbine and the generator are connected mechanically, and the rotation of the turbine propels the rotor of the generator to rotate within the magnetic field. In accordance with the principle of electromagnetic induction, the stator winding of the generator will generate an induced electromotive force, thus realizing the conversion of

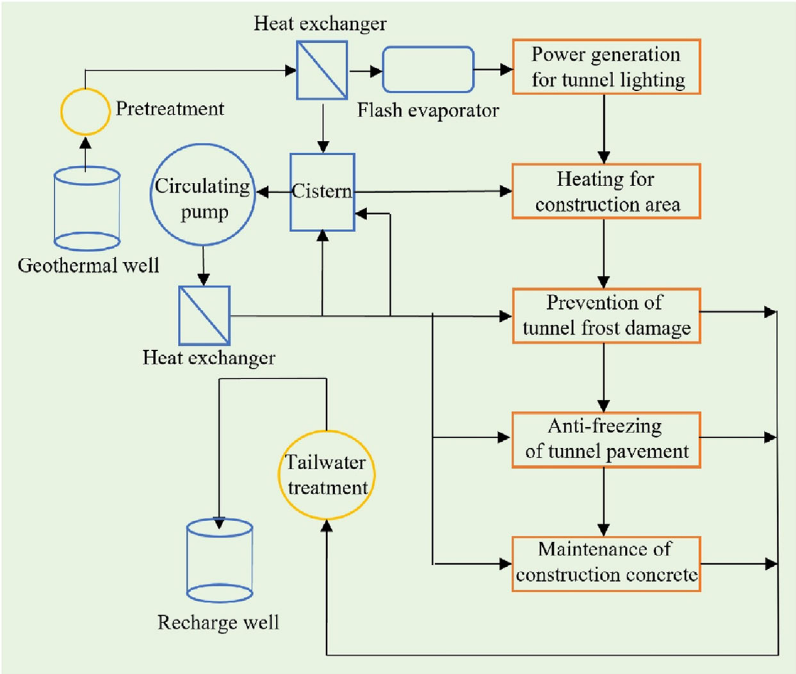

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Figure 2. Comprehensive utilization scheme of geothermal in railway construction period

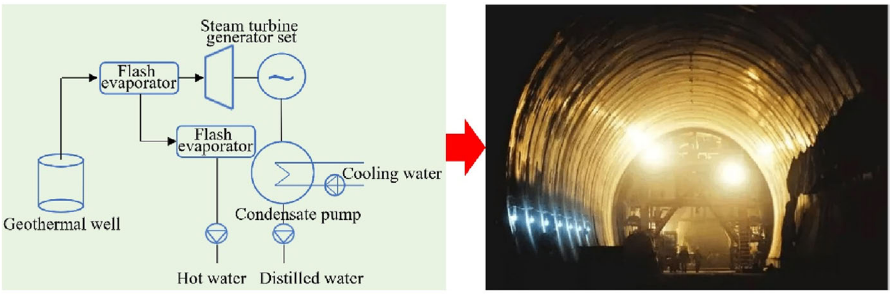

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Figure 3. The scheme to use geothermal energy to generate electricity and light the tunnel

groundwater energy into electrical energy. The utilization of geothermal fluid for power generation can not only lessen the dependence on traditional energy sources and lower operating costs but also contribute to the reduction of carbon emissions, which complies with the requirements of sustainable development. Hence, it is of significant practical importance and application value to conduct research on the tunnel lighting system based on geothermal fluid power generation.

High-efficiency and energy-saving LED lamps are chosen for use as tunnel lighting fixtures. Concurrently, it is essential to set up a comprehensive monitoring platform for the tunnel lighting power generation system. This platform is designed to monitor key parameters in real time, including the groundwater level, flow rate, turbine rotational speed, generator output voltage and current, battery power, and the working status of the lighting lamps. By installing a variety of sensors at each monitoring point, such as water level sensors, flow sensors, speed sensors, voltage and current transformers, power monitors, and illumination sensors, the collected data can be transmitted to the monitoring center. This enables the visual display and remote monitoring of the overall system's operational status, as well as the effective storage and utilization of power.

4.1.2 Heating for construction area. Some railways in mountainous areas are situated in high-cold and high-altitude regions, and during winter, the construction area encounters a relatively greater demand for heating. Under cold weather circumstances, to guarantee the construction progress and safeguard the health of construction personnel, it is imperative to put in place stable and effective heating measures. The heating of the construction area demands rapid heating capabilities and the flexibility to adjust both the heating range and temperature so as to cater to the requirements of different construction stages and various working areas. Meanwhile, given the temporary nature of the construction area, the heating system ought to possess characteristics such as easy installation, convenient disassembly, and effortless movement. Additionally, strict cost control is necessary for this heating system.

Firstly, underground hot water or steam is extracted from the geothermal well and then conveyed to the geothermal heat exchanger. When the circulating medium undergoes heat exchange with the rock and soil within the underground heat exchanger, it proceeds to enter the evaporator of the heat pump unit. Inside the evaporator, the circulating medium transfers heat to the refrigerant, prompting the refrigerant to evaporate into a gaseous state. Subsequently, the gaseous refrigerant enters the compressor. Under the compression exerted by the compressor, its temperature and pressure rise, transforming it into a high-temperature and high-pressure gaseous refrigerant. This high-temperature and high-pressure refrigerant then enters the condenser and engages in heat exchange with the heating circulating water, releasing heat to the heating circulating water. As a result, the temperature of the heating circulating water increases. The heated heating circulating water is then transported via the heating pipe network to the terminal heat dissipation equipment, where it releases heat indoors, thereby achieving the purpose of heating. After passing through the condenser, the refrigerant reverts to a liquid state (as detailed in Figure 4).

Throughout the entire operational process, the heat pump unit accomplishes the transfer of heat from a low-temperature to a high-temperature zone by consuming electrical energy. This not only enhances the utilization efficiency of geothermal resources but also empowers the geothermal heating system to fulfill the heating demands of various temperature requirements within the construction area.

4.1.3 Prevention and control of tunnel frost damage. Frost damage to railway tunnels in cold regions pertains to the ailments that result from the freeze-thaw cycles and frost heaving of the surrounding rock within railway tunnels under cold environmental conditions. Classified based on its location, it can be segregated into five distinct categories: lining frost damage, drainage system frost damage, ballast bed frost damage, surrounding rock frost damage, and portal frost damage. In cold regions, tunnel leakage and freezing damage are reciprocally causative. This interaction further leads to lining cracking, spalling, the formation of hanging ice, and road icing, all of which can directly imperil the structural safety of the tunnel and substantially augment the costs associated with tunnel maintenance.

As depicted in Figure 5, by installing a geothermal insulation system, which consists of geothermal pipelines, thermal insulation materials, and temperature control systems, either within the surrounding rock of the tunnel or behind the lining, the geothermal energy can be exchanged to raise the temperature inside the tunnel and prevent negative temperatures and freezing. Firstly, an installation groove is excavated behind the surrounding rock or the lining. Subsequently, the geothermal pipeline is laid out, fixed, and connected. Among these steps, the geothermal pipeline is arranged in an annular pattern and positioned as close to the surface of

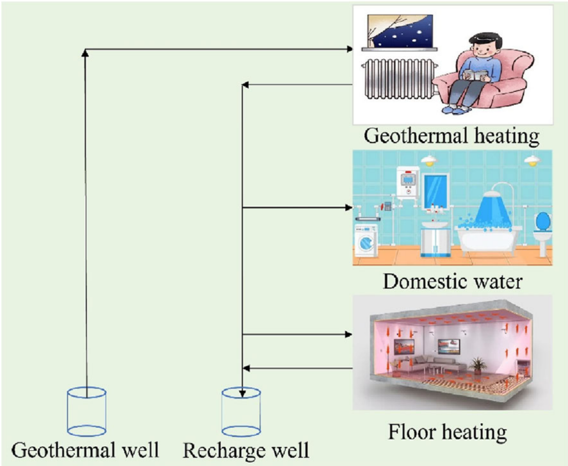

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Figure 4. The scheme of heating construction area by using geothermal energy

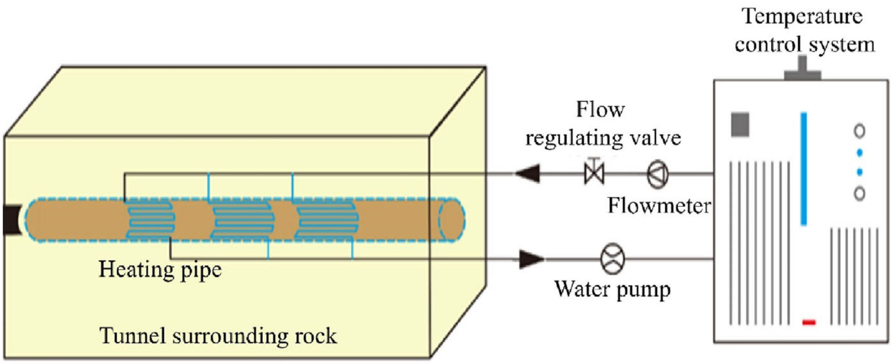

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Figure 5. Conceptual map of freezing damage control in tunnels using geothermal energy

the surrounding rock as possible to enhance the heat transfer efficiency. The circulating geothermal fluid within the pipeline transfers heat to the surrounding rock, maintaining the temperature of the surrounding rock within a specific range and thus preventing frost heaving damage. After the installation is finished, the filling and packaging of the thermal insulation material are carried out. The thermal insulation material serves to reduce heat loss towards the interior of the tunnel and improve the energy utilization efficiency. Finally, the temperature control system is installed. Through the temperature sensor, the temperature of the surrounding rock is monitored in real time. Based on the preset temperature threshold, the flow rate and temperature of the geothermal fluid are automatically adjusted to ensure the stability of the heat preservation effect. It is anticipated that this will mitigate the impact of tunnel freezing damage on the tunnel structure. The principle of this scheme is illustrated in the figure.

4.1.4 Anti-freezing of tunnel entrance and exit pavement. In alpine mountain area, the tunnel entrances and exits are susceptible to the formation of ice. In some areas, over the course of a year, the cumulative time during which the snow cover on the road surface at the tunnel entrance exceeds 10 cm in thickness is more than 180 days, and the duration of ice presence is over 210 days. The snow and ice at the tunnel entrance and exit lead to a reduction in the road's friction coefficient, making it difficult for vehicles to travel and potentially resulting in hazardous situations such as skidding and sideslips. This significantly decreases the speed of transport vehicles. Moreover, the raw materials, equipment, and personnel necessary for construction are unable to reach the construction site punctually and smoothly, thereby impeding the construction progress. Consequently, it is of utmost urgency to propose effective measures to address the anti-freezing issue at the tunnel portal section and the snow melting and de-icing of the road surface in high-altitude and severely cold regions.

The road geothermal snow melting and ice melting technology involves embedding heat pipes within the road surface. The system utilizes a unit to extract low-level geothermal energy from the ground via the underground heat exchanger. After being boosted by the heat pump, the fluid with a relatively higher temperature is then transported to the pipes located in the road surface through a water pump. As the high-temperature hot fluid flows within the pipes, heat is transferred to the road surface via convective heat transfer. Once the temperature of the road surface reaches above 0 °C, the ice and snow on the surface will melt, thereby fulfilling the aim of snow and ice melting (as detailed in Figure 6). The road geothermal snow melting and deicing system primarily consists of a buried heat exchanger, a control device, a water collector, and snow melting pipelines. The main operational modes of the geothermal snow melting system are categorized into the summer heat storage mode and the winter snow melting mode. In summer, the road circulating thermal fluid is employed to transfer the intense solar radiation heat energy to the underground soil for storage, which is known as underground energy storage. In winter, the circulating hot fluid extracts heat to the road surface to elevate the road surface temperature and thus melt the snow and ice. It is advisable to make use of the geothermal energy along the line and lay geothermal heating pipelines beneath the temporary pavement of the tunnel to form a geothermal heating network. The pipelines should be made of materials that are resistant to high temperatures and corrosion. They are to be laid according to a specific spacing and layout to ensure that the road surface can be heated evenly. Through the control center, the flow rate of the geothermal fluid can be adjusted to maintain the road surface temperature above the freezing point and prevent the road surface from icing.

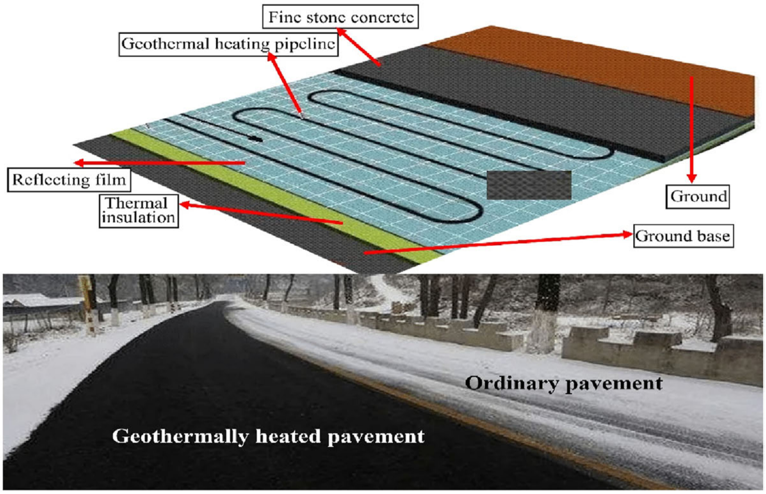

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Figure 6. Conceptual diagram of using geothermal heat to prevent freezing of tunnel inlet and outlet pavement

4.1.5 Maintenance of construction concrete. In railway construction, concrete is the main material for building key structures such as bridges, tunnels, and track foundations. The quality of concrete directly affects the durability, safety and service life of railway engineering. In the cold environment, the raw materials and mixing process of the concrete mixing station are easily affected by low temperature, which leads to the prolongation of the setting time of the concrete, the slow development of the strength and even the freezing damage, which seriously affects the quality of the concrete.

Mixer is the core equipment of concrete production, and its mixing process needs to be carried out in a suitable temperature range. Low temperature will slow down the hydration reaction during concrete mixing and affect the workability and strength development of concrete. The heat preservation requirement of the mixer is mainly to keep the ambient temperature in and around the mixing drum at a certain level, and the general requirement is not less than 5 °C. The batching machine hopper is used to store concrete raw materials such as sand and stone. In a low temperature environment, these raw materials are easy to freeze, affecting the accuracy of ingredients and the smoothness of cutting. Therefore, the insulation requirements of the batching machine hopper can maintain the temperature in the hopper above 0 °C to prevent the freezing of raw materials.

The plate heat exchanger is installed at the bottom of the batching machine hopper, and equipped with a small fan. The temperature sensor is set in the silo and connected to the control system. When the temperature in the hopper is lower than 0 °C, the control system automatically starts the geothermal circulating pump to increase the geothermal fluid flow, so that the temperature in the hopper of the batching machine is not lower than 0 °C. At the same time, the fan is started to promote the air circulation in the hopper, so that the heat is evenly distributed. When the temperature in the mixer is lower than 5 °C, the geothermal circulating pump is started. The mixer adopts a jacketed heat exchange structure, and the geothermal fluid in the jacket is provided by a hot water pump. A high-precision temperature sensor is installed in the mixing drum to monitor the concrete temperature in real time. According to the temperature feedback, the control system adjusts the speed of the hot water pump and the temperature of the geothermal fluid to ensure that the concrete temperature in the mixing drum is not less than 5 °C.

4.2 Geothermal comprehensive utilization scheme of railway during operation period

In cold regions or during winter, the need for tunnel anti-freezing is essential. In a similar way, the heating demand for station buildings is especially significant, necessitating a substantial amount of heat energy. Conversely, in summer, certain areas face cooling requirements to ensure a pleasant indoor environment. The implementation of a comprehensive geothermal energy utilization plan can fulfill a portion of the energy demands during the operation of railway. This not only reduces operating costs but also yields notable economic, environmental, and social benefits. The subsequent discussion will center on the comprehensive geothermal energy utilization scheme during the operation of railway. This will encompass aspects such as subgrade anti-freezing, track snow melting and de-icing, tunnel anti-freezing (as detailed in Figure 7), geothermal stations, and a special line for health and wellness tourism.

4.2.1 Anti-freezing in operating tunnel. In alpine mountain areas, tunnels are influenced by three main factors, namely air pressure, temperature, and humidity. A large amount of humid air gives rise to fog, which then condenses to form a water film. This water film is highly susceptible to the impact of low temperatures and readily transforms into ice within the tunnel. The presence of ice on the road surface causes road traffic to lose its anti-skid capability, thereby posing serious safety risks to driving. In fact, it has consistently been one of the most perilous hazards in alpine mountainous regions. When compared to ice on pavements at corners and ramps, the ice inside the tunnel is especially challenging to melt. This is primarily due to the influence of the high-altitude topography and geomorphology, which create conditions that impede the natural melting process. Consequently, in areas rich in geothermal

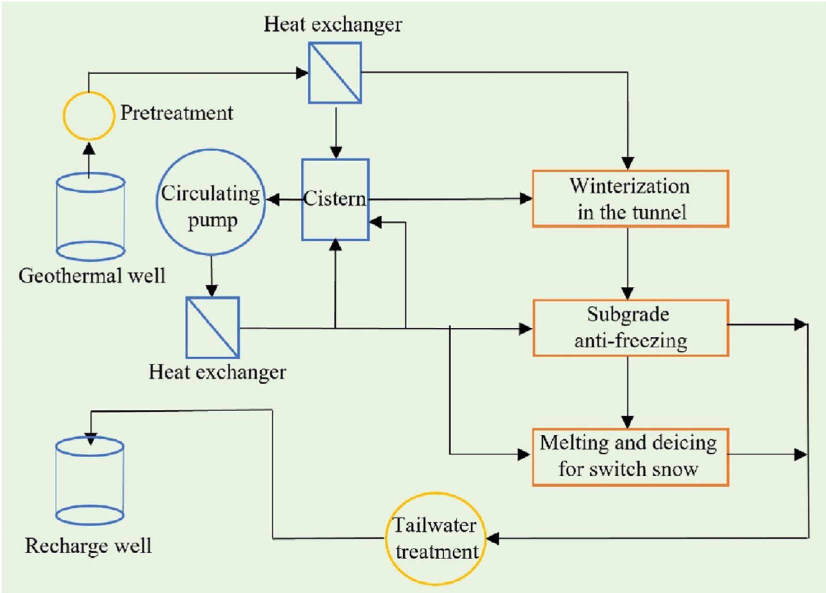

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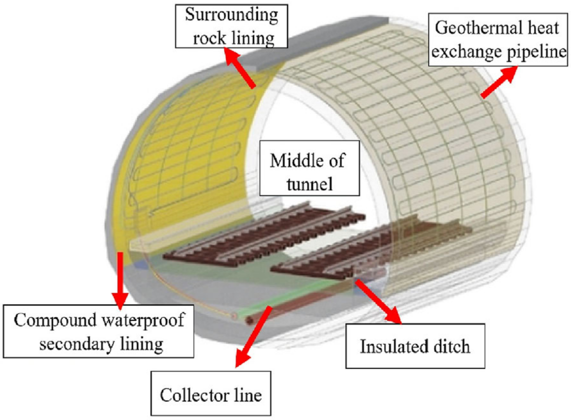
Figure 7. Geothermal comprehensive utilization scheme of railway during operation period

resources, geothermal energy can be harnessed to carry out snow melting and deicing operations at the speed-adjusted inlet and outlet of the tunnel. By utilizing geothermal energy in this way, it is possible to provide a heat source to raise the temperature of the affected areas, facilitating the melting of the ice and thus enhancing traffic safety within the tunnel.

To address the issue of freezing damage in tunnels within cold regions, a heat exchanger heating system can be installed in the tunnel (Qian, 2019). This system utilizes the tunnel lining as a heat exchanger to draw geothermal energy from the surrounding rock in the middle of the tunnel, with the aim of heating both the tunnel lining and the tunnel inlet drainage system. In cold areas, the temperature of the surrounding rock in the middle of the tunnel is significantly higher than that at the tunnel entrance. Hence, the lining in the middle of the tunnel is identified as the optimal installation location for the absorption pipe. The system mainly consists of a primary circuit, a secondary circuit, and a heat pump. In the primary loop, the absorption tube positioned between the primary lining and the secondary lining is connected to the front end of the heat pump via the collecting tube, forming a closed loop. Within this loop, a heat carrier fluid containing antifreeze circulates to extract geothermal energy from the surrounding rock. The heated fluid is then further heated by the heat pump and subsequently transported through piping to the heating pipeline, which in turn heats the tunnel lining and the thermal insulation ditch. The heating pipe located between the secondary lining and the insulation layer as well as within the insulation ditch constitutes the secondary circuit. After being enhanced by the ground source heat pump, it is employed to heat the lining and thermal insulation ditch of the tunnel entrance section, thereby reducing the freezing damage to the operating tunnel (as detailed in Figure 8).

4.2.2 Anti-freezing of subgrade in railway operation period. In severe cold climate zones, railway engineering encounters a major problem in the form of the periodic freezing expansion and thawing settlement of foundation and soil structures, which alternate in line with the changing seasons. For subgrade engineering specifically, aspects like space bulge and the upper driving load resulting from frost heave can exacerbate the migration of water and



Source(s): Authors' own work

Figure 8. Schematic diagram of using geothermal energy for operating tunnel frost protection

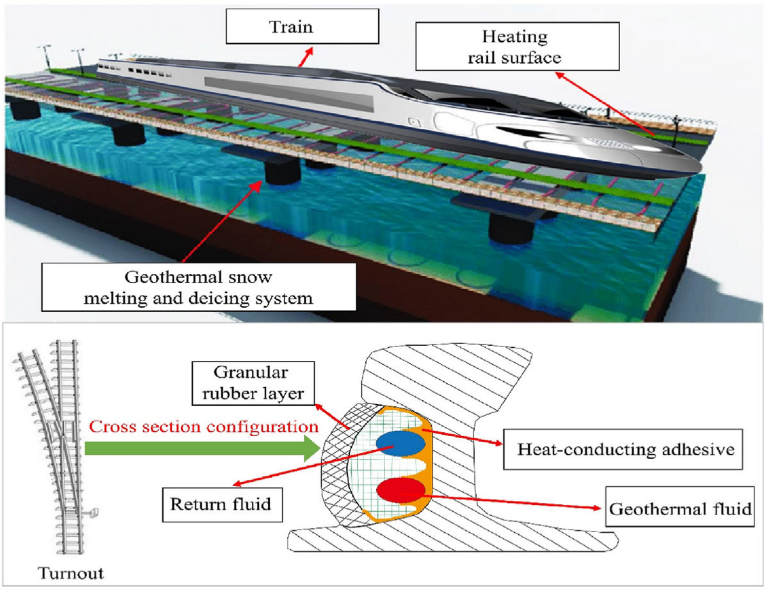
particles within frozen soil fillers. This, in turn, can trigger secondary issues such as mud pumping. The fundamental cause of subgrade frost heave lies in the rapid and excessive heat loss experienced by filler and foundation soil in the cold environment of winter. This leads to a sharp decline in temperature, dropping it below the freezing point. Under certain soil and water conditions, an ice-water phase change expansion occurs. Given that frost heaving is an inherent characteristic of granular materials, controlling subgrade frost heave has become one of the crucial challenges that railway operations in cold regions must confront.

To prevent frost heaving damage during the operation of a railway subgrade, it is advisable to install a geothermal pipeline network beneath it. The pipeline should be made of high-pressure and corrosion-resistant materials, and its layout and spacing should be determined based on the width, length, and geological conditions of the subgrade. By introducing geothermal fluid into the pipeline, the geothermal heat can be utilized to maintain the temperature stability of the subgrade soil, thereby averting frost heave. To enhance heat transfer efficiency, materials with good thermal conductivity can be placed around the pipe. Additionally, temperature sensors should be installed on the subgrade surface and at various depths to monitor the temperature changes of the subgrade in real-time. The flow and temperature of the geothermal fluid can be adjusted by an automatic control system to ensure that the subgrade remains at an appropriate temperature. This system can effectively address the issue of railway subgrade frost heave and guarantee the stability and safety of the railway tracks. The relevant measures are anticipated to considerably reduce subgrade frost heave, minimize track irregularities and line maintenance costs associated with subgrade frost heave, and offer favorable environmental and economic benefits.

4.2.3 Turnout snow melting de-icing. The climate in the high and cold mountainous regions indeed exhibits characteristics such as insufficient heat, a frigid climate, and a large daily temperature difference. In winter, the railway tracks in cold areas frequently experience snowfall and freezing. Across the country, the snow and ice season has a wide-ranging impact and endures for an extended period, with 60% of railway lines being affected by such weather conditions. In alpine mountainous areas, there is snow cover for most of the year, except during June to August. The presence of a large amount of high-humidity air is prone to being affected by low temperatures, leading to the formation of dark ice on the railway tracks. This ice can cause wheel slips, as exemplified by the incident on December 14, 2023, on the upward section of Xierqi to Life Science Park of the Beijing Metro Changping Line, where a train rear-end collision occurred due to a snowy track slip. Moreover, continuous snow and ice cover can easily bury lines and turnouts, resulting in the detention or shutdown of train sections. However, in alpine mountainous areas rich in geothermal energy, the utilization of geothermal energy for snow melting and deicing of turnouts holds great promise and offers a practical solution to mitigate these challenges. This could involve installing geothermal heating systems near the turnouts to melt the snow and ice, ensuring the smooth operation of the railway tracks and enhancing safety and efficiency.

As depicted in Figure 9, the railway turnout snow melting and de-icing system that relies on geothermal energy primarily consists of several components, namely the geothermal energy acquisition device, the heat exchange system, the monitoring and control system, and the snow melting and de-icing device.

Firstly, by introducing cathode and anode electrodes at the inlet of the geothermal water collection, the ions within the geothermal water can be decomposed or made to actively precipitate. This serves to decrease the ion content in the geothermal water and consequently reduces the likelihood of corrosion or scaling occurring inside the pipeline. Simultaneously, by adding perfluoropolyether derivatives and tetraethyl orthosilicate to the inner wall of the pipeline, a superhydrophobic coating can be formed on it. Through this method, the geothermal water is prevented from directly coming into contact with the interior of the pipeline, which further diminishes the probability of the pipeline being corroded or fouled. During the heat extraction stage, an organic working fluid with a lower boiling point is added in place of water to enhance the efficiency of geothermal heat extraction. On this foundation, the efficiency of geothermal heat extraction can be managed by installing flowmeters and regulating valves. To guarantee the effectiveness of long-distance heat transfer, thermal insulation materials can be incorporated into the pipe wall. Moreover, a multi-layer thermal insulation structure with a staggered arrangement can be designed to cut down on heat loss during the long-distance heat transfer process. When it comes to the heat transfer stage, the employment of a double-tube heat exchanger can effectively boost the contact area between



Source(s): Authors' own work

Figure 9. Snow melting and deicing scheme of railway switch in alpine mountain area based on geothermal energy

the geothermal fluid and the pipe wall. At the same flow rate, the flow rate of the working fluid is relatively low, which is conducive to maximizing the heat transfer process. Finally, the heat pipe of the track snow melting and deicing device is connected to the return pipe. The liquid working fluid is guided by the return pipe and ultimately returns to the collector, thereby achieving a safe, energy-efficient, and efficient snow melting effect.

4.2.4 Geothermal railway station. Railway transportation is an important mode of transportation, and the energy mode of station construction is of great significance to the transformation of transportation energy. Geothermal resources have become an ideal choice for energy supply in railway stations due to their renewable, environmentally friendly and stable characteristics. Geothermal stations usually adopt the combination of ground source heat pump system and geothermal heating and cooling, and exchange heat with underground rock and soil through underground buried pipe heat exchanger. For the heating system of the station, the principle is that the hot water circulates in the pipeline buried under the floor, and the heat is transmitted upward in the form of thermal radiation. At the same time, radiators are also used in some local areas or rooms with high heating rate requirements. The radiator transfers the heat of hot water to the surrounding air by convective heat transfer. After the air is heated, the density becomes smaller and rises, and the colder air around is supplemented to form natural convection, so that the indoor temperature rises rapidly. In the aspect of refrigeration, the geothermal station uses the principle of ground source heat pump. Through the components such as compressor, evaporator, condenser and expansion valve, the refrigerant circulates in the system to realize the transfer of heat from indoor to underground. When the heat in the station is transferred, the indoor temperature will be reduced, so as to achieve the effect of refrigeration. In terms of public water supply, geothermal fluids transfer heat through heat exchangers to the water in the domestic hot water storage tank. This heat exchange process ensures that domestic water can be heated to an appropriate temperature. At the same time, in order to cope with the peak and trough of hot water demand, the system will be equipped with heat storage tank and auxiliary electric heating device. The heat storage tank can store hot water during low demand periods, while the auxiliary electric heating device plays a supplementary role when the amount of hot water is insufficient to ensure the continuous supply of hot water.

Taking Chengdu East Station as an example, the ground source heat pump of Chengdu East Station has an average start-up time of 100 days in the whole winter, and runs for 12 hours a day. It consumes about 2 million degrees of total electricity and can output about 9 million degrees of electric energy. Compared with the traditional energy supply mode, it is found that if the electric boiler is used to output 9 million degrees of heat energy, it needs to consume 10 million degrees of electricity, and the gas boiler needs to burn 900,000 cubic meters of natural gas. This means that the ground source heat pump system of Chengdu East Railway Station saves about 8 million degrees of electricity in a winter, which greatly reduces carbon dioxide emissions. It can be seen that geothermal stations have significant economic benefits and environmental protection, and should be popularized and applied in the future railway.

4.2.5 Railway hot spring health tourism line. Taking into account the distinctive natural scenery and the plentiful geothermal resources in China, it is highly advisable to develop railway tourism and health care lines. Select areas along the railway that are rich in geothermal resources and boast a beautiful environment to establish tourism and health care sites. Subsequently, construct geothermal hot spring resorts, health hotels, rehabilitation centers, and other related facilities in the vicinity of these sites. Leverage the health care benefits of geothermal hot springs to develop a diverse range of hot spring convalescence packages, including hot spring baths, hot spring massages, hot spring spas, and so on. This way, personalized health care services can be offered to cater to the different requirements of passengers. Simultaneously, integrate the surrounding natural landscape resources. Design tourist routes like hiking trails and ecological sightseeing paths, thereby organically combining geothermal health care with natural tourism. In doing so, unique railway tourism health care products can be created. Moreover, make use of geothermal resources for heating, cooling, and domestic hot water supply within the tourism and rehabilitation sites. This will ensure that tourists can enjoy a comfortable living environment during their stay. Such an integrated approach not only enriches the tourism experience but also maximizes the utilization of local geothermal resources, bringing multiple benefits to both the tourism industry and the local economy. Simultaneously, efforts should be made to fully exploit the ice and snow and forest resources, promote regional linkage to develop the tourism industry along the route, and construct a high-standard "hot spring + snow mountain + forest" wellness tourism base. This will not only boost the local tourism economy but also contribute to the overall development of the region, attracting more tourists and promoting the integration of various industries, thus creating a more prosperous and vibrant economic and cultural landscape along the railway.

5. Conclusion

This study commences with a thorough and systematic compilation of the distribution of geothermal resources across China, and further expounds on the present state of utilization of these resources in China. In view of the practical traits manifested by the railway during both its construction and operational epochs, a detailed and methodical examination of the geothermal utilization paradigms pertinent to the railway has been executed. It is anticipated that the resultant findings will furnish substantial support and constitute a dependable point of reference for the comprehensive exploitation of geothermal resources along the railway. Specifically, the ensuing conclusions have been drawn:

(1) Although China's geothermal resources are exceedingly copious, however, in the affiliated areas, the employment of these geothermal resources is preponderantly centered on hot spring leisure bathing. This mode of utilization is comparatively elementary, bereft of well-devised and rational planning. Consequently, the utilization rate of the geothermal resources lingers at a relatively subdued level.

(2) The comprehensive utilization mode of geothermal energy during the construction period of railway includes power generation for tunnel illumination, heating of construction areas, anti-freezing measures in tunnels leveraging shallow geothermal energy, anti-freezing of tunnel pavements, and maintenance of construction concrete.

(3) The comprehensive utilization mode of geothermal energy during the operation period of railway includes anti-freezing within operation tunnels, anti-freezing of the railway roadbed within the operation line, snow melting and deicing of railway switches, establishment of geothermal power stations, and the planning of hot spring health tourism along the railway.

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