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Heat Hazards in High-Temperature Tunnels: Influencing Factors, Disaster Forms, the Geogenetic Model and a Case Study of a Tunnel in Southwest China

Chengkun Wang [1], Zhengyu Liu [2,*], Fengkai Zhang [2,*], Qian Guo [3,4], Zhao Dong [5] and Peng Bai [1]

[1] School of Qilu Transportation, Shandong University, Jinan 250061, China; 201714563@mail.sdu.edu.cn (C.W.); 15966330398@163.com (P.B.)
[2] Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China
[3] School of Future Technology, Shandong University, No. 17923 Jingshi Road, Jinan 250061, China; hhu_gq@163.com
[4] School of Water Conservancy and Environment, University of Jinan, No. 336 Nanxinzhuang Sourth Road, Jinan 250022, China
[5] School of Civil Engineering, Shandong University, Jinan 250061, China; doongzhao1997@163.com
* Correspondence: liuzhengyu@sdu.edu.cn (Z.L.); sduzfk@163.com (F.Z.)

Abstract: The construction of extensive tunnels in regions characterized by high geothermal activity presents significant challenges and inherent risks that affect both the safety and operational efficiency of construction personnel. This study investigated the factors influencing geothermal fields in shallow crustal rock formations through a comprehensive examination of existing literature and a detailed analysis of case studies. In addition, this study categorizes the geogenetic models of high-temperature heat hazards into three major classifications. Research findings indicate that several key factors significantly influence the geothermal fields. These factors, which include the deep geothermal background, heat transfer conditions, and localized additional heat sources, are paramount in shaping the geothermal field. Notably, it is observed that among these factors, the presence of additional heat sources, particularly the circulation of underground hot water, poses the most considerable threat to safety and operational efficiency. Moreover, this study utilizes a representative high geothermal tunnel in Southwest China to conduct a field investigation. This investigation assesses the potential for high-temperature thermal hazards within the tunnels, evaluates the geological conditions, verifies the factors governing the geothermal field, and outlines specific measures for the prevention and control of high geothermal tunnels. In conclusion, this study provides a structured analysis of lessons learned from these experiences, along with practical countermeasures for addressing high-temperature thermal hazards during the various stages of tunnel construction. The findings of this research serve as a valuable reference for those investigating the mechanisms behind geothermal disasters in tunnel construction. Furthermore, they offer practical guidance to ensure the secure and efficient excavation and sustainable operation of tunnels in the challenging geological environments characterized by high geothermal temperatures.

Keywords: high-temperature tunnel; heat hazard; influencing factor; disaster forms; geogenetic model

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1. Introduction

Tunnel excavation often encounters various geological disasters such as collapse, large deformation, and water and mud inrush. These disasters are posing major construction safety concerns and can severely delay project progress [1–7]. The issue of high geotemperature presents one of the inevitable geological disasters inside a tunnel during the construction and operation stages [8,9]. During the construction of ultra-long tunnels, encounters with high rock temperature and high-temperature water gushing are not uncommon [10–15]. In some cases, rock or hot water temperatures can even reach

80 or 90 °C. For instance, the rock temperature in a tunnel in China, reaches a remarkable 89.9 °C [12]. Similarly, a tunnel in SW China experiences temperatures exceeding 65.4 °C [13], while the Bulunkou-Konger Power Station Diversion Tunnel in China records even higher temperatures, peaking at 105 °C [14].

In the construction of deep-buried, long tunnels within regions characterized by high temperatures, the issue of heat hazards becomes especially pronounced when the rock temperature exceeds 35 °C, and the relative humidity surpasses 80% [16]. During the construction and operation of high-geotemperature tunnels, the high temperatures profoundly affect grouting materials, support structures, and the tunnel environment, posing a substantial threat to the safety and well-being of construction personnel and diminishing construction efficiency [17–20]. For this reason, it is crucial to study the high temperature issue for the sustainable development of tunnels.

There are two main reasons that can explain the difficulty in managing the issue of high geotemperatures, i.e., the intricate geological origin of high geotemperatures and technological constraints. High geotemperature issues predominantly manifest in regions abundant in geothermal and underground hot water resources. These areas often feature numerous thermal faults within the deep rock strata, characterized by a random orientation. High-geotemperature areas cannot be avoided during tunnel construction in these regions, and high-geotemperature tunnels frequently arise. Moreover, high temperatures in tunnels often occur simultaneously with high-temperature water gushing, significantly amplifying the complexity of tunnel construction. The lack of a comprehensive understanding of the principal controlling factors contributing to high temperatures in tunnels poses a significant challenge to effectively addressing high-temperature issues. Concurrently, the prediction of temperatures along the tunnel alignment often relies on ground drilling for temperature measurement to estimate temperatures at various depths along the tunnel route. However, this method is limited to providing only approximate assessments of high-temperature areas. Temperature forecasting within tunnels typically utilizes borehole temperature measurements to predict temperatures in the surrounding rock ahead of the tunnel. Nevertheless, this approach is afflicted by the "narrow view" issue, rendering it susceptible to omission errors. Currently, there is a deficiency in directly effective methods for the advanced geological prediction of tunnel surrounding rock temperatures, impeding the efficient management of high-temperature issues.

The issue of high geotemperatures has emerged as a prominent research focus within the engineering field, primarily due to its role in triggering a wide array of engineering challenges. To effectively address the recurrent issues of high-temperature heat hazards, this study aims to tackle three fundamental questions:

- Which geological factors may influence geotemperature and how do they affect the rock temperature?
- What are the main disaster forms and geogenetic modes of high-temperature heat hazards?
- What are the countermeasures for high-temperature heat hazards?

In the literature, a multitude of cases related to high-geotemperature tunnel engineering and construction, both domestically and abroad, have been documented. The majority of current studies and engineering practices concentrate on the surrounding rocks' heat conduction pattern, temperature field distributions, the evaluation of humid-heat environments, and the development of heat-insulating lining techniques [21–29]. While some advances have been made in the analysis of the causes of tunnel heat hazards [30–33], the majority of these studies have been carried out on a specific tunnel. There are few systematical studies and discussion on the factors influencing the geotemperature field and the modeling of the causes of heat hazards in tunnels. Hence, the primary objective of this study is to unveil the principal factors influencing the geothermal field of tunnels and to propose preventive and control measures against high-temperature heat hazards. The intention is to effectively manage and control thermal hazards during tunnel construction and operation, and ensure the safe service performance of the tunnel structure throughout its life cycle. Section 2 outlines the primary factors influencing geotemperature field. The

main disaster forms and geogenesis model of heat hazards are proposed in Section 3. In Section 4, the case study of heat hazards in a tunnel in the SW China is carried out. Detailed geological work is conducted to analyze the geological causes of heat hazards. The specific steps for prediction and prevention of high-temperature heat hazards are developed. Ultimately, the lessons learned are summarized. The countermeasures for high-temperature heat hazards are proposed in Section 5. The main conclusions can be seen in Section 6.

2. Factors Influencing the Geotemperature Field

The issue of high temperatures is a recurrent engineering and technical challenge encountered during the construction of long and deeply buried mountain tunnels. The dissipation of heat from various sources within the tunnel contributes to a rise in the internal air temperature. Additionally, the presence of water in the underground rock layers elevates the humidity within the tunnel environment. When temperature and humidity levels surpass certain thresholds, they combine to create a heat hazard.

The main heat sources in the tunnel are rock heat dissipation, hot water heat dissipation, compression heat release, electromechanical equipment heat release and oxidation heat release. Of these, the most significant source is the heat dissipation from the rock, which draws upon the Earth's vast reservoir of thermal energy supplied to the Earth's crust. The Earth's interior harbors an extensive reservoir of heat, referred to as the Earth's internal heat. This heat traverses from the Earth's interior to its surface through mechanisms such as conduction, convection, and radiation. In the process, it shapes the temperature field within tunnels, effectively representing the redistribution and accumulation of shallow geothermal heat within the Earth's crust. This complex interplay is governed by numerous influencing factors that can be distilled into three primary categories:

- The deep geothermal background reflected by regional geothermal heat flow,
- Spatial variations in heat transfer conditions caused by the heterogeneity of the geological structure, and
- The presence or absence of local additional heat sources and their scale and intensity.

2.1. The Influence of the Deep Geothermal Background Reflected by Regional Geothermal Heat Flow

Variations in the regional deep geothermal background manifest as changes in regional geothermal heat flow. Geothermal heat flow studies have consistently revealed that regional geothermal heat flow values closely correlate with regional geotectonic features [34]. Furthermore, alterations in geothermal heat flow observed in the shallow layers of the Earth's crust offer a comprehensive reflection of the subsurface's heat sources, geological formations, and tectonic activities. For instance, the emergence of high geothermal heat flow and temperatures in the Anfang Highway Tunnel in Japan can be directly attributed to volcanic activities [35]. Similarly, the Gaoligongshan Tunnel area lies at the north–south geotropical zone of the Nujiang River and the Gaoligongshan arc geotropical zone. The geothermal zone is related to the strong tectonic activity in the region. Deep and substantial ruptures have funneled heat from the Earth's interior into the shallower strata, resulting in geothermal anomalies and hot water activity within the shallow regions [36].

In the context of uniform geological conditions, the impact of varying geothermal heat flows on the geothermal field at different shallow depths within the Earth's crust is visually represented in Figure 1a, and detailed parameter settings can be found in case 1 of Table 1. Our findings indicate that, when operating under identical conditions, higher geothermal heat flow values result in higher temperatures at corresponding depths, which implies a higher probability of encountering risks in the context of higher geothermal heat flows.

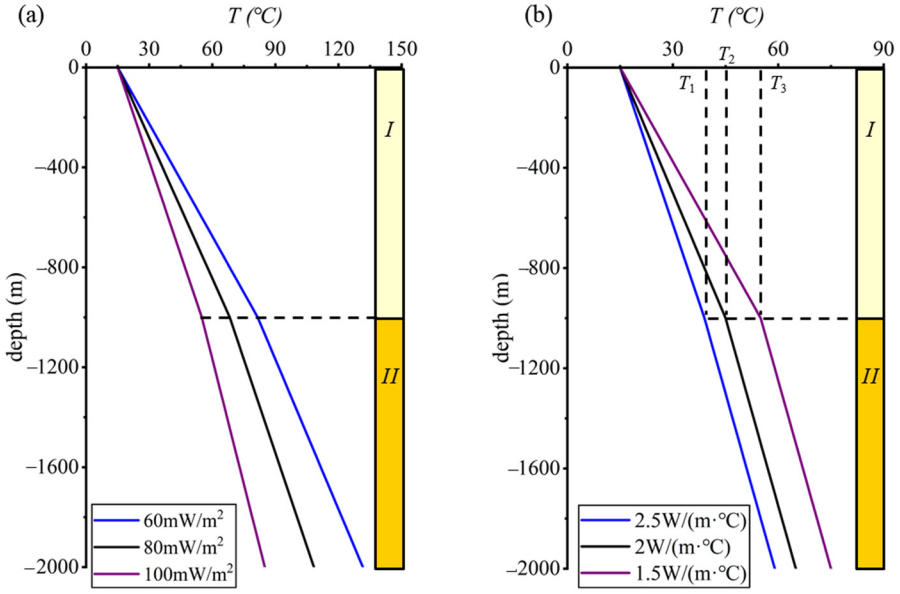

Figure 1. Effects of geothermal heat flow and thermal conductivity of rock formations on the geothermal field. (**a**) The change in the geothermal heat flow; (**b**) the change in the thermal conductivity of rock formations.

Table 1. Geothermal heat flow and thermal conductivity parameter settings.

	Variable	Rock Formation	Thickness/m	Thermal Conductivity λ W/(m·°C)	Geothermal Flow q mW/m^2
Case 1	q	I II	1000 1000	1.5 2	60 → 80 → 100
Case 2	λ_I	I II	1000 1000	2.5 → 2 → 1.5 3	60

2.2. The Influence of Spatial Variations in Heat Transfer Conditions Caused by the Heterogeneity of the Geological Structure

Contemporary geophysical and geological explorations have yielded findings indicating the widespread presence of inhomogeneities in crustal structures, in both the lateral and vertical dimensions. The heterogeneity of geological structures within the shallow crust is coupled with variations in the thermal conductivity of rocks, which determines the spatial variability and inhomogeneity of heat transfer conditions. Consequently, they give rise to a redistribution of geothermal heat flow, which is more uniform in deeper crust layers but becomes increasingly complex as it approaches the shallow crust. This redistribution induces intricate changes in the temperature field. Heat flow tends to follow a path directed away from areas with high thermal resistance and towards regions characterized by lower thermal resistance.

(1) The heterogeneity of rock thermophysical properties: The vertical distribution of the geothermal field is significantly influenced by the varying thermal conductivities of rock strata. Strata with low thermal conductivity often serve as thermal insulation cover. According to the principle of heat flow conservation within the Earth, when there are no additional heat sources, the heat flow value within each rock section of the same borehole is consistent. Consequently, the product of the geothermal gradient within each section of the borehole and the thermal conductivity of the rock is a constant. The geothermal gradient and thermal conductivity of each rock formation are in a reciprocal relationship. As a result, in rock formations characterized by low

thermal conductivity, the geothermal gradient increases, resulting in the phenomenon known as localized heat accumulation.

As depicted in Figure 1b, the thermal conductivity value of stratum I varies while keeping other conditions constant. Specific parameter settings can be found in case 2 of Table 1. As illustrated in the figure, it becomes evident that a decrease in thermal conductivity results in a heightened geothermal gradient, leading to a greater temperature differential for a given thickness of material. When the thermal conductivity is 2.5, 2, and 1.5 W/(m·°C), the corresponding temperatures of the rock at a depth of 500 m are 27, 30, and 35 °C, respectively.

(2) The heterogeneity of the geological structure: The geological structure plays a pivotal role in shaping the distribution of heat flow, consequently impacting the distribution of the geotemperature field (Figure 2). For instance, positive geological tectonic units, such as bedrock uplift areas, anticlinal structure, and crystalline rock zones with high thermal conductivity, exhibit low thermal resistance relative to neighboring surroundings. This facilitates the concentration of geothermal heat flow, resulting in localized heat accumulation. Negative geological tectonic units such as bedrock depression areas, syncline structure, and fault zone descending plates exhibit high thermal resistance relative to neighboring surroundings. This facilitates the dispersion of geothermal heat flow.

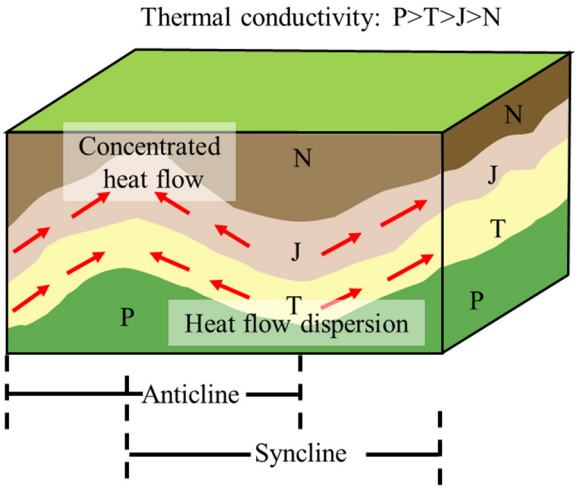

Figure 2. Influence of the heterogeneity of geologic structures on the geothermal field.

This phenomenon arises as an inevitable consequence of the heterogeneous configuration of geological structures under the heat conduction mechanism. A fundamental requirement for this phenomenon is that the thermal conductivity of the bedrock exceeds that of the overlying covering layer. The scope and intensity of the uneven alterations in heat flow distribution resulting from geological heterogeneity are contingent upon the contrast in thermophysical properties between the bedrock and the covering layer as well as the scale of tectonic inhomogeneities. The occurrence of high temperatures within the water diversion and power generation tunnel of the Bulunkou-Gonggeer Hydropower Station can be attributed to the conduction of heat from deep magmatism along well-conducted dykes or graphite-dense zones [37].

2.3. The Influence of the Presence or Absence of Local Additional Heat Sources and Their Scale and Intensity

The presence or absence of localized heat sources as well as their scale and intensity play a significant role in shaping the geothermal field. Two primary categories of additional heat sources are found in the shallow layers of the Earth's crust. One is caused by

groundwater activity, while the other is attributed to exceptionally high heat production within rocks.

(1) Groundwater, with its substantial specific heat capacity and high fluidity, stands out as the most influential thermogenic factor, playing a pivotal role in shaping the geothermal field [8]. Vertical groundwater movement exerts a considerably more significant impact on the geothermal field than horizontal movement. In the vertical motion of groundwater, the upward flow of relatively high-temperature water acts as a localized positive heat source, while the downward flow of lower-temperature water represents a negative heat source (Figure 3). The magnitude of geothermal field anomalies induced by groundwater activity correlates with several factors, including the water circulation depth, its flow velocity, and the temperature differential between the water and the surrounding rock.

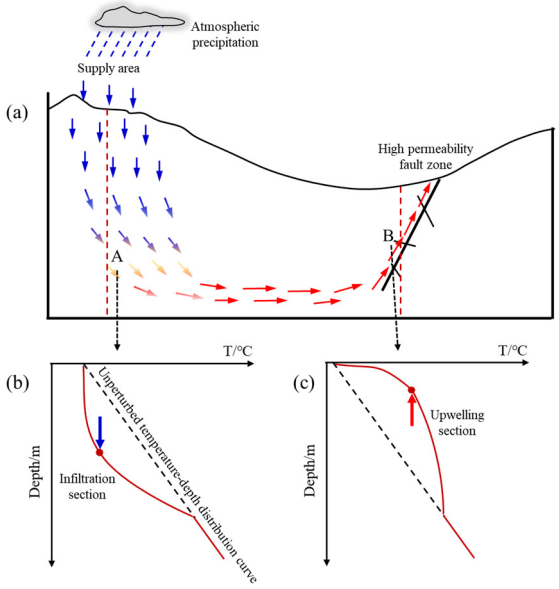

Figure 3. The influence of groundwater circulation on the geothermal field. (**a**) groundwater circulation diagram; (**b**) the effect of low-temperature downward flow on the geothermal field; (**c**) the effect of high-temperature upward flow on the geothermal field. Blue arrow indicates cold water, and red arrow indicates hot water.

Groundwater, as it descends from the recharge area, continuously absorbs heat from the surrounding rock, leading to a reduction in the temperature of the adjacent geological formations. Groundwater is heated by rock temperature during the deep circulation process. High-temperature water flows upward under favorable geological structural conditions, such as high-angle fault zones or steeply sloping permeable layer. Due to the temperature difference, heat is consistently transferred from the high-temperature water source to the surrounding rock formations on both sides. This gives rise to a thermally anomalous zone on both sides of the high-temperature water. The temperature field in the vicinity of the channel comprises the amalgamation of the regular geotemperature field with the supplementary temperature field resulting from the presence of heated water. During the vertical ascent of groundwater, its temperature surpasses that of the surrounding rock, consequently releasing heat into the nearby geological formations.

(2) The presence of radioactive heat-producing elements in rocks can act as an additional heat source. It is a well-established fact that various types of rocks contain trace amounts of radioactive heat-producing elements such as uranium, thorium, and potassium. However, the concentrations of these elements are typically quite low. Consequently, within the limited depth and thickness range of rocks, the heat generation from radioactive elements does not exert a significant influence on the

temperature field. In unique geological settings, some rock formations exhibit substantially higher levels of radioactivity. In specific regions like the Mesozoic volcanic basins of south-central China, the acidic volcanic rock layers display elevated radioactivity heat production.

In summary, local additional heat sources exert a significant influence on the temperature field in the shallow crust, with the degree of impact primarily dependent on the intensity and scale of the additional heat source. Higher-intensity heat sources may lead to a rapid increase in temperature in localized areas, while lower-intensity heat sources may cause comparatively smaller temperature changes. The presence of local additional heat sources also results in variations in the geothermal gradient, especially in the vicinity of the heat source, where temperature changes are more pronounced, and the geothermal gradient is larger. Higher-intensity additional heat sources may give rise to thermally anomalous regions. Generally speaking, the larger the scale of the additional heat source, the more extensive the anomalous areas in the shallow crust affected by it.

3. The Disaster Forms and Geogenetic Model of Heat Hazards

Based on engineering practice and a comprehensive literature review, the disaster forms and geogenetic model of heat hazards in high-temperature tunnels were proposed.

3.1. Classification of Disaster Forms of High-Temperature Heat Hazards

In the mid-19th century, European tunnel construction, including projects like the Sennis, Simplon, and Gotthard tunnels, confronted high geotemperatures as a significant challenge. The primary form of disaster encountered was the high-temperature and high-humidity environment within these tunnels. As we entered the 20th century, the construction of tunnels, such as the Mont Blanc Tunnel, Anfang Tunnel, and the New Gotthard Tunnel, faced severe heat-related challenges. In addition to the development of high-temperature and high-humidity conditions, high temperatures also exacerbated issues like significant deformation of surrounding rock. In the 1960s, during the construction of tunnels on the Chengdu-Kunming Line, China encountered high temperatures for the first time. The surrounding rock temperature ranged from approximately 35 °C to 40 °C, accompanied by the presence of hot water. Subsequent key tunnel projects, such as the Qinling Tunnel, experienced varying degrees of high-temperature challenges. Moving into the 21st century, tunnels in western China, including the Jiwohiga, Sangzhuling, and Gaoligongshan tunnels, have confronted severe high-temperature issues. The high temperatures have significantly impacted issues like substantial deformation of soft rock and occurrences of rock bursts.

Through the comprehensive study of the typical high-temperature tunnel disasters at home and abroad, the tunnel disasters triggered by high temperatures are categorized into the following four major categories (Table 2).

Table 2. The disaster forms of high-temperature heat hazards in tunnels.

Targets of Disasters	Forms of Disasters
Tunnel environment	Damage to physical and mental health of workers Elevated risk of machinery and equipment failures Reduce labor efficiency of workers
Surrounding rocks	Worsen the deformation of soft rock Affect the rock explosion process in hard rock Increase safety risks associated with blasting operations
Support structure	Reduce the anchoring force of anchor rods (ropes) Deteriorate the mechanical properties of concrete Result in lining cracking
Geologic disaster	Heighten the risk of incidents such as hot water inrushes, gas explosions, and landslides

(1) Inducing high temperature and humidity levels within tunnels: High geotemperatures can result in an increase in temperature and humidity levels within tunnels [18]. This, in turn, can lead to reduced labor efficiency, adverse impacts on the physical and mental health of workers [19], and an elevated risk of machinery and equipment failures.
(2) Exacerbating deformation and damage to tunnel surrounding rock: High geotemperatures have the potential to worsen the deformation of soft rock, affecting the rock explosion process in hard rock, consequently increasing safety risks associated with blasting operations.
(3) Triggering failures in tunnel support structures: The high-geotemperature environment may reduce the anchoring force of anchor rods (ropes), deteriorate the mechanical properties of concrete (Figure 4b), and even lead to lining cracking.

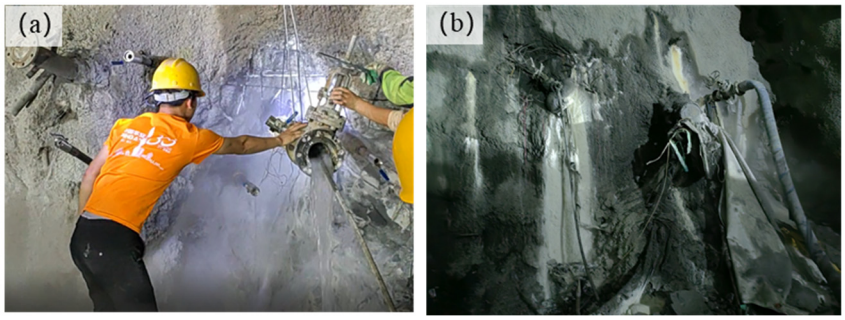

Figure 4. The two forms of disasters of high-temperature heat hazards. (**a**) Hot water gushing out; (**b**) grouting material failure.

(4) Augmenting safety risks in projects: High geotemperatures can heighten the risk of incidents such as hot water inrushes (Figure 4a), gas explosions, landslides, and other accidents.

3.2. Geogenetic Models of High-Temperature Heat Hazards

Considering the primary factors influencing geothermal fields, the causes of high-temperature heat hazards can be classified into three distinct categories: deep-source high-heat, localized heat gathering, and additional heat source. Within these categories, the deep-source high-heat type is affiliated with the deep source classification, whereas the localized heat gathering and additional heat source types are subsumed under the shallow source category.

A more comprehensive delineation of the three principal categories of thermal hazards, taking into account heat-causing factors, heat gathering conditions, and geothermal types, is provided in Table 3.

Table 3. Classification of geogenetic models of high-temperature heat hazards in tunnels.

Heat Hazard Type	Specific Classification	Characteristics
Deep-source high-heat type	—	In regions characterized by high-heat-flow backgrounds, the presence of deep-seated high-temperature sources results in elevated temperatures and heat flow within the shallow layers of the Earth's crust (Figure 5a).
Localized heat gathering type	High thermal resistance rock cover subtype	In areas with a normal regional geothermal background, tunnels situated beneath a thick sedimentary cap layer experience high temperatures and steep geothermal gradients due to the high thermal resistance of the cap layer (Figure 5b).
	Bedrock uplift subtype	Within regions featuring a normal regional geothermal background, the presence of positive geological structures, characterized by lower thermal resistance compared to surrounding bedrock structures, leads to heat accumulation in these areas, resulting in elevated temperatures and increased heat flow (Figure 5c).

Table 3. *Cont.*

Heat Hazard Type	Specific Classification	Characteristics
	High thermal conductivity rock belt subtype	In locations characterized by the normal regional geothermal background, the presence of rocks with significantly high thermal conductivity in the tunnel's surroundings results in the formation of a high thermal conductivity rock zone. This, in turn, causes heat accumulation, resulting in elevated temperatures and increased heat flow (Figure 5d).
Additional heat source type	High heat-producing rock subtype	Under specific geological conditions, the presence of rock layers at the depth of tunnel rich in heat-generating elements acts as an additional heat source. This factor influences the temperature field and becomes a significant contributor to tunnel temperature anomalies (Figure 5e).
	Underground hot water circulation subtype	Tunnels located in the pressure discharge area of a significant groundwater basin or within the discharge zone of a groundwater circulation system in a major fault zone are primarily affected by the rising activity of hot water. It becomes the main factor causing tunnel heating. The tunnels are directly and indirectly affected by hot water, which manifests itself in high rock temperatures and high-temperature water inrushes, respectively (Figure 5f).

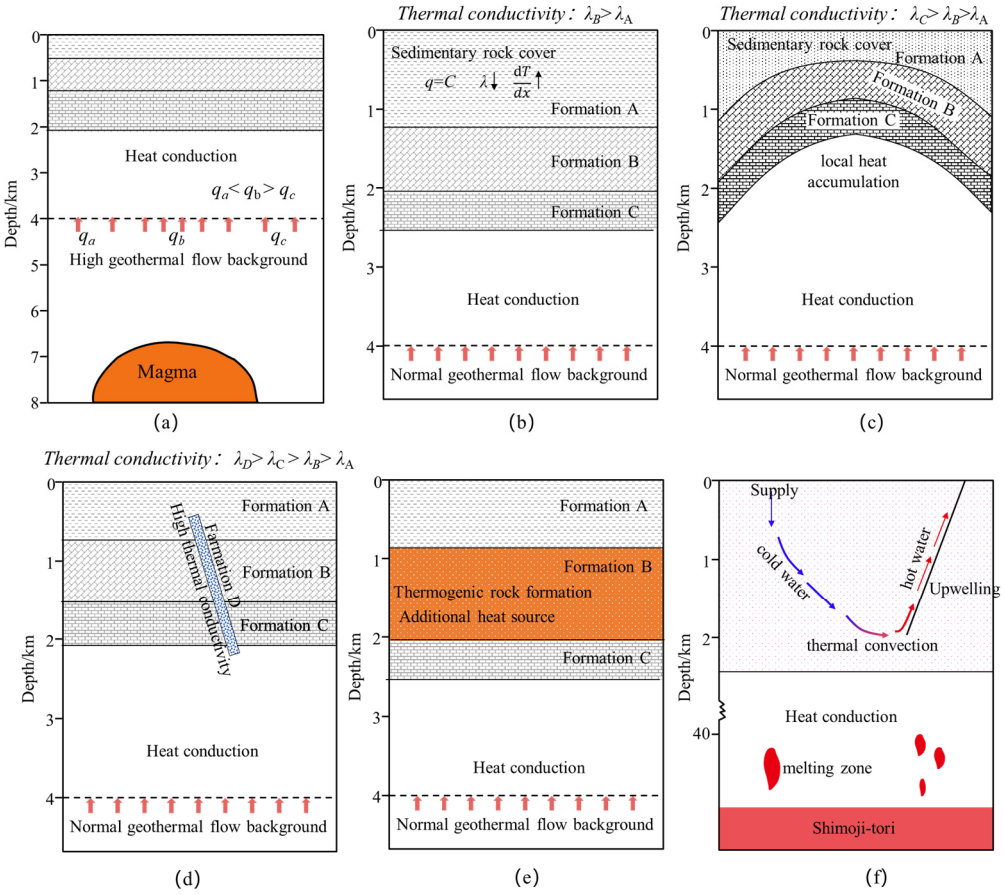

Figure 5. Types of geological origins of high-temperature heat hazards. (**a**) Deep-source high-heat type; (**b**) high thermal resistance rock cover subtype; (**c**) bedrock uplift subtype; (**d**) high thermal conductivity rock belt subtype; (**e**) high heat-producing rock subtype; (**f**) underground hot water circulation subtype.

4. Case Study

Within the context of a high-temperature railroad tunnel project in Southwest China, an extensive on-site geological study was undertaken. The objective of this case study is to provide a comprehensive elucidation of the fundamental factors that govern heat hazards in high-temperature tunnels. Additionally, specific strategies for forecasting and mitigating high-temperature heat hazards are presented, thus ensuring the uninterrupted advancement of the tunnel excavation.

4.1. Engineering Description

The high geothermal tunnel of the Southwest China Railway Tunnel, stretching over 31.7 km in length, boasts a maximum depth exceeding 2000 m and a minimum depth of approximately 40 m (Figure 6). Seven transverse holes were built to help with the excavation of the main tunnel and the tunnel is built using the drilling–blasting method. The area where the tunnel is located is in the vicinity of a tectonic suture zone resulting from the collision of geological plates, with the development of folds and fractures. Notably, it is endowed with abundant geothermal and subterranean hot water reservoirs. Consequently, there are a unique set of challenges in traversing this geological region, such as the risk of ultra-high rock temperatures and high-temperature water inrushes.

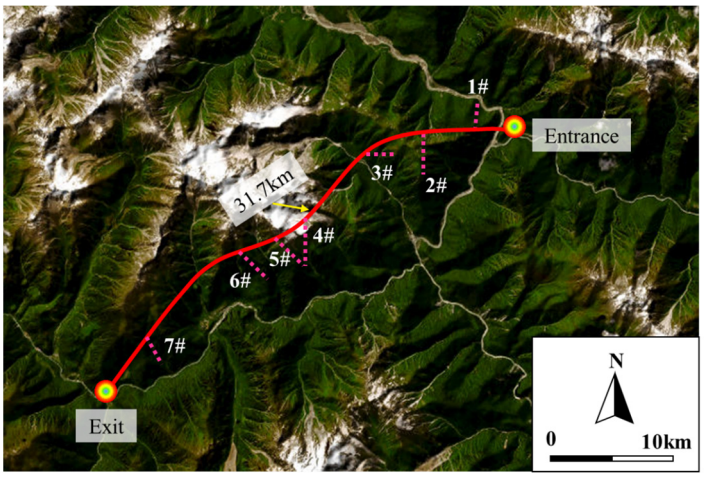

Figure 6. Satellite image of a high-temperature railroad tunnel area in Southwest China. Numbers 1# to 7# represent seven transverse holes.

4.2. Analysis of the Geological Causes of Heat Hazards

The research was carried out on the example of a high geothermal tunnel 5# transverse hole in Southwest China, with a total length of about 2.47 km. The main lithology is grayish-white Paleo-Middle Paleozoic gneiss (Figure 7). Based on the surface survey and borehole temperature measurement results, the temperature along the tunnel was estimated. In Figure 7, the temperature along the tunnel is generally high, with the surrounding rock temperature approximately 28 °C over 1.7 km, accounting for 69% of the total length. The area where the rock mass temperature is greater than 60 °C exceeds 350 m. The problem of heat hazards is more prominent.

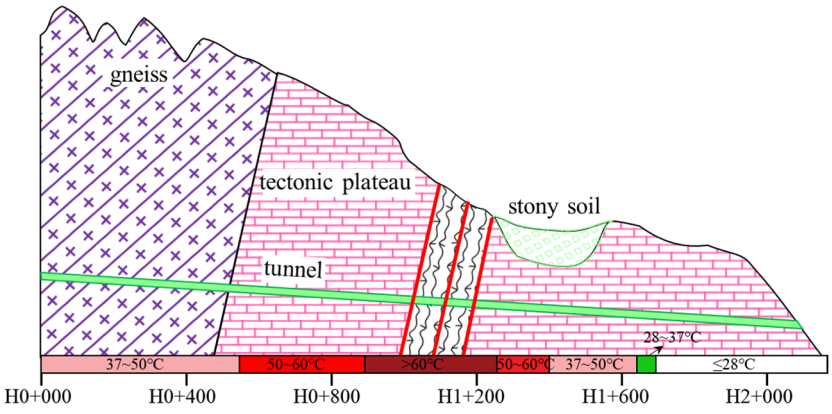

Figure 7. Geological longitudinal section and temperature forecast of 5# transverse hole.

Since the start of construction in May 2021, the surface monitoring temperature of the surrounding rock has been greater than 30 °C, up to 76.9 °C, starting at mileage H2+415.

In the mileage area of H1+307~H2+289, H1+270~H2+258, high-temperature water has been encountered several times with the highest water temperature of 93.5 °C and the maximum surge of water up to 215 m^3/h. The ambient temperature inside the cave could reach 47.6 °C, which seriously affected the tunnel construction.

Analysis reveals that the 5# transverse hole belongs to the type of groundwater cycle genesis. The geothermal heat flow rate in this area ranges from 85 to 95 mW/m^2, surpassing the continental average by 1.5 times. Its comprehensive heat source includes the frictional heat generation of fractures accompanied by the land–land collision mountain cutting process in the suture zone, as well as the local melting within the crust and the Cenozoic igneous rocks. The precipitation and snowmelt at the elevation of 3500~4300 m in the north is transported to the deep south through the deep and large fracture zone in the project area, and warmed up in the background of higher earth heat flow. Simultaneously, water gains additional heat enrichment as it travels along the deep and large fracture of the suture zone, constituting the main hot water recharge. Through a long time deep circulation, when the hot water transported to the south to the area near the fracture convergence or the fissure intensive decompression zone, the hot water rises and overflows, and is discharged to the surface near the river gully. It is currently revealed that the high-temperature water section of 5# transverse hole is located on the right side of the deep ravine and at the junction of steep and gentle terrain. Due to the low topography and pressure near the deep-cut gullies, high-temperature water in the deep parts rises up and accumulates in the deep-cut ravine sections. Simultaneously, the deep-cutting gully and both sides are affected by slope stress, and the rock mass is relatively broken, easily forming a strong groundwater runoff zone.

4.3. Prediction, Prevention and Control of High-Temperature Heat Hazards

The underground circulation of hot water within this tunnel plays a pivotal role in shaping the geothermal field of the surrounding rock. Obtaining detailed information on water- and heat-conducting channels such as faults and fracture zones is the basis for analyzing the engineering geothermal field before excavating into the high geothermal area. Consequently, a macro-geological investigation is conducted during the initial tunnel design phase. In the actual tunnel excavation process, advanced geological forecasting is carried out to ensure precise detection. This is typically achieved through the utilization of advanced drilling methods as the primary approach, complemented by geophysical exploration techniques. These methods are combined with the findings from the initial geological investigation. The goal is to obtain a rich dataset of geological information ahead of the tunnel's progress, enabling us to predict the temperature conditions of the rock formations and the type and magnitude of thermal hazards.

The thermal water inrush that occurred at mileage H1+260 was taken as an example. Figure 8 presents the results of temperature detection in the vicinity of H1+278~H1+246. It reveals the presence of an exceptionally high-temperature zone within the range of H1+252~H1+248, hinting at the possible existence of a high-temperature heat source within this interval. Figure 9 shows the results for the multi-borehole-induced polarization detection in the range of H1+270~H1+246. Within this context, it becomes evident that a region characterized by low resistivity materializes at H1+252~H1+246. This observation suggests the likely presence of groundwater in this specific area.

The comprehensive detection results in Figures 8 and 9 show that there is high-temperature water area near the H1+252~H1+246 interval, which will cause engineering disasters in tunnel excavation. Carrying out overrun drilling at H1+270, high-temperature water emerges as shown in Figure 10, which verifies the validity of the analysis of the geological causes and the factors influencing the generally high geothermal field in this tunnel.

The tunnel may encounter both identified and unmet adverse geologic conditions during construction. In order to reduce the risk of ultra-high rock temperature and high-temperature hot water gushing out from the tunnel, the specific steps to predict and prevent high-temperature heat hazards are shown in Figure 11. Before excavation, large water- and heat-conducting structures (e.g., faults) are identified through preliminary geological

reports and macro-geological surveys. Then, comprehensive geophysical exploration methods are used to detect the rock temperature and hot water. According to the results of geophysical exploration inversion, the scope of fine geological investigation can be narrowed down. Secondly, the geological work, i.e., advance drilling and geological investigation, should be performed carefully to obtain detailed geological information. On the basis of analyzing the grade of thermal hazards, the design of cooling, support and blasting program is carried out according to the detailed information of adverse geology.

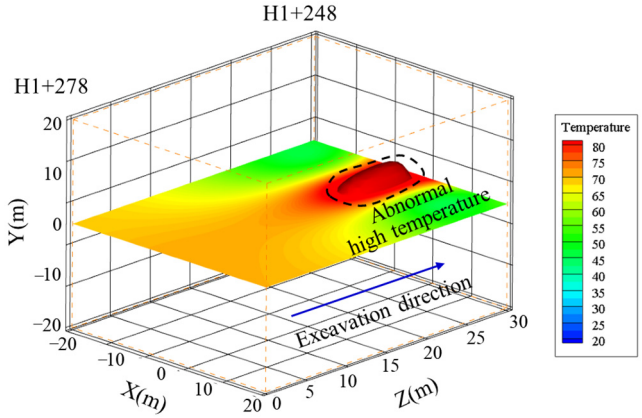

Figure 8. Temperature field detection results obtained through the heat source inversion from mileage H1+278 to H1+248.

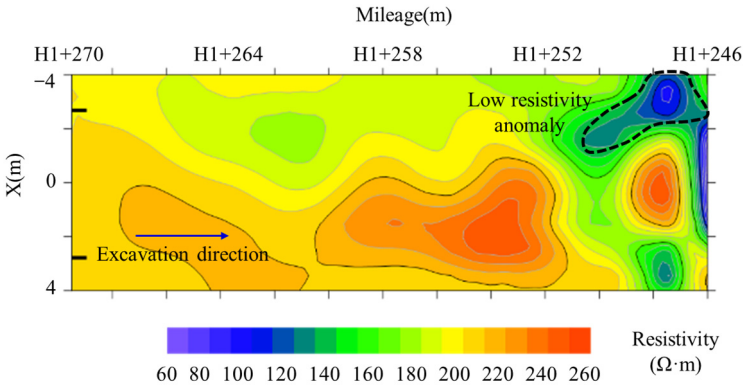

Figure 9. Inversion result of multi-borehole-induced polarization tomography from mileage H1+270 to H1+246.



Figure 10. High-temperature hot water revealed through advance drilling at H1+270.

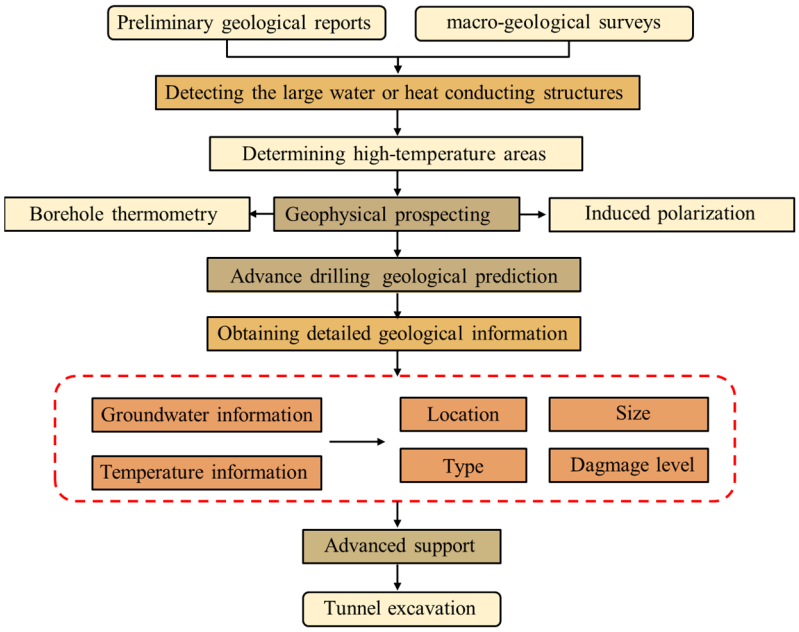

Figure 11. Procedure of control of high-temperature heat hazards.

5. Lessons Learned and Discussion

5.1. Lessons Learned

The experiences obtained from heat hazard cases and the detailed information in the high geothermal tunnel of the Southwest China railway tunnel are summarized as follows.

- The localized additional heat source, arising from groundwater circulation, significantly impacts the temperature distribution in the Earth's crust. This influence is primarily expressed through two key processes: heat conduction and heat convection, which are, respectively, manifested as ultra-high rock temperature and high-temperature hot water within the context of the tunnel project.
- The geothermal gradient attributed to groundwater circulation in this region surpasses the Earth's average geothermal gradient. In some areas, this gradient is several times higher, leading to a pronounced issue of high geotemperatures. For example, the highest recorded water temperature in this tunnel reaches 93.5 °C, while the highest rock temperature attains 77 °C.
- The existence of high-temperature hot water (greater than 80 °C in this tunnel) significantly impacts the consolidation process of grouting materials. Conventional grouting materials are susceptible to failure under these conditions.
- Owing to the heat conduction effect, the groundwater circulation, serving as an additional heat source, engenders a broader spectrum of heat effects. The tunnel heat hazard area is influenced by temperature conditions over a wide geographical range.

5.2. Countermeasures for High-Temperature Heat Hazard Prevention and Control

The process of high-temperature heat-induced hazard control can be divided into two stages, which are the stage of geological investigation and the stage of excavation. The countermeasures for each stage are developed based on the different features of each stage.

5.2.1. Stage of Geological Investigation

In the tunnel design phase, a comprehensive investigation of the geological conditions within the strata is imperative, followed by the selection of the most suitable route. This meticulous approach significantly diminishes the likelihood of geological hazards. The geological investigation comprises the following key aspects:

(1) Regional geothermal environment investigation: During the investigation and planning of underground engineering, the prediction of high geothermal temperature

issues can be obtained by inquiring pertinent data pertaining to the distribution of geothermal resources within the project area.

(2) Hot springs examination: The presence of hot springs, particularly those of high temperatures, often signals the potential existence of geothermal resources in the project area, potentially posing challenges related to high geothermal temperatures. Investigating the causes of hot springs within the project's scope, including an analysis of water temperature, water quality, the local tectonic environment, hydrogeological conditions, and the correlation between hot springs and the groundwater system's chemical composition, is crucial to determine whether high geothermal temperatures could pose issues at the project site.

(3) Geothermal parameters assessment: This involves the determination of constant temperature depth and its corresponding temperature, as well as the geothermal gradient, which represents the increase in rock temperature per 100 m of depth. These parameters serve as critical foundational data for analyzing the geothermal field in underground engineering. Therefore, comprehensively understanding the geothermal parameters in the region, through advanced logging techniques, is essential for predicting and addressing potential high geothermal challenges.

(4) Identification of exposed high geothermal temperature forms: By considering regional structural characteristics, rock conditions, groundwater recharge and discharge patterns, and the relationship between the elevation of hot springs and the tunnel's alignment, a preliminary assessment of the exposed forms of high geothermal temperatures at the project site can be made. This enables informed decision-making in the selection of construction measures and design schemes.

5.2.2. Stage of Tunnel Excavation

In regions characterized by high geothermal activity, conducting a comprehensive geological investigation is imperative. This investigation should encompass data collection, field investigation, drilling and temperature measurement, physical exploration and other means. The primary goal of this investigation is to meticulously determine the range and temperature values of the subsurface environment where the tunnel will be constructed. This critical information serves as a foundational resource for designing the tunnel and establishing a robust construction plan.

(1) Data collection: Collect high-temperature heat hazard data, topography and geomorphology, stratigraphic lithology, geological structure, hydrogeology, the type of surrounding rock, and on-site geological records.

(2) Surface exploration: Surface exploration methods are employed to conduct extensive investigations along the tunnel's alignment. Based on the outcomes of surface exploration, borehole temperature measurements are conducted to ascertain temperature profiles at various depths within the tunnel. The borehole results are compared with those obtained from surface exploration, and a systematic classification of high-temperature segments is carried out.

(3) Tunnel geological forecast: Geophysical prospecting techniques within the tunnel are adopted to detect the temperature distributions and water content in front of the tunnel. This aids in the analysis and prediction of the geological conditions ahead of the tunnel's construction. Building upon the findings of the physical exploration, borehole temperature measurements are executed to corroborate and complement the geophysical results. Finally, the classification of high-temperature heat hazard types, their spatial distribution, water content levels, and heat damage severity are analyzed and judged comprehensively.

To effectively address high geothermal tunnel heat hazards, it is crucial to first ascertain the nature of the disaster and classify heat hazard levels. Finally, combined with the existing heat hazard prevention and control countermeasures, the prevention and control of heat hazards in high-geotemperature tunnels are carried out.

(1) Ventilation optimization: Ventilation stands as a primary and widely employed cooling measure in preventing and mitigating heat hazards. When heat hazard levels are relatively low, optimization of the ventilation system and methods, among other strategies, proves effective in managing the situation.
(2) Thermal insulation technology: High-rock-temperature tunnels demand the development of novel high-temperature-resistant thermal insulation materials, building upon existing thermal insulation technology. Furthermore, exploring more effective ways of laying thermal insulation layers is also necessary.
(3) Water insulation technology: Hydrothermal high-temperature tunnels present a unique challenge, given the combined influence of ultra-high-temperature rock and high-temperature fissure water. On the basis of the heat insulation technology, it is essential to research and develop innovative, high-temperature-resistant, and corrosion-resistant water-insulating materials. These materials should be combined with high-temperature fissure water diversion and sealing measures.
(4) Moisture and heat control technology: For extreme-temperature and -humidity environments, it is necessary to give full consideration to the respective advantages of the existing artificial and non-artificial cooling technology, and a variety of technologies work together.

In short, the most suitable and effective prevention and control measures are selected for different disaster forms and levels. This approach ensures efficient and precise management of heat hazards in high geothermal tunnel environments.

6. Conclusions

This research focused on preventing and controlling high-temperature thermal hazards, a common and severe engineering geological hazard. The factors influencing the shallow geothermal field within the Earth's crust were evaluated by means of extensive literature review and a detailed case study. Then, the disaster forms and geogenetic model of heat hazards in high-temperature tunnels were proposed. Taking a high geothermal tunnel in Southwest China as an example, the high-temperature thermal hazard was studied and then the countermeasures for high-temperature thermal hazards in actual practice were proposed. Based on the systematic analysis and case study, the following main conclusions can be drawn:

(1) The deep geothermal background, heat conduction conditions, and local additional heat sources are the most important factors influencing the geothermal field. Among them, additional heat sources, especially underground hot water circulation, cause more harm.
(2) The tunnel hazards caused by high geothermal temperatures are divided into four categories: causing a hot and humid environment inside the tunnel, aggravating the deformation and damage of tunnel surrounding rock, inducing the failure of tunnel supporting structure, and increasing the safety risk of the project.
(3) Three types and six subtypes of high-temperature thermal hazard causation models were proposed. Notably, the subtype involving underground hot water circulation in the shallow Earth's crust is identified as the most deleterious.
(4) A case study of high-temperature thermal hazards in a southwestern Chinese tunnel is meticulously presented. The amalgamation of comprehensive geophysical exploration and surface geological survey emerges as an effective methodology for acquiring and evaluating detailed geological conditions. For the assurance of tunnel excavation safety in the region, specific measures for forecasting and preventing high-temperature thermal damage in tunnels are advocated.
(5) Proposed countermeasures for addressing high-temperature heat hazards in actual projects are delineated for two stages of tunnel construction: the geological investigation stage and the construction stage.
(6) The insights gained from our research have a certain degree of relevance and applicability to tunnels in other parts of the world. The fundamental principles and

methods we employed in our investigation can serve as a valuable foundation for understanding and addressing similar challenges in different tunnel environments.

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