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# Review and Prospect of Evolution Law of Freezing Temperature Field at the Interface of Subway Connecting Passage based on Heat Convection-Seepage Theory

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## Abstract

**The artificial ground freezing (AGF) method is essential for reinforcing subway connecting passages in special geological conditions. Heat convection and groundwater seepage complicate the evolution of the freezing temperature field at interfaces, threatening construction safety. This paper reviews domestic and foreign research on the field from numerical simulation, on-site monitoring, and theoretical aspects, emphasizing the significance of studying the coupled effect of seepage and convective heat transfer for safe construction.**

## Keywords

**Convective Heat Transfer, Metro Connecting Passage, Temperature, Frozen Wall.**

## 1. Research Purpose and Significance

With the rapid development of China's economy, modern urban transportation has formed a comprehensive three-dimensional transportation mode that can "go up to the sky" and "go down to the ground". Subways, for example, have far-reaching significance beyond simply connecting residential areas, workplaces, and commercial districts. For urban rail transit, they can directly link passenger stations, airports, and high-speed rail stations, just like all transportation arteries in the country have become interconnected capillaries. In addition to alleviating traffic pressure, subways also promote larger, more punctual, and convenient personnel flow between provinces, cities, and within cities.

Many large cities are plagued by problems such as traffic congestion, which severely restricts the long-term operation of the social economy. Therefore, subway construction has become an inevitable choice to ease urban traffic and improve the urban environment. In subway construction projects, the construction of connecting passages is a crucial and high-risk link. During this process, it is necessary to maintain the stability of the surrounding soil to avoid adverse impacts on upper-layer buildings and underground pipelines.

However, in some special geological environments, the groundwater level is shallow, and the stratum is similar to quicksand layers, muck, and mucky soil. Under such conditions, conventional methods are insufficient to stabilize the soil. The artificial ground freezing (AGF) method must be adopted to achieve the desired goals, which has been verified through practice as an effective technique for stratum reinforcement.

The artificial ground freezing technology refers to the use of artificial refrigeration methods to transport low-temperature refrigerants into weak strata with a certain water content and groundwater flow velocity. This causes the water and surrounding soil particles in the stratum to freeze, forming a frozen wall with excellent impermeability, high strength, and large elastic modulus. With the protection provided by the frozen wall, the excavation of internal soil and the construction of permanent support structures can be carried out safely. The advantages of the freezing method are as follows:(1) Good adaptability to surrounding structural shapes: If the freezing holes are accurately planned, the freezing time can be guaranteed, and frozen walls of various shapes with good uniformity can be formed.(2) Excellent water insulation performance: After the frozen wall is formed (closure), it has high strength, good continuity, and effective water insulation.(3) Minimal stratum pollution: The freezing method only increases the strength of the in-situ soil by reducing the temperature without changing the stratum composition, thus causing minimal pollution to the stratum.

The key to the actual construction of the artificial ground freezing method lies in the reliability of the frozen curtain. Frozen soil is a four-phase medium composed of soil particles, water, ice, and gas. The content of unfrozen water and ice in frozen soil is greatly affected by temperature changes, which significantly impacts the safety of frozen soil engineering. The artificial freezing temperature field describes the spatial distribution and temporal evolution of the temperature of rock and soil around freezing pipes. During the freezing process, the physical parameters of the soil change with temperature, involving phenomena such as phase change, heat and mass transfer, moving boundaries, and moving internal heat sources, making it an unsteady temperature field with phase change.

Due to the complexity of its evolution law, engineering accidents such as water and sand gushing often occur during construction because the frozen wall fails to meet the design requirements, seriously threatening project safety. On July 1, 2003, during the construction of Shanghai Metro Line 4 using the artificial ground freezing method, a serious engineering accident occurred because the freezing temperature did not reach the design value, resulting in a direct economic loss of 150 million yuan. In August 2017, the Rastatt Railway in Germany suffered a severe collapse due to freezing failure. The restoration work lasted from July to October, causing a daily economic loss of up to 12 million euros. The collapse also buried a shield machine worth 18 million euros and led to the detention of a large number of passengers.

Since the incomplete development of the frozen wall during freezing construction can lead to serious engineering accidents, exploring the evolution law of the temperature field during freezing construction and monitoring the development of the frozen wall is an important part of the research on the freezing method reinforcement of connecting passages, especially at the weak junctions of temperature distribution.

The formation of frozen soil is affected by temperature. In addition to the significant heat loss caused by heat conduction between the soil and freezing pipes, heat convection at the junctions of connecting passages also results in substantial cold loss, reducing the freezing rate, affecting the formation of frozen soil, and exerting a great impact on the strength and thickness of frozen soil, thereby endangering construction safety.

Furthermore, under groundwater seepage conditions, the formation of the frozen curtain will experience drift, leading to a decrease in the thickness of the frozen wall. Therefore, it is necessary to study the influence of convective heat transfer on the temperature field at the boundary under different influencing factors and the combined effect of seepage and convective heat transfer on the temperature field at the boundary (hydrothermal coupling), which also provides important reference significance for the safe construction of connecting passages.

## 2. Research Status at Home and Abroad

### 2.1. Numerical Simulation Status

The calculation of the freezing method involves the coupling of force field, displacement field, and temperature field, and the governing equations are particularly complex and difficult to fully consider. With the development of computer software, numerical simulation tools can be used to solve such complex problems, and many scholars at home and abroad have conducted auxiliary research using numerical simulation software. By comparing the numerical simulation results with actual monitoring data to verify their correctness, further comparative simulation studies can be carried out on this basis, and the results are relatively convincing.

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Wu Yajun and Yang Min [1-2] used AC3D software to numerically simulate the deformation and stress of the frozen curtain during the construction of the Dalian Road Tunnel connecting passage using the freezing method, determined the appropriate thickness of the frozen curtain, and identified the most unfavorable location of the frozen curtain.

Fu Yong, Hu Jun, and Wu Yuwei [3] conducted a three-dimensional analysis of the development and spatial distribution of the temperature field during the artificial freezing process based on the engineering background of the artificial ground freezing reinforcement of the connecting passage of Nanning Metro Line 3. They compared the calculation results with the measured results to verify the feasibility of numerical modeling and conducted a series of analyses on influencing factors such as thermophysical parameters and environmental soil conditions.

Lin Wenshu and Lin Jianping [4-5] took the connecting passage between Fanhu Station and Hankou Railway Station as the research background, analyzed the stress of the frozen curtain of the connecting passage using ANSYS, obtained the safety factor based on the stress distribution of the frozen curtain to judge its safety status, and through comparing the safety factors of the frozen curtain during the excavation process, indicated that excavation has a certain impact on the frozen curtain but remains within the safe range.

Yu Changyi and Lu Mingyue [6] studied the development characteristics of the horizontal freezing temperature field in subway connecting passages. The simulation results are consistent with the measured data, verifying the effectiveness of the finite element method [7]. The finite element analysis can be used to simulate similar projects and guide relevant design and construction.

Zheng Lifu, Gao Yongtao, et al [8]. studied the freezing method for the connecting passage of the Zhuhai-Zhuhai Airport Intercity Rail Transit. They used Rhino3D for auxiliary modeling and Griddle for mesh generation, which was then imported into FLAC3D for numerical simulation. They studied the surface frost heave, thaw settlement, and tunnel segment deformation caused by different frozen wall thicknesses, analyzed the variation trends and causes of the results, and optimized the design of the frozen wall thickness by comparing with the actual construction process.

Hu Xiaorong, Rao Zhiqiang, et al. used ABAQUS to numerically simulate the freezing method construction of the connecting passage between Shida South Road Station and Pengjiaqiao Station of Nanchang Metro Line 1, calculated and analyzed the freezing temperature in different seasons. On the basis of proving the rationality of the model, they proposed through data comparison that the construction should preferably be carried out in autumn.

Mei Yuan, Zhao Liangjie, et al. relied on the freezing method construction of a connecting passage in Xi'an Metro, conducted finite element analysis using ABAQUS, studied the influence of temperature on the connecting passage, and explained the reasons for the error between the finite element analysis results and the measured data.

## 2.2. On-Site Monitoring Status

On-site monitoring is a method that can best reflect the actual engineering situation and is also a relatively convincing research method. During the freezing method construction, by reasonably embedding monitoring instruments such as stress, strain, and temperature measuring tubes, the collected monitoring data can accurately reflect the soil temperature change, soil pressure change, and surface displacement of the actual project. Sorting out and analyzing the monitoring data can deepen the understanding of the project and verify the rationality of numerical simulation. Domestic scholars have conducted a series of studies on on-site monitoring of the freezing method construction of subway connecting passages.

Mengheng Zhang, Heng Wan, et al. took the first phase station of Harbin Rail Transit Line 2 as the background, effectively controlled the impact of excavation on surface and pipeline settlement through the freezing method construction. Through on-site monitoring, the pipeline and surface settlement were less than the construction control values, indicating that the freezing method can ensure the safe excavation of the connecting passage.

Yue Fengtian, Qiu Peiyun et al. studied the Dalian Road River-Crossing Tunnel, conducted on-site monitoring of China's first frozen project of a river-bottom tunnel connecting passage, analyzed the variation laws of freezing brine temperature, frozen soil temperature, and frost heave pressure, providing engineering experience for future freezing of river-bottom tunnels.

Ye Xiaowei, Ding Peng et al. proposed the fiber Bragg grating sensing technology to conduct real-time monitoring of the temperature field and stress field during the freezing method construction for the pump room connecting passage in the Yangtze River-Crossing Tunnel of Wuhan Metro Line 2, which improved the on-site monitoring accuracy, stability, and sensitivity, and further deepened the understanding of the temperature and strain of the frozen curtain.

Lin Jianping [4-5] focused on a connecting passage of Xiamen Rail Transit Line 3 located in gravel stratum. He analyzed the freezing hole monitoring, freezing system monitoring, and frozen wall temperature field monitoring to optimize and adjust the construction, providing valuable reference materials for future freezing method construction.

### 2.3. Theoretical Research Status

Foreign scholars started the research on the temperature field in the freezing method earlier. In the mid-20th century, the former Soviet scholar CyMTMH. M. M., as the founder of the artificial ground freezing theory, first carried out research on the freezing temperature field. Later, representative figures such as KyupgBueB. A. B, Trubachev, and Bahorkin emerged in the field of thermophysical research on the temperature field. Trubachev established the freezing temperature field theory, taking a single homogeneous isotropic and non-flowing aquifer as the main research object, and established the freezing temperature field theory based on the single-tube plane steady-state temperature field. Domestic research on the temperature field of artificial freezing shaft sinking originated in the 1950s. Initially, the research on the temperature field mainly focused on on-site tests and empirical equations, using analytical solutions and semi-analytical solutions for one-dimensional linear problems to study the freezing In terms of theoretical research, scholars in the industry have proposed some calculation formulas to describe the characteristics of the temperature field. Xiao Chaoyun, et al. first introduced the double-row pipe calculation formula to calculate the thickness of the frozen curtain to improve the large error of the existing formulas for calculating the thickness and development speed of the frozen curtain when calculating multi-row pipe freezing, and derived a simplified average temperature calculation formula based on this.

## 3. Conclusion

The artificial ground freezing (AGF) method is critical for reinforcing subway connecting passages in special geological conditions, with its safety relying on the evolution of the freezing temperature field. Heat convection and groundwater seepage at interfaces hinder frozen wall development, posing construction risks. Existing research via numerical simulation, on-site monitoring, and theoretical analysis has provided valuable support for practice. Future studies should focus on the seepage-convective heat transfer coupling effect to optimize construction parameters and enhance construction safety and reliability.

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