Influence of Frost Heave and Thaw Settlement of Connected Aisle on Tunnel Structure

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Abstract. The artificial freezing method has been widely used in the construction of subway tunnel connected aisle. By monitoring and analyzing the displacement of the tunnel during the construction of the freezing connected aisle, the uplift and settlement values of the tunnels on both sides are obtained. The results show that in the process of freezing and excavation, the tunnels on both sides of the connected aisle produce upward displacement; in the process of thawing after construction, the tunnel near the connected aisle produces settlement. Within six months after completion of construction, the settlement of the tunnel is about 4 mm more than that of the tunnel unaffected by the construction of the connected aisle. The engineering measures to reduce the frost heave and thaw settlement of the connected aisle are put forward, which provides a reference for similar projects.

1. Introduction

Because of its good adaptability, freezing method has become the main construction method in complex aquifer. However, there is not much research on the impact of frost heave and thaw settlement on the surrounding environment, especially on the impact of tunnels.

Many domestic scholars have studied the freezing method for construction of the connected aisle. In terms of the freezing temperature field and displacement field, Yang Ping [1] has carried out the full-range field measurement on the background of the freezing method project of the connected aisle in soft soil tunnel, and has analyzed the formation of the freezing wall and the whole process of thawing. Yu Hui [2] demonstrated the feasibility of freezing construction technology of water-rich sand layer subway connecting passage based on Xi'an subway. Wu Fan et al. [3] measured the temperature field of thawing and the temperature variation law of deep soil based on soft soil tunnel, and put forward the grouting measures to control the settlement.

Many domestic scholars have studied the characteristics of frozen soil through the frost heave and thawing test. For example, Zhao Xuewen [4] studied the test method of frost heave characteristics, the mechanism of frost heave and the law of frost heave. Yan et al. [5] aiming at the special environment of deep season frozen soil, the characteristics of repeated frost heave and thaw settlement of silty sand under different initial moisture content, dry density, load and freeze-thaw times were studied by laboratory tests. Cheng Hua et al. [6] taking Guangzhou metro as a prototype, through establishing a large-scale physical test model, the formation law of freezing wall, frost heave and thaw settlement effect during artificial horizontal freezing method construction are studied. Zhang Ting [7] developed a test device for freezing temperature and frost heave which can be used to collect data from microcomputers. The freezing temperature, frost heave and thaw settlement tests of typical soils in...
Nanjing area were carried out, and the changing rules of freezing temperature with soil quality, water content, dry density, salt content and water quality were obtained. Because the experimental study cannot fully reflect the actual project, some scholars began to use finite element software to analyze the temperature field, displacement field and stress field of the soil during the construction and excavation of the freezing method connected aisle. Ding Hang et al. [8] analyzed the three-dimensional temperature field of Zhengzhou Rail Transit Line 1 through the establishment of three-dimensional temperature field mathematical model and ANSYS software. Wang Yanyang [9] established two physical models of freezing curtain with uniform temperature field and temperature gradient by using finite element analysis software Midas/GTS, and carried out three-dimensional simulation analysis of the excavation of connected aisle.

In summary, although many previous studies have been done on the freezing temperature field and the deformation of frost heave and thaw settlement, there is still a lack of research on the thawing process and the influence of frost heave on tunnel structure. It is of great theoretical and practical significance to study the thawing temperature field and the actual development law of the frost heave and thaw settlement of the contact passage in the water-rich stratum and putting forward the prediction method of the post-construction thaw settlement.

2. Mathematical model of freezing temperature field
The frozen temperature field in the connected aisle is mainly a transient heat conduction problem with phase transition. The calculation model considers heat transfer and frozen soil theory. In three-dimensional case, the governing differential equation of the frozen temperature field is as follows:

$$C^* \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k^* \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k^* \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k^* \frac{\partial T}{\partial z} \right)$$

(1)

In the formula, \(T\) is the soil temperature, \(^\circ\text{C}\); \(t\) is time, s; \(C^*\) is equivalent volume specific heat \(\text{kJ}/(\text{m}^3\cdot\text{^\circ}\text{C})\); \(K^*\) is the equivalent thermal conductivity, \(\text{W}/(\text{m} \cdot \text{^\circ}\text{C})\).

\[
C = \begin{cases} 
C_f & (T < T_d) \\
\frac{C_f + C_u}{2} + \frac{L}{T_r - T_d} & (T_d \leq T \leq T_r) \\
C_u & (T > T_r)
\end{cases}
\]

(2)

\[
k^* = \begin{cases} 
k_f & (T < T_d) \\
k_f + \frac{k_u - k_f}{T_r - T_d} (T - T_d) & (T_d \leq T \leq T_r) \\
k_u & (T > T_r)
\end{cases}
\]

(3)

In the formula, \(k_f\) and \(k_u\) is thermal conductivity of frozen soil and unfrozen soil, \(\text{W}/(\text{m} \cdot \text{^\circ}\text{C})\); \(C_f\) and \(C_u\) is volume specific heat of frozen soil and unfrozen soil, \(\text{kJ}/(\text{m}^3\cdot\text{^\circ}\text{C})\); \(T_d\) is Freezing temperature of soil, \(^\circ\text{C}\); \(T_r\) is soil thawing temperature, \(^\circ\text{C}\); \(L\) is phase change Latent heat of unit volume soil, kJ/m\(^3\).

3. Numerical simulation of connected aisle
3.1. Introduction
In a soft soil area, the subway tunnel was about 14m deep and the center distance of the two parallel tunnels was about 14.5m. After the shield tunnel was completed, the connected aisle and the pump station were constructed by freezing method. The single circular shield tunnel was constructed by a
single layer of reinforced concrete lining (segment) assembled by staggered joints. The lining ring width was 1200mm, thickness was 350 mm, tunnel inner diameter was 5.5 m (Figure 1).

Figure 1. Profile of connected aisle with the shield tunnel

The numerical simulation of the connected aisle can be carried out by using the built-in thermodynamic analysis module of ANSYS, Midas/GTS, ABAQUS and so on. The connected aisle was composed of a horn mouth and horizontal passage connected with the steel lining segment. The horizontal passage of the connected aisle was a straight wall circular arc arch structure. The initial support (steel support, shotcrete) thickness of the passage was 270mm, and the secondary lining was 500mm thick (Figure 2).

Figure 2. Contact passage numerical model

3.2. Influence of construction on Tunnel

3.2.1. Influence of connected aisle construction on Tunnel. Hao Runxia et al. [10] showed that the contact passage had obvious influence on the vertical displacement of the tunnel on both sides. The scope of impact was 5 rings on each side of the link center line (a total of 10 rings, around 12m). Its vertical displacement had great development in construction of connected aisle (Figure 3).

Figure 3. Cumulative vertical displacement of tunnel
From the figure 3, it can be seen that after freezing, the tunnel occurred frost heave and uplift about 0.5-1.2mm upward; during the excavation of the connected aisle, the tunnel uplift occurred about 3-5 mm upward; during the thawing process, the tunnel had caused settlement and the settlement reached 6 mm after 180 days.

During the freezing process, due to the large water content of the muddy silty clay in the freezing range, a certain frost heave occurred during the freezing process, which led to a certain vertical displacement of the tunnel. When the connected aisle was excavated, because of unloading, the soil will rebound upward within the excavation range, which will lead to the tunnel displacement upward. From the two upward displacements, the upward displacement caused by excavation and unloading was obviously greater than that during the freezing process. During the thawing process after the construction of the connected aisle, the stress field of the surrounding soil changed once again, and the frozen soil melted and sank to a certain extent, resulting in the tunnel displacement downward, but the displacement was smaller than the displacement of the excavation unloading.

3.2.2. Analysis of tunnel displacement after connected aisle thawing. In order to analyze the vertical displacement of tunnels after thawing, the vertical displacement of monitoring points changed more obviously in the first 24 days after thawing than in the later period, the change rate was about 0.17 mm/d; the settlement rate of the tunnel was about 0.05 mm/d during 24-60 days after thawing and 0.02 mm/d during 60-180 days after thawing. It can be seen that the settlement rate gradually decreased with the increase of time. At 24 days after thawing, the subsidence of the monitoring point 5-10 was obviously larger than that of the segments on both sides. During the continuous monitoring, although the vertical displacement of monitoring point 1-3 and monitoring point 12-14 still occurred downward, the settlement rate was obviously lower than that of monitoring point 5-10. During the construction of the connected aisle, the monitoring points 1-3 and 12-14 were almost unaffected. Therefore, it can be considered that the subsequent settlement was not caused by the influence of the construction of the connected aisle by freezing method, but the normal settlement after the completion of the shield tunnel. After 60 days of thawing, obvious settlement grooves appeared in the tunnel on the side of the connected aisle, with a depth of about 4 mm and an influence range of about 17 m.

3.3. Measures to reduce the influence of connecting passage construction
From the point of connected aisle construction process, the side shield tunnels uplifted upward during the freezing and excavation process before the construction; the side shield tunnels occurred settlement during the thawing process, and the settlement rate of the affected tunnels during the construction process was significantly higher than that of the unaffected tunnels. From the point of view of existing subway lines, the depth of settlement tank could reach 10-40 mm and the influence range could reach 30-40m after several years of subway operation.

The uneven settlement not only affected the smoothness of the line, but also led to structural cracking and segment opening, and then caused leakage. The irregularity of the railway led to the increase of dynamic stress in the train passage, and the leakage of the structure accelerated the consolidation settlement. Finally, a vicious circle was formed by the superposition of many factors.

Therefore, measures should be taken to reduce the construction effects. During the freezing process, the surrounding soil water migrated to the frozen soil, which resulted in the increase of the water content of the frozen soil and the decrease of the strength of the frozen soil after thawing; during the excavation and unloading process, the bottom soil rebounded upward, and the porosity of the surrounding soil increased after deformation, which also increased the late settlement of the affected tunnels. When the contact passage is frozen, the following measures may be taken into consideration:

Reduce the cooling temperature and speed up the freezing speed.
Control the freezing extent to the minimum required.
Control Water movement amount of the freezing surface by increasing the viscosity of pore water.
Complete the excavation and structural construction of the contact passage as soon as possible.
Grouting on the side and bottom of shield tunnels is carried out in the process of thawing and after thawing.
4. Conclusions
Considering the initial stratum temperature, the convective heat transfer between soil and air at the interface between the tunnel and the connected aisle, a mathematical model of transient temperature field is established to provide a basis for calculation.

The process of tunnel excavation can be simulated by the finite element software Midas/GTS, and the ground settlement caused by tunnel construction can be well reflected by adjusting the parameters of the modeling. In the actual construction process, the software can be used to simulate the excavation process, so as to predict and control the ground settlement and stratum displacement caused by the excavation.

The stratum displacement at the flare mouth of the connected aisle is larger and stress concentration is easy to occur. In addition, the discontinuous section of the connected aisle is also easy to occur stress concentration, so the support should be done in time for these parts.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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