Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 6622177, 9 pages
https://doi.org/10.1155/2021/6622177

Review Article

Research on the Ground Subsidence Mechanism of Cross Passage Caused by Freezing Method Construction

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Received 20 November 2020; Revised 10 March 2021; Accepted 17 March 2021; Published 25 March 2021

Academic Editor: Ma Jianjun

At present, the built or newly built underground structures are mostly concentrated in developed areas along the coast, lakes, and rivers, while deep soft soil is widely distributed in these areas. The cold heat treatment method is one of the advanced foundation treatments and has broad application prospect. However, geothermal exchange and temperature field change are complex Stefan problems with mobile boundaries, internal heat sources, and phase changes. It is important to determine the freezing area and freezing temperature reasonably under the premise of ensuring the safety of the frozen construction. Therefore, this paper summarizes the research methods of freezing method construction of cross passage and introduces the research on the constitutive model of freezing undisturbed soil, the theory of freezing wall calculation, and the evolution mechanism of the temperature field. Then, a brief evaluation is made in view of the lack of research, and the development direction of this field is put forward with the research characteristics. It is to deepen the understanding of the deformation mechanism of cross passage embedded in soft soil caused by the freezing and melting.

1. Introduction

Since the 21st century, the urban population size and living space are under tremendous pressure with the continuous acceleration of urbanization. The development of underground space is undoubtedly an effective means to relieve traffic congestion and improve the living environment. Entering the new era, underground space and structure construction still has great potential and will be developed to a greater extent. As a fast, efficient, and environment-friendly means of transportation, subway gradually plays an irreplaceable role in modern urban passenger transport. Beijing, Shanghai, and other big cities have built a number of underground railways, forming an efficient transportation network, and some cities are carrying out (or preparing) the construction of underground rail transit. At present, the built or newly built underground structures are mostly concentrated in developed areas along the coast, lakes, and rivers, while deep soft soil is widely distributed in these areas. The cross passage connecting the upper and lower tunnels has the dual functions of emergency evacuation and collection and drainage, and it also is an indispensable part of subway construction. However, due to the special conditions, the construction of the cross passage often faces huge risks. Therefore, the cold heat treatment method is widely used in the excavation process of underground tunnels. The cold heat treatment method is one of the advanced foundation treatments and has broad application prospects [1]. The freezing method is the first choice for the construction method of the connecting channel due to its strong adaptability and better water resistance. During the construction of the connecting passage freezing method, the ice-water phase changes and the soil strength gradually increases as the temperature decreases, eventually forming a high-strength water-proof frozen soil heavy curtain. However, the heat exchange and temperature field changes in the freezing

process of rock and soil are a complex Stefan problem with moving boundaries, internal heat sources, and phase changes [2, 3]. In the process of strengthening soil by artificial freezing, the stratum temperature gradually decreases as the heat exchange process progresses. When the soil temperature reaches the freezing point, the invasion of crystals, lens bodies, ice mezzanines, etc., formed by the freezing of pore water and migratory water in the soil, will cause the increase of soil volume, which in turn will cause the soil to freeze and expand [4]; on the contrary, after the artificial freezing is stopped at the end of the construction, the frozen soil gradually melts as the temperature of the soil layer rises. The ablation of ice intrusion will cause the volume of the soil to decrease. The soil is saturated and supersaturated, which reduces the bearing capacity of the soil. Under the action of the overburden, drainage and consolidation will occur, which will cause the soil to melt and settle [5, 6].

There are many reasons for ground subsidence in actual engineering, such as underground pumping, excavation of foundation pits, establishment of nearby tall buildings, and freezing construction [7]. The expansion and melting of the soil during the freezing process will adversely affect the existing buildings around, which limit the application of artificial freezing method. The freezing temperature field changes the circulation of groundwater, and then, the action of solid water suction further causes water migration; therefore, the surrounding soil water is continuously supplied [8]. When the thawing process is completed, the water in the soil diffuses slowly to the surrounding soil, causing the water content in the soil to increase; at this time, the soil becomes soft, and even to the extent that it will causes piping, quicksand, and liquefaction [9, 10]. The change of soil properties during the freezing process directly affects underground and above-ground structures. We know that various and intricate pipelines are buried in the ground in municipal engineering, and the newly built subway connecting channel will pass up or down the existing subway line. It can be seen that the complexity of the environment is apparent in the construction of the subway cross passage freezing method. For example, under the effect of various factors such as unreasonable design or improper construction, the amount of frost heave and thaw settlement during the freezing and thawing process of the formation is not effectively controlled in time, which has a direct effect on the surrounding environment of the project. At least, it will extend the construction period increasing the cost of the project. More serious, it can cause damage to underground pipelines, existing operating subway lines, surface buildings, and roads. In serious cases, freezing pipes may lead to catastrophic accidents and cause major economic losses. For example, in the freezing construction engineering of the Tianhe Passenger Station of Guangzhou Metro Line 3, the maximum surface frost heave exceeded 400 mm during the freezing period, resulting in certain damage to surface roads and underground pipelines; another example is about Nanjing Metro 1: the freezing and strengthening project of the bypass passage and pumping station of a certain section of the line. After the completion of the construction, there were serious thawing and deformation of the surface during the thawing phase. The cumulative surface settlement reached 122 mm, far exceeding the 30 mm alarm value specified in the municipal engineering. Fortunately, the surface of the freezing project was an urban road, and there was no other loss except for the settlement of the road surface.

In the application of the artificial freezing method in the subway cross passage project, the stratum uplift caused by the frost heave of the soil and the stratum settlement caused by the thawing of the frozen soil after the completion of the project have been proposed due to the special requirements of the surroundings. Therefore, there are more strict requirements for reliability [11]. The formation process of frozen soil is basically a physical and mechanical process. During this process, the properties of soil have changed essentially [12–15]. As the freezing temperature increases, the frost heave caused by the ice-water phase transition and the thaw settlement caused by the thawing of the frozen soil curtain will increase sharply after the completion of the support of the connecting channel [16]. Excessive volume changes in the freezing and thawing area will often cause large deformations on the ground surface, which would destroy underground pipelines or cause inclination and cracks in adjacent buildings (structures). In particular, frost heave and thaw settlement affect the built shield cross passage; it has an adverse effect. Therefore, a frozen area too large or a freezing temperature too low is not the better case in the construction of freezing method [17, 18]. The freezing temperature and freezing area are theoretically controlled by factors such as engineering geological conditions, hydrogeological conditions, shield connection channel size, and buried depth. However, the current limited understanding of the freezing and thawing process, frozen soil parameters, and the true freezing state has led to excessively large freezing areas and low freezing temperatures during the construction process to ensure absolute safety. As a result, it not only caused excessive frost heave and thaw settlement but also directly caused excessively long construction period and huge energy consumption. Therefore, under the premise of ensuring the safety of freezing construction, it is very important to reasonably determine the freezing area and freezing temperature [19].

In summary, limited to understanding the soft clay freeze-thaw processes, frozen soil parameters, and frozen soil areas, the freezing period is usually extended in subway cross passage freezing method, so as to enhance the freezing effect and reduce construction risks. In the freezing method construction process, too large freezing area and too low freezing temperature are adopted for the so-called "absolute safety," which causes excessive frost heave and thaw settlement of the soil in the freezing area and finally leads to excessively long construction period and energy waste. In this way, the freezing curtain is often much larger than the designed thickness in actual freezing construction, and even the inside of the freezing curtain is frozen into a solid body, which causes a great waste of energy and also increases the amount of surface uplift. Therefore, the frost heave and thaw settlement effect of the ground is worthy of in-depth and

systematic research during the freezing construction period of the subway cross passage in soft ground. It is not difficult to see that it can effectively predict the impact of the freezing method on the surrounding environment, predicting the formation law of the freezing temperature field to determine the strength and stability of the freezing wall, and analyzing the frost heave and thaw settlement in the freezing construction. It can provide basic data for economic and social indicators such as energy saving and shortening construction period, which is of great significance to the promotion of the application of freezing method construction in engineering.

2. Research on the Frost Heave and Thaw Settlement

2.1. Constitutive Model of Frozen Undisturbed Soil. As early as the late 17th century, the natural phenomenon of soil frost heave has been observed in the project, and it was mistakenly believed to be caused by the bending and deformation of the soil. Later, it is generally believed that the frost heave is due to the expansion of the volume of water in the soil. Until the 1930s, this view was rejected. It was believed that the phase change of pore water in the soil would increase the volume of the soil by 9%, and the water migration during the freezing process was the main cause of frost heave [20].

In the freezing process of fine-grained soil, when the freezing rate is not very high, the pore water in the soil undergoes phase transformation to form pore ice and in-situ volume expansion occurs. In addition, the surface of the soil particles always adsorbs the unfrozen water film. When the pore water of the soil is frozen, the equilibrium state is affected such as soil temperature, pressure, water content, mineral particle surface energy, and water activity in the unfrozen water film. As destroyed, the water vapor elasticity at the lower temperature of the soil is smaller, the adsorption force of the soil skeleton and the crystallization force of ice crystals are larger, and the water activity in the unfrozen water film is lower. In this way, various force gradients appear along the direction of heat flow. Under the action of the potential energy gradient, unfrozen water migrates from the unfrozen area to the direction of the freezing front, and the pore ice continues to separate and accumulate. Finally, it accumulates to form a permeable layer of ice, leading to frost heave of the soil [21]. Therefore, soil frost heave can be divided into two parts, namely, frost heave caused by pore water phase change and frost heave caused by unfrozen water migration, which are generally called in-situ frost heave and partial frost heave, respectively.

In the 1960s, on the basis of finding the water absorption dynamics in the interstices of soil particles, the frost heave of water migration was explained according to the capillary theory (the first frost heave theory). In the 1970s, in order to explain the formation process of discontinuous ice lens in the process of water migration, it was considered that there was a frozen edge zone filled with water and ice between the warm end of ice lens and the freezing front, which was the transition zone from unfrozen to frozen soil. The pore water content continues to increase from the freezing front to the warm end of the ice lens, while the unfrozen water film gradually thins, which reduces the unfrozen water content and permeability coefficient in the freezing edge area and makes it more and more difficult for water to migrate until it freezes. The water migration stops somewhere in the edge, and pore ice accumulation occurs there, so a new ice lens is produced (the second frost heave theory) [22, 23]. According to the second theory of frost heave, the cross-sectional model of frozen soil is shown in Figure 1. Frozen from top to bottom, the upper part is frozen soil, the lower part is unfrozen soil, the middle is the frozen edge, the upper interface of the frozen edge is the warm end of the ice lens (or ice separation front), and the lower interface is the frozen front.

Subsequently, many scholars conducted related researches on the formation, development, and characteristics of the freezing margin from different angles. The frost heave theory can better describe the formation of discontinuous ice lens in the water migration and more perfectly reveal the frost heave mechanism of soil, so it has now been generally recognized [24, 25]. In the past century, various frost heave models have been proposed in the experimental and theoretical studies of frost heave, including capillary models, rigid ice models, partial condensation potential models, hydrodynamic models, thermal models, and empirical formulas for frost heave rates [26].

The current research lacks a constitutive model suitable for soft soil affected by subway construction and a reasonable constitutive model suitable for frozen soil.

2.2. Frozen Wall Calculation Theory. In terms of frozen wall calculation theory, according to the equivalent cross section solution form of the average temperature of the frozen soil curtain temperature field under the arrangement of pipes, Hu et al. [27] obtained a general empirical formula for the average temperature of the frozen soil curtain under the single-row, double-row, and three-row pipe configurations using numerical fitting methods. Based on theoretical analysis and physical model experiment, the formation mechanism and change law of the frozen wall are systematically studied when the double-row pipes are in the seepage formation, and the influence law and significance of various influencing factors on various indexes of the frozen wall were analyzed [28]. Based on the Nanjing metro shield tunnel end vertical freezing reinforcement project, the calculation experience formula was obtained for the average temperature of the straight double-row pipe and the multirow pipe freezing wall at the end of the active freezing period considering the thermal radiation effect of the ground connecting wall [29]. The stability of the frozen wall of underwater tunnels based on the theory of fluid-structure coupling was studied by using finite-difference numerical calculation methods [30, 31].

2.3. Temperature Field Evolution Mechanism. Due to the limitation of the measured data and the regional limitation, the test data can only reflect part but not all. Without considering the heat loss and groundwater flow, a thin slice

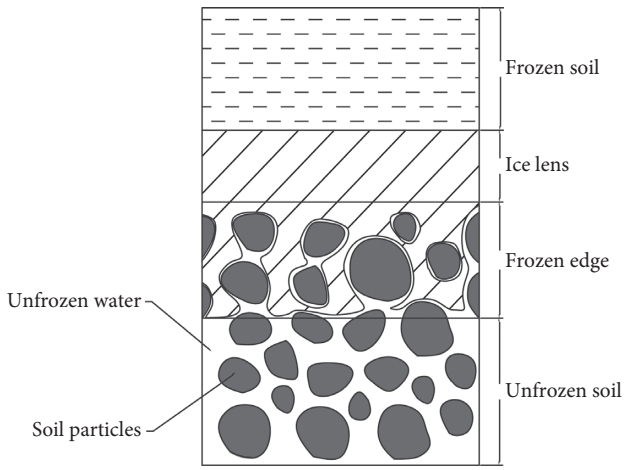

Figure 1: Frozen section model (second frost heave theory).

with a thickness of 1 m was taken as the research object, and it is considered that the research object is homogeneous and continuous within the range of the thin slice. Therefore, the freezing temperature field can be simplified as an axisymmetric plane problem (as shown in Figure 2). The temperature field of freezing zone is calculated by using the stable heat conduction of circular tube. The calculation process is extended from the temperature field of freezing column of single freezing tube to the temperature field of freezing wall. It is assumed that the amounts of heat absorbed and released by the freezing pipe are equal, and then the thickness of the freezing wall with temporary supporting function is determined. In Figure 2, E is the freezing wall thickness, n is the geotechnical state, $n = 1$ stands for melting soil and $n = 2$ stands for frozen soil, τ is freezing time, r is the radius of any heat conducting surface in frozen soil cylinder, r_1 is the outer radius of the freezing tube, r_2 is the outer radius of frozen string, and t is the temperature inside the temperature measuring hole.

Wang [32] established the mathematical model of water-heat coupling in the frozen soil of the multicircle pipe based on the principle of similarity theory and the artificial multicircle pipe freezing model test and realized the temperature field and moisture field of the multicircle pipe freezing by using the finite element method. Hu et al. [33–35] derived the steady-state temperature field of a ring-shaped single-loop frozen tube based on the water-heat heterogeneous similarity principle, and based on the characteristics of the heat transfer process similar to groundwater flow. The field analytical solution is combined with the actual problem for simplification, and a freezing model of the dislocation arrangement of the single-loop freezing tube is proposed. Yang and Rong [36] studied the freezing temperature field distribution and the frost heave force manifestation law of the deep swelling clay layer in a mine auxiliary shaft through thermal-mechanical coupling calculation analysis.

The properties of frozen soil are very complex. Compared with unfrozen soil, the formation of ice will increase the volume of the soil and redistribute the internal moisture, which makes the mechanical properties of frozen soil extremely unstable. At present, the design of the freezing curtain is relatively large and too conservative. It is necessary to strengthen the research of freezing mechanism and freezing theory. Most of the existing studies have not considered key factors such as seepage, while the flow of the water body affects the accuracy of the mathematical model of the temperature field. Therefore, it is necessary to perfect the mathematical model of the freezing temperature field considering the seepage conditions.

2.4. Frost Heave and Thaw Settlement Mechanism. Whether it is natural frozen soil or artificial frozen soil, the ice crystals in the soil will melt and decrease in volume after absorbing heat. First, thermal thawing settlement occurs. After that, the thawed soil will be drained and consolidated due to its own weight and external load, resulting in compaction settlement. Among them, thermal thawing settlement has nothing to do with pressure. The total settlement of the soil produced by the combined effect of the two settlements is called the thawing settlement of frozen soil, referred to as the thawing settlement [37].

The existence of ice crystals in frozen soil makes the frozen soil have physical, mechanical, and thermal properties which are obviously different from that of unfrozen soil and determine the unique compression property of frozen soil in the process of thawing; that is, the frost heave characteristics of frozen soil determine the thawing settlement characteristics to a large extent. Generally speaking, the greater the frost heave of frozen soil, the greater the thaw settlement. When frozen soil melts, its internal structure also changes drastically, that not only affects its compressibility but also has a greater impact on its water permeability. Tests show that the permeability coefficient of thawed soil is much greater than that of undisturbed soil with the same composition. With the progress of consolidation, the permeability coefficient gradually decreases, but it is still higher than that of unfreeze-thaw undisturbed soil. This is because during the formation of frozen soil, the composition of soil particles and pore structure has changed due to the production of ice crystals, which makes it difficult for frozen soil to return to its original state even after it has melted.

Cui [38] carried out related research on frozen soil thawing settlement and proposed a calculation formula for stable settlement of frozen soil after thawing in one-dimensional situation for the first time by using indoor experiment and field measurement methods. This formula has been widely used in the prediction of the thawing settlement of natural frozen soil foundations in the former Soviet Union, North America, and China, and it has been used until now. Waston et al. [39] decomposed the tight settlement of frozen soil into two parts, namely, the compaction settlement caused by its own weight and the compaction settlement caused by the additional load. The index reflecting the strength of frost heave of the soil in the project generally adopts the frost heave rate, which is expressed as the ratio of the frost heave to the thickness of the frozen ground in practical applications. Especially in China, whether it is a cold area project or an artificial freezing project, the frost

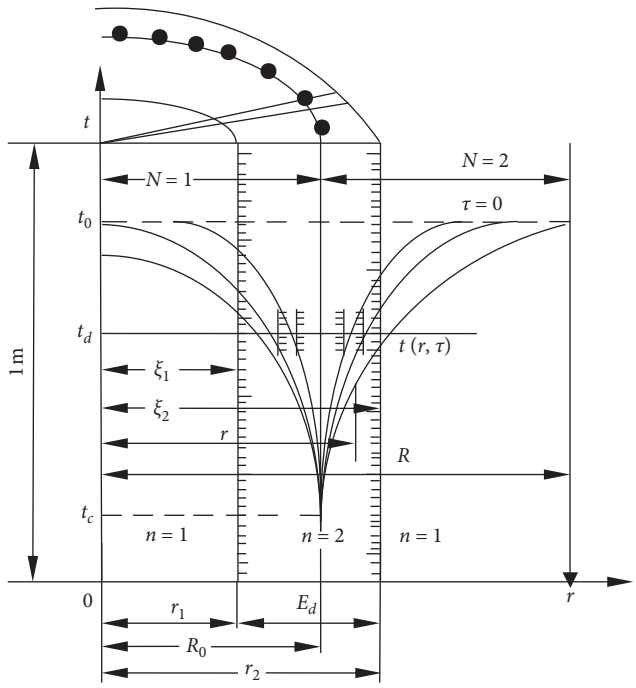

Figure 2: Freezing temperature field diagram.

heave rate is widely used to measure and judge the degree of frost heave deformation of the formation. In view of the complexity of frozen soil thawing settlement, the thawing settlement calculation model is far less advanced than the frost heave model. Most experts and scholars focus on the thawing settlement coefficient, compaction coefficient, and the relationship between the two and the basic physics of frozen soil. In particular, Crory [40] proposed that the dry bulk density and water content of the soil can be used to calculate the melting coefficient.

China is in the period of rapid development of urban rail transit, the subway construction in major cities is actively promoted, and the artificial freezing method is also widely used. However, the phenomenon of frost heave and thaw settlement of soil layer has more or less impact on the surrounding environment of the project. Therefore, scientific and engineering personnel have carried out a series of researches on the frost heave and thaw settlement characteristics of the stratum during the freezing construction period of the subway connecting channel, mainly by the analytical method, numerical simulation, model test, and field measurement, and have achieved corresponding results.

Chen [41] carried out a centrifugal model test with the freezing project of the cross passage of the Huangpu River Tunnel to simulate the frost heave phenomenon of sandy clay under artificial freezing conditions. Ning [42] gave an empirical regression equation for frost heave and thawing settlement through freezing model tests and used random medium theory to predict the frost heave deformation of the formation. Yue et al. [43] took the freezing construction of the cross passage of the Dalian Road Cross-river Tunnel in Shanghai as a prototype, conducted a small model test study, studied the frost heave and thaw settlement of the soil, and obtained the vertical soil under load. Li et al. [16] established a freezing construction model test integrating temperature field, humidity field, and mechanical field according to similar criteria. By simulating the excavation process, they studied the formation law, frost heave, and thaw settlement effect of artificial horizontal freezing method. Based on the similarity theory, Li et al. [28] established a plum blossom shaped double row pipe freezing model test system under the effect of seepage, carried out orthogonal test research on the main influencing factors of freezing wall formation in seepage formation, and carried out single-row pipe freezing contrast test under the same conditions. Zhu et al. [44] used an underground connecting passage project as a prototype and conducted a horizontal freezing model test based on similar theories to study the frost heave and thaw settlement characteristics of the soil during the freezing method.

Further, Cheng and Zang [45] studied the frost heave phenomenon of horizontal freezing and simulated the development process of horizontal frost heave considering the influence of excavation by using the finite element method. Liu et al. [9] used FLAC^{3D} finite-difference program to simulate and analyze the frost heave and thaw settlement of the soil constructed by the freezing method under complex geological conditions. The comparison with the measured value on site shows the rationality of the numerical analysis model. Wang et al. [46] established two physical models of the freezing heavy curtain with a uniform temperature field and a temperature gradient based on the finite element method. The three-dimensional simulation of the excavation of the connecting passage shows that there is stress concentration at the bell mouth during the freezing process of the connecting passage. The displacement of the heavy curtain bottom plate varies greatly.

In addition, Wang et al. [47] analyzed and summarized the monitoring data of brine temperature, frozen soil temperature, surface settlement, pressure relief pore pressure, tunnel deformation, etc. during the freezing method construction process of a subway bypass in Shanghai. She et al. [48] proposed a prediction model of surface settlement caused by double tunnel excavation in saturated loess and verified the reliability of the prediction model. Ou et al. [49] studied the ground surface during the excavation of the left and right lines of the two-line tunnel through monitoring and analysis of the ground settlement on the construction site.

Based on the current research status, it can be seen that the research on the mechanism and model of soil frost heave and thaw settlement has achieved fruitful results. However, in terms of engineering applications, most of them have been developed for the problem of one-dimensional soil freezing and thawing, and the research objects are naturally frozen soil bodies. With the increasing application of artificial freezing method in subway cross passage projects, it is related to the success of the project whether frost heave and thaw settlement can be effectively controlled during freezing construction or not, and the problem of soil freezing and thawing cannot be reduced to one-dimensional problem. The problem should

be a two-dimensional or three-dimensional problem. For this reason, experts and scholars have used a variety of methods such as theoretical analysis, numerical simulation, and model tests to conduct a series of studies on the frost heave and thaw settlement characteristics of the subway freezing construction period and have achieved initial results. There are still shortcomings reflected in the following aspects.

In terms of numerical simulation of frost heave and thaw settlement during the freezing construction period of subway cross passages, the existing results are basically a separate analysis of stratum frost heave and thaw settlement, and the numerical simulation calculation for the whole process of the actual construction of connecting passage freezing has not been realized. We failed to conduct an integrated comprehensive analysis of the active freezing period (stratum frost heave), maintenance freezing period (excavation of the connecting passage), and freezing wall thaw period (stratum thaw). In the existing numerical simulation studies, part of the frozen wall studied has a uniform temperature field, and the transient freeze-thaw process of the frozen wall is not considered. In this way, it is difficult to accurately reflect the frost heave and thaw settlement of the ground during the freezing construction of the cross passages. Some studies are too simplistic in the process of numerical simulation of soil freezing and thawing deformation. For example, most studies adopt negative thermal expansion coefficients to simulate the problem in the treatment of soil frost heave deformation, which is contrary to the frost heave mechanism of soil. The second is that the value of the expansion coefficient is unfounded, and most studies regard the freezing and thawing deformation of the soil as the characteristics of isotropic deformation, which does not conform to the actual situation. Several studies have attempted to start from the true frost heave mechanism of the soil and consider the in-situ frost heave and subcondensation frost heave of the soil, so as to numerically analyze the frost heave problem of the ground during the freezing construction period of the connecting passage, but the input parameters are involved in the analysis process. Therefore, the results are greatly restricted in serving actual engineering [50, 51]. In view of this, the effective simulation of frost heave and thaw settlement during the freezing construction period of the subway connecting passage needs to be solved urgently.

Regarding the model test study of ground frost heave and thawing settlement during the freezing construction of subway cross passages, due to the particularity and complexity of the test implementation process, the model material cannot use similar materials, but only the site soil, and the model adopts the geometric similarity ratio. Further, the initial stress field of the soil needs to be loaded to meet the similar conditions. In this way, the law and magnitude of frost heave and thaw settlement of the formation obtained from the model test need to be further verified. Therefore, the reasonable implementation procedure and process of the freezing engineering simulation experiment of the subway connecting passage need to be resolved [52–56].

The research is mostly limited to the scope of the freezing front. For freezing engineering, the deformation and strength characteristics of the soil are more important during the freezing and thawing process. A large number of tests have shown that the strength properties of frozen soil have both sides that range from the strength properties of melting soil friction materials at high temperatures to the strength properties of lattice materials of frozen soil at low temperatures. Only the analysis and research on the deformation and strength properties of frozen soil cannot meet the needs of actual engineering and cannot fully reveal the change law of the strength and deformation characteristics of the soil during the freezing process [53, 54]. In the current related numerical simulation studies, some studies did not consider the transient freezing process of the frozen wall, so they cannot accurately reflect the frost heave and thaw settlement of the ground during the tunnel freezing construction. Many studies used negative thermal expansion coefficients to simulate the problem in the treatment of simulating soil frost heave deformation, which is not consistent with the frost heave mechanism of soil [55]. In addition, the value of the expansion coefficient is mostly based on experience without a solid theoretical basis, and most studies regard the freeze-thaw deformation of the soil as an isotropic deformation feature, which is also very different from the actual working conditions. From the perspective of engineering application, few model tests under specific geological environments have been carried out as the geological environment faced by artificial frozen soil construction becomes more and more complex, and there is a lack of comparative analysis work on-site measured data and indoor model test data [56]. Horizontal freezing construction is carried out in water-rich soft soil areas. The laboratory macro- and mesomechanical tests for theoretical research on frozen soil properties have not yet been carried out, and the comparative analysis of field measured data and numerical simulation calculations is still lacking.

3. Conclusions

In summary, the current problems are that the design of the freezing wall is unreasonable, the evolution and development mechanism of the freezing temperature field is not clear enough, and the mechanism of frost heave and thaw settlement in the freezing process is not clear. It is not theoretically possible to clarify the location of the area that caused the settlement, the magnitude of the impact, and the accuracy of measures such as grouting.

(1) The formation process of frozen soil is basically a physical and mechanical process. During this process, the properties of the soil undergo essential changes. The freezing temperature field is an unstable heat conduction problem with complex boundary conditions with phase transitions, moving boundaries, and internal heat sources.

(2) The important parameters such as the freezing curtain, the average temperature, and the temperature distribution of the freezing wall are not controlled accurately due to the lack of understanding of the evolution law of freezing temperature field of deep soil, and the strength and stability of the

freezing wall are not guaranteed, which makes the construction of the connecting passage prone to problems.

(3) The monitoring temperature is the temperature of the temperature measuring tube, not the temperature of the soil in freezing engineering. The existence of the temperature measuring tube destroys the original temperature field. The thermodynamic parameters of steel and soil are very different, which will inevitably cause a large measurement error, and it cannot accurately reflect the true state of the measuring point. We should accurately grasp the development status of frozen soil, improve the temperature measurement method or reveal the relationship between the temperature measurement result and the real temperature of the frozen wall, and have a special effect on the accurate temperature measurement and objective understanding of the temperature field during the construction of the cross passage.

(4) It is an effective supplement to on-site temperature measurement to predict the freezing temperature field under complex conditions since the current temperature field calculation method is ideal. When conducting theoretical analysis and numerical simulation, the thermophysical parameters of soil are basic data, which can generally be obtained through laboratory thermophysical experiments or through inversion. Compared with other materials, soil has many types of thermal and mechanical parameters, complex testing, and large dispersion. Therefore, strengthening the study of soil thermal and mechanical parameters is a basic work.

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.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant no. 41877251) and the special fund for Basic Scientific Research and Young Backbone Teachers of Zhongyuan University of Technology (Grant nos. K2020QN015 and 2020XQG14).

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