

Simulation of Temperature Field in Railway Embankment Filling in Seasonal Frozen Areas

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ABSTRACT

In order to examine the temperature field changes of railway roadbed in seasonal frozen areas under different filling heights, a typical cross-sectional model of Chagan Lake Station railway was established using the finite element numerical simulation software ANSYS. The temperature parameters of the roadbed were calculated based on the atmospheric temperature of local meteorological data, and the temperature fitting curve was used as the temperature boundary condition. Under different filling quantities, the temperature field of the roadbed was simulated for a freeze-thaw cycle, and the temperature curve changes were analyzed. The results indicate that as the filling height increases, the freezing depth line also increases accordingly. When the filling height is 2.5m, the maximum freezing depth at the roadbed is 1.7m. In a freeze-thaw cycle, the freezing process of soil develops from top to bottom, and the melting process develops in two directions: from top to bottom and from a certain depth of soil upwards, with the characteristics of "unidirectional freezing and bidirectional melting". The freezing period starts from early December of each year to the end of March of the following year, and completely melts until the end of April. Melting develops faster than freezing.

KEYWORDS

Filling the Roadbed; Temperature Field; Seasonal Freezing Zone; Numerical Simulation.

1. INTRODUCTION

China has a wide range of frozen soil areas, most of which are seasonal frozen soil areas, the phenomenon of soil frost heave in seasonal frozen soil areas is the main cause of damage to many buildings and vehicles. Especially on railway roadbed, frost heave phenomenon will lead to roadbed deformation and cracks, and will have long-term adverse effects on the material properties of soil. Moreover, the railway subgrade will produce regional settlement in the long-term service process, which is called post-construction settlement, which will affect the workload of line maintenance and railway operation capacity, and can only be adjusted by lifting the track and repairing the ballast. In order to explore the relationship between the amount of fill and frost heave effect, this paper focuses on the frost heave problem of the ballast track roadbed at Chagan lake Station, relying on the Chang-Bai Railway capacity expansion and reconstruction project. ANSYS finite element software is used to simulate the change law of the temperature field and displacement field of the roadbed at different fill heights.

In the early stage, the research of frozen soil temperature field in China mostly used the methods of field investigation, field exploration, field inspection, one-dimensional linear model analysis, semi-analytical method, etc., to explore the variation law. The numerical solution of one-dimensional

nonlinear high temperature field proposed by BonaiCina c. and Comini G.(2013) has led scientists around the world to begin to explore this field in depth, and has rapidly promoted the progress of this field[1]. In 2000, Galerkin finite element method was introduced to analyze the foundation temperature field in permafrost region by numerical simulation(Wang et al., 2010), and establish the finite element analysis method of controlling differential equations and various influencing factors, in order to better understand the mechanism[2]. After the application of Galerkin method, the finite element analysis technology has been widely used in the engineering field at the beginning of this century, especially in the construction of the Qinghai-Tibet Railway project, which provides an effective solution for the thermodynamic characteristics of the permafrost foundation. The finite element formulas of the second and third types of boundary conditions provided by Miron et al.(2013) can effectively simulate convective heat transfer in porous media, and their reliability can also be effectively verified by comparison with actual data[3]. Through finite element numerical simulation, Jiang Fan(2014) et al. found that using finite element model to study the convection and heat transfer characteristics of long-term frozen soil foundation could obtain more accurate results[4]. In addition, Lai Yuanming (2013) ,Sun Zengkui(2014) et al. also conducted finite element numerical simulation. The high temperature field of permafrost soil foundation is studied and compared with that of common soil foundation. Good results are obtained[5,6]. Based on the actual measurement data, Shen Yupeng(2018)et al. constructed a numerical model to study the temperature variation of the embankment of the station yard and the ordinary embankment[7].

Tan Yiqiu(2021)and Li Dongqing(2012) constructed a prediction model for the temperature field of the roadbed in seasonal frozen soil by using statistical regression method, while Li Dongqing further constructed a coupled mathematical model involving the three fields of water, heat and force, as well as a complex differential equation to analyze it[8,9]. In addition, Zhang Yuzhi(2014), Qi Changqing (2014)Yue Zurun(2015), Tai Bowen(2017) ,Qi Zhigang(2019) and Xu Yuezhen(2022) also constructed a ground temperature estimation formula based on the actual observation and collected data, so as to determine the basic boundary conditions of the model[10,11,12,13,14]. Through numerical simulation, we study the distribution rule of road base temperature, and use it as an important basis for predicting and controlling road freezing in winter.

2. ENGINEERING GEOLOGY OVERVIEW

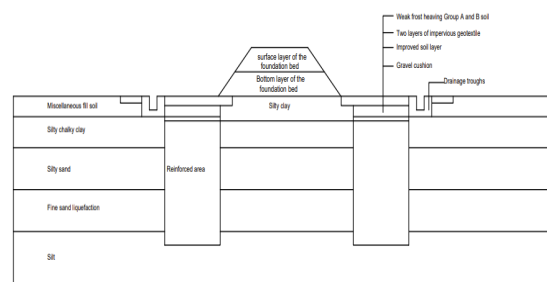


Figure 1. Calculation Model Diagram

Chagan Lake Station is located near Chagan Lake Tourist Resort in Songyuan City, Jilin Province. It is an important station of Changbai High-speed Railway, which is 182 km away from Changchun and 151 km away from Baicheng. It is a Class I double-line electric high-speed railway. The local climate belongs to the temperate humid ~ sub-humid continental climate, according to the impact of climate on the railway project, the region is a seasonal freezing area. Soft soil foundations are prevalent in the zone, much of which is caused by alluvial diluvium, and the soil types are divided into silt and silty clay, with the upper part consisting of fine sand and the middle of sand and gravel. The lower part is mainly the widely distributed Quaternary Holocene loose accumulation of silty soil layer and silt, the distribution thickness is generally 5~15m, and some can even exceed 25m. In this paper, the

K173+600 subgrade cross-section diagram of the long white line is used to simulate the prototype, and the finite element model is combined to simulate the 1:1 subgrade system model, as shown in Figure 1:

The geometric parameters of the roadbed are as follows:

The thickness of the surface layer of the foundation bed is 2m, the filler is graded gravel cushion, the bottom layer of the foundation bed is 0.5m, the filling soil layer is group A and B filler, and the embankment slope is 1:1.5. To improve the insulation effect, the upper layer is laid with weak frost heaving Group A soil, and the following two layers of impervious geotextile are distributed, and the improved soil layer and gravel cushion are added on it, and finally the geogrid is laid, the thickness is 0.5m, 0.1m, 0.3m. There are drainage troughs on both sides, which are concrete structures. The external layers are mixed fill, silty chalky clay, silty sand, fine sand liquefaction and silty soil layer, with thickness of 0.9m, 2.1m, 3m, 3m and 6m, respectively. The reinforcement layer is 10m thick and 6m wide. According to the actual situation of the project, the embankment of the bid section is filled by layers, each layer is 0.5m thick, and A total of 5 layers are filled. The first layer is composed of group A and B fillers, and the last four layers are composed of graded gravel.

3. MODELING THE FINITE ELEMENT TEMPERATURE FIELD

3.1. Thermal Parameters

The heat sources can be divided into three categories: solid particles, aqueous solutions, and air. To better study these heats, we need to consider density, thermal conductivity, enthalpy, freezing temperature, and other thermal properties.

3.2. Boundary Conditions

Through the study of two-dimensional finite element calculation model of railway subgrade structure, we find that the boundary conditions are affected by external environmental factors, which can be divided into upper, two sides and lower parts. The upper boundary conditions can be fitted as follows according to the local atmospheric temperature (select July 15, 2021 - July 14, 2022):

$$T = 5.643 + 18.18 * \sin\left(\frac{2\pi}{365} t + \frac{68}{169} \pi\right) \quad (1)$$

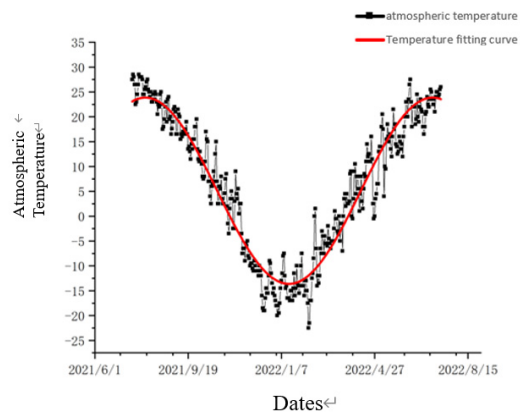


Figure 2. Temperature fitting curve

Since the soil around the subgrade maintains a natural state, it can be regarded as a completely isolated adiabatic boundary, and when the finite element software ansys is used for analysis, it will not be processed, so it can be identified as a completely isolated adiabatic boundary condition.

According to the latest research results, the lower boundary of the subgrade structure is in the constant temperature zone, so the temperature value at the bottom should be set to a fixed value. Through the in-depth analysis of relevant references and the comprehensive consideration of the temperature change in Northeast China, the temperature value of the lower boundary of the slope is finally determined to be 7.59°C.

3.3. Solution Method

In order to describe the temperature field more accurately when calculating the temperature field of the roadbed by finite element method, a quadrilateral mesh element is adopted in this paper. The length of the surface soil depth is 0.1m with a depth of 0-3m, and the length of the underlying soil is 0.5m. A total of 52750 mesh elements and 4722 nodes are set. Before the transient analysis of the temperature field of railway roadbed, it is necessary to apply the initial temperature field to the roadbed. The initial temperature field is usually determined by the maximum temperature of the soil mass. Therefore, the initial conditions are created in the summer of July 15, 2021, when the internal temperature of the soil mass is above 0°C. At this time, we apply thermal pressure to the top and side walls of the road and perform a stability analysis to derive the initial temperature field of the road. From the initial temperature, according to the specified time period, we can use the principle of transient thermodynamics to estimate and predict the temperature change of the roadbed.

4. ANALYSIS OF TEMPERATURE FIELD RESULTS

4.1. Verification of Temperature Field Model

In view of the fact that the roadbed project has not yet been completed and the local testing data of the roadbed in the seasonal freezing area is lacking, in order to ensure the accuracy of the roadbed temperature field model, we must compare it with the maximum freezing depth given in the project, combine the previous research results and the analysis of the temperature field change law to ensure the reliability and effectiveness of the model. The results of model calculation show that the maximum freezing depth of soil near the foundation of the railway roadbed appears about 252 days after the maximum surface temperature, that is, in the middle and late March of the next year, the maximum freezing depth of soil near the foundation reaches 1.35m. It conforms to the measured value of local maximum freezing engineering depth. Figure. 2 shows the temperature zone where the soil temperature is 0°C at the maximum freezing depth.

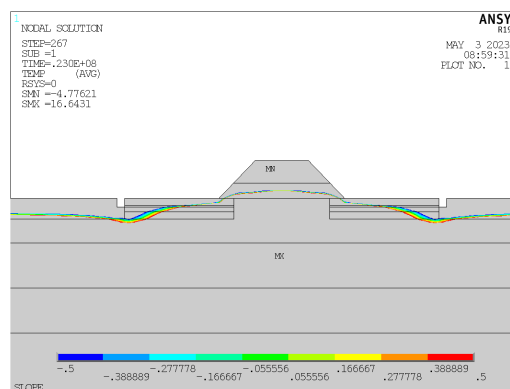


Figure 3. 0 °C temperature line at maximum freezing depth

After simulation, we found that the soil in the roadbed began to freeze on November 20, and the ice range reached its maximum around mid-to-late March of the following year. At the beginning of April, the ground will melt, until the beginning of May, the entire underground soil will be completely melted. This law is very consistent with other similar studies, so we consider this model to be credible and worthy of further exploration and analysis.

4.2. Analysis of Initial Temperature Field

The boundary condition of the initial temperature field of the railway roadbed is: the highest atmospheric temperature in summer is 23.86°C on the upper surface of the roadbed. The bottom of the roadbed is used as a constant temperature zone, and the input temperature is 7.69°C. The steady-state temperature field of the primary roadbed is analyzed, and the calculated results are taken as the initial temperature field of the subsequent transient temperature field. As can be seen from Figure 3.7, the temperature distribution decreases from top to bottom along the soil depth.

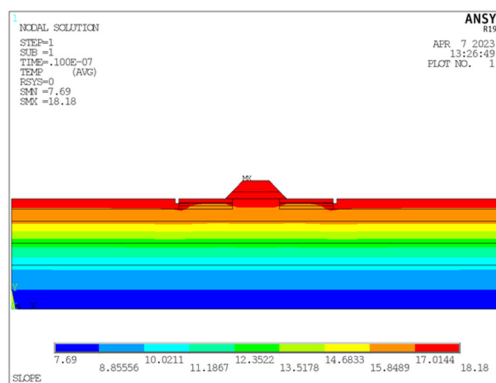
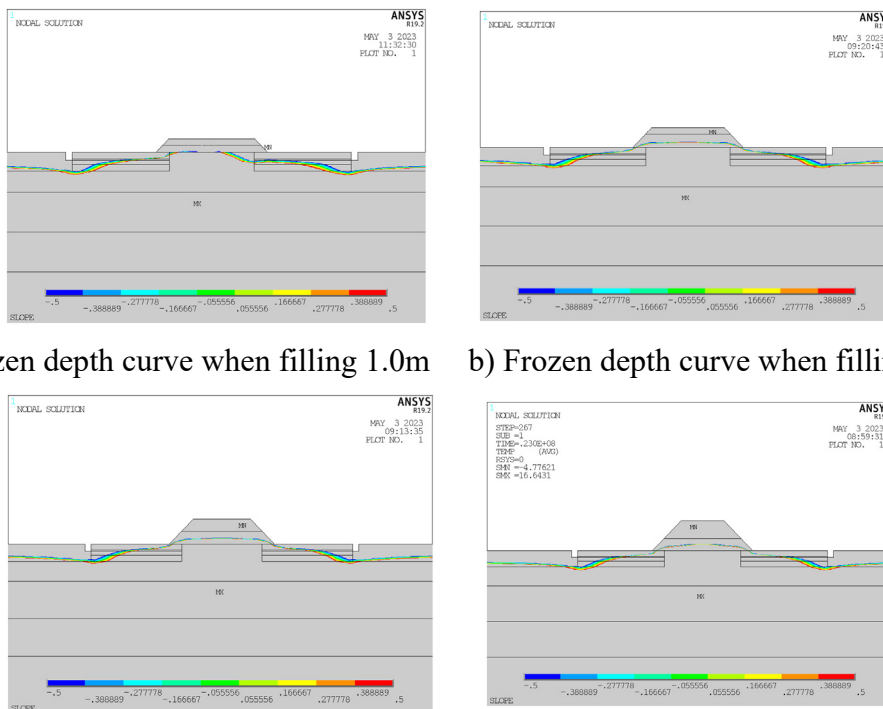


Figure 4. Initial temperature field of slope

4.3. Analysis of Freezing Depth under Different Fill Heights



a) Frozen depth curve when filling 1.0m b) Frozen depth curve when filling 1.5m

c) Frozen depth curve when filling 2.0m d) Frozen depth curve when filling 2.5m

Figure 5. Frozen depth curve at different filling heights

The temperature field of the subgrade is analyzed when the filling height is 1.0m, 1.5m, 2m and 2.5m. According to the analysis results, the time of maximum freezing depth is slightly different for the soil under the subgrade with different filling heights, but the difference is not big, and they all reach in mid-April. The maximum freezing depth is reached 7-10 days earlier when the filling height is 1.0m than when the filling height is 2.5m. The results of different filling heights reaching the maximum freezing depth are shown in Figure 4. The figure 5 shows the temperature band cloud map of $-0.5^{\circ}\text{C}\sim 0.5^{\circ}\text{C}$.

According to Figure 4, when the fill height increases, the freeze depth line will rise accordingly, and the difference in the maximum freeze depth value is small regardless of the fill height. When the filling height is 1.0m, the maximum freezing depth at the subgrade is 0.8m, and when the filling height is 2.5m, the maximum freezing depth at the subgrade is 1.7m. During the thawing of frozen soil, the positions of frozen soil cores generated in the subgrade with different fill heights are relatively fixed, roughly appearing within 2 meters below the surface of the subgrade, and the positions of frozen soil cores gradually increase with the increase of fill height. During the melting period, the position near the slope foot melts earlier than the shoulder and the center of the line, and the range of this position increases with the increase of the fill height.

In order to understand the variation law of subgrade temperature field during freeze-thaw process, taking the filling height of 2.5m as an example, the subgrade temperature field in different aspects is analyzed deeply.

4.4. Variation of Freezing Depth with Time

The freezing temperature of subgrade soil is 0°C . Through numerical simulation, we can calculate the change of freezing depth with time at different locations, such as the center of the line, the shoulder of the road, the bottom of the slope, and the foundation soil with and without insulation layer, as shown in Figure 5.

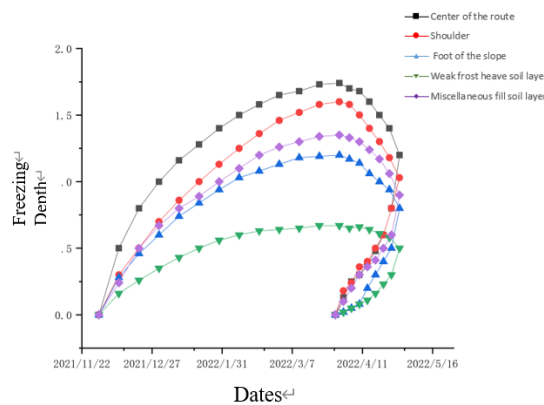


Figure 6. Curve of freezing depth over time

It can be seen from Figure. 5 that after the subgrade filling is completed, the freezing depth will gradually increase with the development of time during the freezing period, and the maximum freezing depth at each node will decrease sharply during the melting period. The soil in the center of the line and the shoulder of the road is more likely to freeze, and the increment and maximum freezing depth of the freezing depth are larger than that of the underlying soil. The maximum freezing depth at the road shoulder is slightly smaller than the maximum freezing depth at the center of the line during the same period, and the maximum freezing depth at the center of the line can reach 1.73m. Compared with the soil without insulation layer, the freezing depth of the soil with insulation layer is smaller and the freezing curve is smoother, indicating that the insulation layer can significantly reduce the effect of freezing. The freeze-thaw cycle began in early December and continued for 120 days until the maximum freeze-thaw depth was reached. Then, this situation becomes more obvious, from

the beginning of April, the ground began to melt, until the beginning of May, the melting process is basically finished. The melting period develops faster than the freezing period. The maximum freezing depth can be 1.35m below the foundation soil.

After the maximum freezing depth is reached, the low-temperature load will no longer be transferred downward, and at this time, the surface temperature will gradually rise. From the freezing period to the melting period, two 0°C temperature zones will be generated, which is because the lower part of the soil is already in the frozen soil state, the soil temperature is already below zero temperature, and the atmospheric temperature near the soil surface has gradually increased. Gradually, a temperature above zero will be applied to the surface of the soil, so that the surface temperature of the soil is greater than zero, so two 0°C temperature lines will be generated. Then, with the development of time, an elliptical part of frozen soil will be gradually produced in the soil foundation. When the frozen soil is completely melted, the subgrade soil enters a complete freeze-thaw cycle, which marks the end of the melting period.

4.5. Variation Characteristics of Ground Temperature with Depth

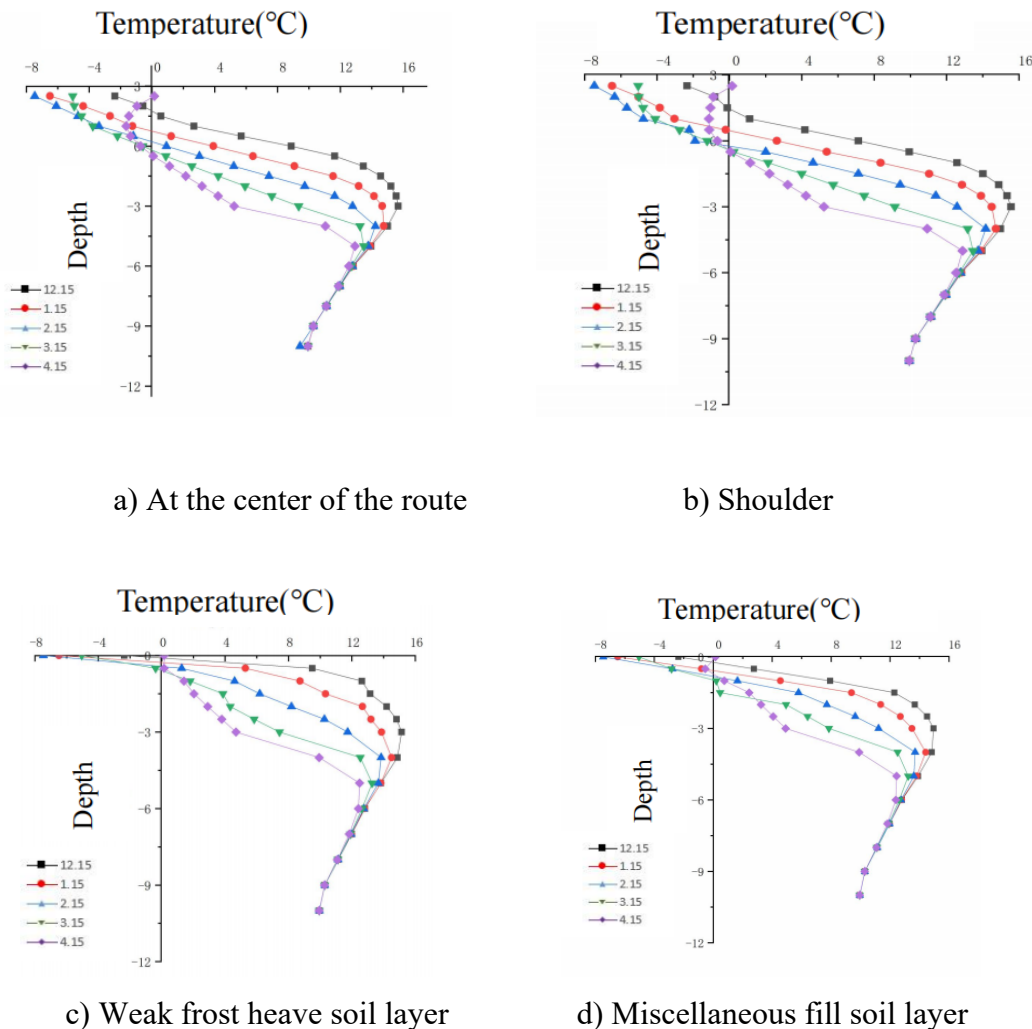


Figure 7. Ground temperature variation curve with depth at different locations

In order to better explore the relationship between soil temperature and depth in the stratum, we selected the subgrade soil mass and foundation soil mass with a depth of 10m, and drew the temperature change curve on the 15th day of each month through numerical simulation, as shown in Figure 6, so as to determine the influence range of ground temperature more accurately.

According to the curve of ground temperature variation with depth shown in Figure 6, during the soil freezing period, the soil temperature changes with depth within 10m below the subgrade soil and the subgrade soil as follows: when the soil depth gradually increases, the soil temperature increases first and then gradually decreases, and finally tends to be stable, maintaining at a temperature value. The variation range of surface soil temperature is large, and the variation range begins to decrease with the increase of depth, and finally approaches the constant temperature zone. At a depth below 6m, the temperature of the soil mass changes little or basically unchanged over time. In the range of soil depth from 2.5m to 3m, with the development of time, the soil depth at the same temperature becomes larger and larger. The temperature of the soil at the same depth becomes lower and lower. When the depth is 3m to 5m, the soil temperature varies with the depth at different time nodes. In the early freezing period, the higher the depth, the lower the soil temperature. In the late freezing stage, the soil temperature increases first and then decreases with the increasing of the depth. When the depth is greater than 5m, the change rule is that the greater the depth, the soil temperature gradually decreases.

5. CONCLUSION

In this chapter, based on the heat conduction principle of transient temperature field, the subgrade cross section design diagram of typical section k173+600 at Chagan Lake Station on the Changbai Line in the seasonal frozen soil area is selected as a typical model by using finite element software ansys, and the steady state and transient state of the temperature field are calculated and analyzed. Based on the detailed study of the theoretical knowledge of heat transfer, the selection basis and value of the model thermodynamic parameters such as the density, thermal conductivity, specific heat and enthalpy of freezing state, phase transition state and melting state, boundary conditions, grid division and solving process are explained. The reliability of the model was verified by freezing depth comparison. The main contents are as follows:

- (1) In a freeze-thaw cycle, the freezing process of the soil develops from the top down, and the melting process develops from the top down and from a certain depth of the soil up in two directions, with the characteristics of "one-way freezing, two-way melting". The freezing period starts from the beginning of December each year to the end of March the following year, and the complete melting until the end of April. Melting develops faster than freezing. The maximum freezing depth was 1.35m at the end of March.
- (2) The weakly heaved soil has less freezing depth than the mixed fill soil and is less affected by temperature. Group A and B packing and graded gravel layer at embankment are more susceptible to frost heave, and the range of frost depth is larger. In railway operation, more attention should be paid to the effect of frost heave at the subgrade.
- (3) It can be seen from the curve of freezing depth with time that the freezing depth at the shoulder reaches the maximum and the melting ends later than that at the center of the line. The soil at the position of foundation soil reaches the maximum freezing depth and the melting end time is earlier than the road shoulder and the center of the line. As the heat transfer of the soil mass is not obvious, the heat energy is lagging behind in the process of downward transfer to the soil layer, which makes the subgrade soil mass in the seasonal freezing area appear at the end of March when the maximum freezing depth is reached, rather than in January when the temperature is lowest.
- (4) The freeze-thaw cycle mainly occurs in the surface part of the soil. When the depth of the soil is greater than 2m, a freeze-thaw process is less affected by temperature. The surface soil varies greatly under the influence of temperature, and the development trend of freezing and melting process is roughly linear. From early December to February of the following year is the rapid development stage, from February to early April is the stable development stage, and from early April to early May is the rapid melting stage.

(5) The variation of soil temperature with depth presents different rules at different time nodes. During the freezing period, the temperature decreases first and then increases and then decreases with the increase of depth. During the melting period, the temperature first increases and then decreases with the increase of depth.

ACKNOWLEDGMENTS

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