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Stability analysis of ballasted Track subgrade in permafrost areas during deep Seasons

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***Abstract**: In seasonally frozen areas, severe temperature changes will have a huge impact on railway subgrade. Based on the subgrade engineering at the entrance of Limin tunnel of Harbin Mudanjiang railway passenger dedicated line, this paper uses the finite element software ANSYS module to establish the CRTSIII slab ballasted track subgrade foundation structure model, and uses the thermodynamic coupling analysis method to convert the temperature field calculation results into equivalent thermal load applied to the finite element model. The results show that the displacement curves of the key monitoring points of the subgrade during the freeze-thaw cycle are highly consistent with the deformation laws of the characteristic points of the foundation, showing that the typical freeze-thaw cycle thaw settlement rate is greater than the freezing rate; The maximum displacement in the frost heave stage is 3.08mm, and the settlement value in the thaw settlement stage is 1.28mm; the freeze-thaw deformation response at the slope shoulder is the earliest and the deformation amplitude is the largest, and the deformation amplitude at the subgrade center is also small, while the freeze-thaw deformation response at the slope toe is the latest and the deformation amplitude is the smallest. The stability of slope shoulder position and subgrade center area needs to be paid attention to, which provides theoretical support for the design optimization and long-term service performance evaluation of ballasted track subgrade.*
Key words: *Seasonal frozen area; Ballasted track; Finite element analysis; Thermodynamics; stability*

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I. Introduction

China has a vast territory, and the distribution of frozen soil is extremely broad. Seasonal frozen soil area accounts for more than half of the land area, and many railway lines need to cross seasonal frozen soil area. Unlike the widely studied ballastless track of high-speed railway, ballasted track is still an important track structure in the frozen soil area with colder climate and more complex geological conditions because of its relatively simple structure, easy maintenance and good drainage and elastic performance. The unique periodic freeze-thaw cycle process in deep seasonal frozen soil region makes the subgrade soil undergo drastic volume changes, which will have a serious impact on the stability of the subgrade. Many scholars have carried out extensive research on the stability of Subgrade in cold regions by combining field monitoring, indoor model test, numerical simulation and other methods. In Railway Engineering in deep seasonal frozen soil area, the evolution of Subgrade Temperature Field and frost heave deformation mechanism are the core issues. Based on the long-term monitoring data of Qingshuihe test section of Qinghai Tibet railway, shenyupengl[1]. Revealed the coupling mechanism between subgrade geometry and thermal condition. Tanyiqiu[2]. Established a time-varying prediction model of temperature field based on the monitoring data of Subgrade Temperature in seasonal frozen soil area, providing the basis for maintenance decision-making. Yuezurun, Tai Bowen[3-4]. studied the thermal effect of insulating guardrail on Haqi passenger dedicated line through numerical simulation, and confirmed that thermal insulation measures can effectively control heat flow and inhibit frost heave in the lower part of subgrade slope and slope toe area. Donglianchen[5]. Constructed a multi field coupling model of subgrade moisture temperature stress based on partial differential equation, and explored the development law of frost boiling. Zhang Yuzhi[6] and others combined the three-dimensional finite element model and field monitoring to clarify the coupling mechanism of frost heave deformation and thermal response in the seasonal frozen soil section of Harbin Dalian high speed railway, and pointed out that the increase of frost heave rate would lead to the significant increase of freezing depth, uneven uplift displacement and tensile stress. Based on ABAQUS, Wang Ziyu[7] developed the subgrade coupling model with infinite element boundary and phase change module, and realized the full coupling simulation of thermal mechanical field. Mao Xuesong[8]. Studied the evolution characteristics of temperature field of Seasonally Frozen Subgrade by combining theory and numerical method. Qizhigang's[9]Simulation on Lanzhou Xinjiang High Speed Railway shows that the low embankment structure shows more significant freezing depth characteristics in the slope and lower part due to the difference of soil parameters. Dongliang[10]. Studied the transition section of Alpine Road and bridge, and found that its temperature field distribution and frost heave deformation were highly dependent on the thermophysical properties of the filler and climatic conditions. Wangyunjia[11]and others innovatively put forward the calculation method of frozen front concave deformation, and revealed the variation law of frozen front geometry by using COMSOL. For ballastless track, zhouxiaoyong[12] built its temperature field model and systematically revealed the spatial and temporal distribution characteristics; Xuhao[13]. Established a coupled temperature deformation field model and found that the amplitude of frozen wave deformation was significantly related to the wavelength. Based on this, a method for predicting deformation based on the wavelength was proposed; Xuxinyu[14] and others pointed out that the stress state was the most unfavorable when frost heave occurred in the middle area of the track slab; Tian Jincheng[15] quantitatively analyzed the significant effect of frozen wave waveform on track dynamic response. Jiangdong[16] pavilion through the freeze-thaw cycle test, the water thermal coupling characteristics and frost heave mechanism were revealed, and the frost heave effect of the insulation layer was verified; Based on the thermodynamic theory, Niu Hao[17] clarified the driving effect of temperature gradient on the frost heave deformation of Beijing Baotou railway subgrade.

II. Numerical simulation of freezing thawing process

2.1 establishment of finite element model

Based on the multi physical field coupling theory, a three-dimensional numerical model of high-speed train track subgrade dynamic interaction is constructed by using ANSYS finite element software. By setting the geometric parameters such as subgrade height, subgrade width, subgrade slope, subgrade width, subgrade depth and subgrade length, as well as the material parameters and the minimum element size, the grid division can be automatically completed (the grid thickness will automatically change twice from the loading center to the site edge), and then the calculation model of finite element temperature field of double track railway subgrade is constructed. The model is conducive to parametric analysis to explore the influencing factors. In this paper, the model is divided into hexahedral grid elements. The total number of elements in the model is 798812, and the total number of nodes is 816721. According to the linear expansion coefficient of the material shown in table 1, the temperature stress constitutive relationship is constructed.Figure 1 shows the Subgrade model of ballasted track

Table 1 Linear expansion coefficient of different structures

structure type	rail	Ballast	Weak frost heaving soil	Silty clay	Muddy silty clay	Gravel cushion	Improved soil	filled soil	Loose and slightly dense silty sand liquefaction	Soil in reinforcement area
Coefficient of linear expansion α	1.18e-5	1.25e-4	1.15e-4	1.25e-4	-1.6e-4	2.05e-4	1.25e-4	1.45e-4	1.35e-4	1.25e-4

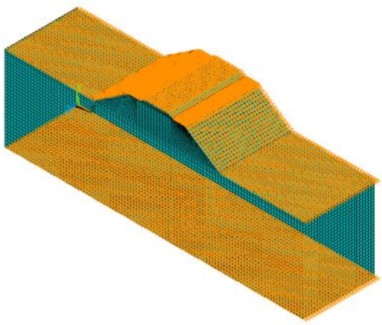


Figure 1 Subgrade model of ballasted track

2.2Basic principles of thermal analysis

Based on the theory of elasticity and isotropy assumption, the three-dimensional thermal mechanical coupling equilibrium equations for the ballasted track subgrade foundation system are established as follows:

Equilibrium equation:

$$\begin{cases} \dfrac{\partial\sigma_x}{\partial_x}+\dfrac{\partial\tau_{xy}}{\partial_y}+\dfrac{\partial\tau_{xz}}{\partial_z}=0 \\ \dfrac{\partial\sigma_y}{\partial_y}+\dfrac{\partial\tau_{xy}}{\partial_x}+\dfrac{\partial\tau_{yz}}{\partial_z}=0 \\ \dfrac{\partial\sigma_z}{\partial_z}+\dfrac{\partial\tau_{xz}}{\partial_x}+\dfrac{\partial\tau_{yz}}{\partial_y}=0 \end{cases} \tag{1}$$

Where: σ is normal stress; τ is shear stress;[σ] - soil stress matrix, expressed as $\left[\sigma_x\sigma_y\sigma_z\tau_{xy}\tau_{xz}\tau_{yz}\right]^T$.

Geometric equation:

$$[\varepsilon]=\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_x\end{bmatrix}=\begin{bmatrix}\frac{\partial_u}{\partial_x}\\ \frac{\partial_y}{\partial_y}\\ \frac{\partial_y}{\partial_z}\\ \frac{\partial_y}{\partial_z}\\ \frac{\partial_u}{\partial_y}+\frac{\partial_y}{\partial_x}\\ \frac{\partial_y}{\partial_z}+\frac{\partial_w}{\partial_y}\\ \frac{\partial_u}{\partial_z}+\frac{\partial_w}{\partial_x}\end{bmatrix} \tag{2}$$

Where: - ε is the positive strain component; γ is the shear strain component;u, v, w -- displacement in x, y, $z$direction corresponding to coordinate axis.

Physical equation:

$$[\sigma]=\frac{E}{(1+\mu)(1-2\mu)}\begin{bmatrix}1-\mu & \mu & \mu & 0 & 0 & 0 & \\ \mu & 1-\mu & \mu & 0 & 0 & 0 & \\ \mu & \mu & 1-\mu & 0 & 0 & 0 & \\ & 0 & 0 & 0 & \frac{1-2\mu}{2} & 0 & 0\\ & 0 & 0 & 0 & 0 & \frac{1-2\mu}{2} & 0\\ & 0 & 0 & 0 & 0 & 0 & \frac{1-2\mu}{2}\end{bmatrix}([\varepsilon]-[\varepsilon]_{iel}) \tag{3}$$

It can be simplified as:

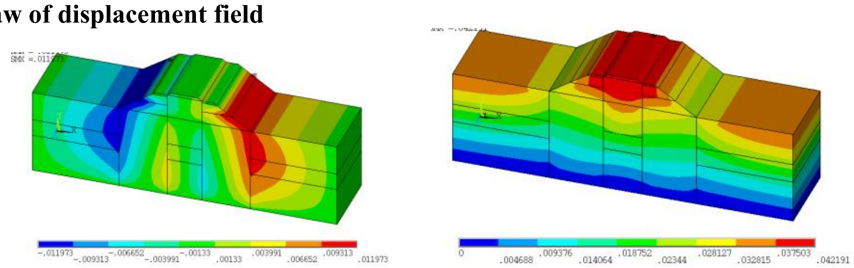
$$[\sigma]=[D]\left([\varepsilon]-[\varepsilon]_{isl}\right) \tag{4}$$

Where: E - elastic modulus of structure or soil mass, Pa; μ —Poisson's ratio of structure or soil;[D] -- elasticity matrix.

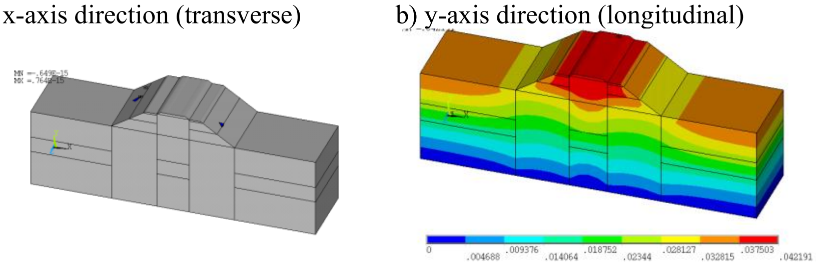
Based on the assumption of linear elasticity, the mathematical model established in this paper realizes the thermal mechanical coupling analysis through the following simplification:

$$[\sigma]=[D][\varepsilon] \tag{5}$$

2.3 variation law of displacement field



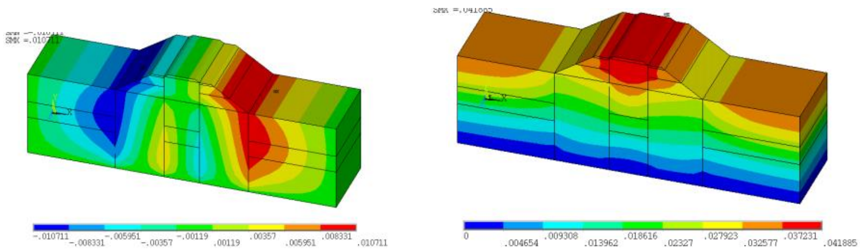
a) x-axis direction (transverse) b) y-axis direction (longitudinal)



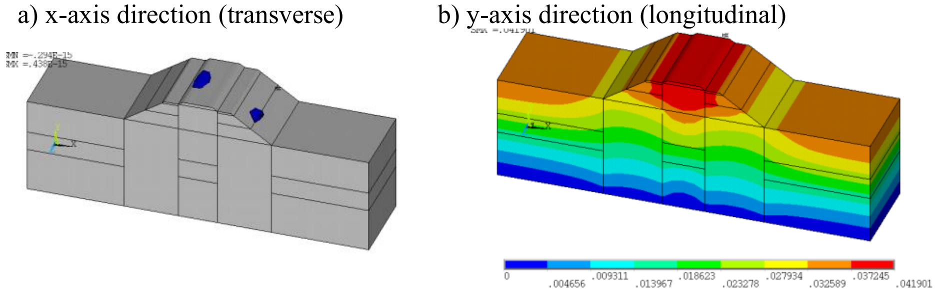
c) z-axis direction (longitudinal) d) resultant displacement

Fig. 2 Displacement Response Characteristics at Key Locations of Monitoring Point4 During Freezing Periods

Figure 2 shows the displacement response characteristics of the characteristic positions of monitoring point 4 during the freezing period on January 31, 2024. The numerical simulation results show that in the x-axis direction (transverse), due to the stress field on the right side of the subgrade structure, the characteristic point has a positive displacement of 3.0mm; In the y-axis direction (longitudinal), there is an upward displacement of 3.1mm due to frost heave effect. This is due to the volume expansion caused by the phase change of water in the frozen soil during the freezing process. With the decrease of temperature, the unfrozen water continues to transform into ice crystals, forming a significant expansion deformation of the frozen soil skeleton; In the z-axis direction (longitudinal), no obvious displacement was observed due to the geometric symmetry and boundary constraints of the model. By analyzing the combined displacement cloud map, it can be found that the total displacement vector of the ground object point is 3.23mm, which has obvious spatial directionality. The results of displacement vector synthesis show that although the point is affected by lateral stress and vertical frozen soil uplift force at the same time, the vertical displacement component is larger in the comprehensive displacement, resulting in the comprehensive displacement direction closer to the vertical direction, indicating that the vertical deformation is the dominant factor in the subgrade displacement field in the frozen period; The influence of transverse stress on deflection in displacement direction is relatively limited; Vertical deformation plays a decisive role in the deformation mechanism of Subgrade in cold regions.



a) x-axis direction (transverse) b) y-axis direction (longitudinal)



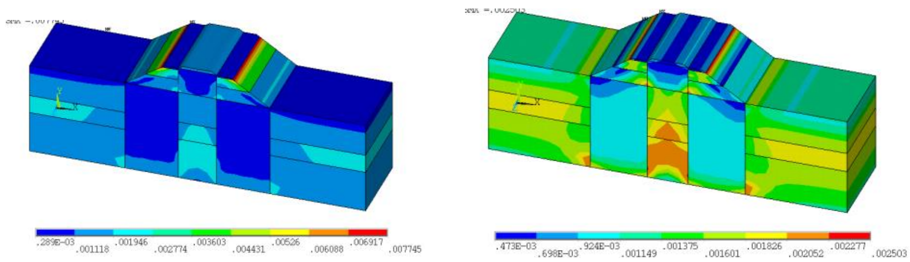
c) z-axis direction (longitudinal) d) resultant displacement

Fig. 3 Displacement Response Characteristics at Key Locations of Monitoring Point4 During Thawing Periods

Figure 3 shows the displacement response characteristics of the characteristic positions of monitoring point 4 during the melting period on April 30, 2024. The numerical simulation results show that the characteristic point produces only a small displacement of 0.18mm in the x-axis direction, which is relatively reduced compared with the freezing period. This is due to the weakening of soil mechanical properties caused by the increase of temperature, the significant decline of soil strength caused by the thawing of frozen soil skeleton, and the redistribution of stress to the inner side of the subgrade caused by the volume shrinkage caused by the phase change of ice water, and the melting effect partially offsets the original transverse stress. The displacement field analysis in Figure 3 further reveals the typical deformation characteristics of the characteristic points in the melting period: in the y-axis direction, the position produces a downward displacement of 1.3mm, which is due to the phase change failure of the frozen soil skeleton with the increase of temperature, the volume contraction of the soil caused by the melting of ice crystals into water, and the consolidation settlement caused by the discharge of pore water. The displacement vector in Z direction is 1.31mm, and the deviation rate from the vertical displacement is very small, which indicates that the vertical thawing settlement deformation is dominant; The influence of horizontal displacement can be ignored. This deformation mode is in sharp contrast with the freezing period, which shows that the deformation mechanism of Subgrade in cold regions has a great relationship with seasons.

2.4 variation law of stress field

Figure 4 shows the dynamic evolution characteristics of subgrade stress field during seasonal freeze-thaw cycles. In the freezing stage, the stress distribution presents a typical double-layer structure, and the surface area is dominated by freeze-thaw expansion, forming a tensile stress zone; The deep soil layer shows compressive stress concentration. This is due to the phase change expansion effect caused by the downward movement of the frozen front and the constraint effect of the unfrozen zone on the accumulation deformation of frozen soil. After entering the thawing period, the stress field is obviously reversed, and the surface thawing settlement zone produces compressive stress, while the deep layer maintains the state of compressive stress due to the lag of temperature transmission. Within the range of both sides of the subgrade centerline, the stress distribution shows good symmetry, which verifies the rationality of the boundary conditions in the model. The stress time history curve in Figure 5 clearly illustrates the typical mechanical response of subgrade structure under the coverage of ballast layer. The simulation results show that the composite system of ballast and subgrade shows two key mechanical characteristics. Due to the sudden change of stiffness, a stress concentration zone is formed in the central area; The slope shoulder is controlled by the sliding surface, forming an asymmetric stress distribution. In the freezing development stage, the central line tensile stress rises rapidly, and the peak stress in the slope shoulder area is 0.128mpa due to the effect of three-dimensional constraints, both of which show a single peak variation law. After entering the melting settlement period, the residual tensile stress of 0.069mpa remained in the centerline, while the slope shoulder area transited to a compressive stress state of -0.08 MPa. This stress reversal phenomenon is highly consistent with the displacement monitoring data. On this basis, the subsequent train dynamic load analysis should focus on the stress concentration effect in the central area.



a) Freezing stage b) Melting stage

Fig. ıracterization of the dynamic evolution of the roadbed stress field

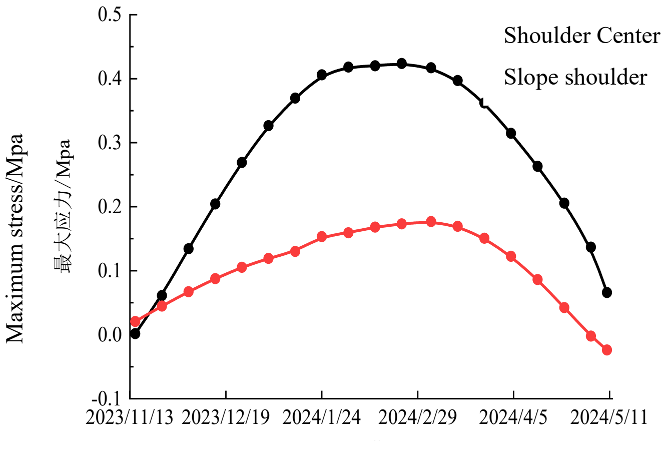


Fig. 5 Str ourse curve

2.5 thermal stability analysis of Subgrade in seasonal frozen area

The thermal stability of frozen soil refers to the ability of frozen soil to maintain the freezing and thawing process of original permafrost and the change of annual average ground temperature under the change of external temperature and heat [18]. Therefore, the thermal stability index of subgrade is introduced:

$$S_t = \frac{Q_t}{Q_+} \tag{6}$$

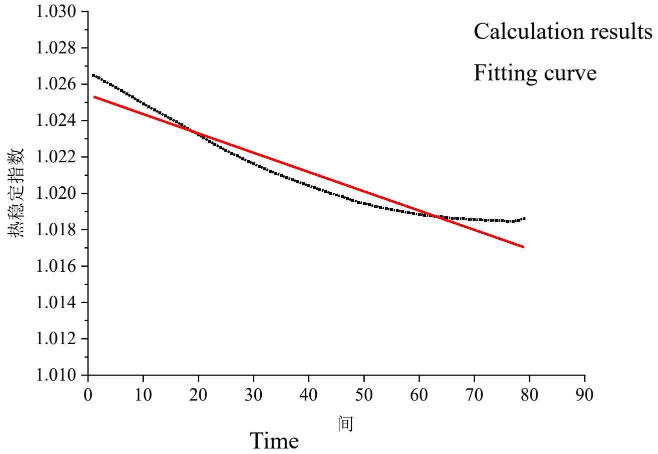


Fig. 6 Thermal stability index

The abscissa unit in the figure is 2D. According to reference[18], the model belongs to thermal stability transition type II, indicating that common human activities will only have a small impact on subgrade stability, which is not enough to cause serious problems.. Using the leven marguardt iterative algorithm, the thermal stability index in the figure is fitted by the exponential function . The fitting function expression is:

$$f\left(t\right)=e^{0.0251-0.000104t} \tag{7}$$

The calculation results based on the thermodynamic coupling model show a very high fitting accuracy R^2=0.995, which can accurately describe the long-term evolution of subgrade stability in seasonal frozen soil areas. The prediction analysis shows that the thermal stability index of subgrade will remain in a relatively safe range in the initial operation period (t ≤ 7.2 years). With the extension of operation time (t ≈ 38.3 years), the system will enter a dangerous state, which may cause structural damage. The prediction results are based on the current trend of climate boundary conditions, without considering the impact of extreme weather events and ignoring the maintenance intervention measures. As a basic evaluation tool, the prediction results of the model need to be dynamically adjusted in combination with field monitoring data to improve the reliability of long-term prediction.

III. Conclusion

In this chapter, based on the thermoelastic theory, the constitutive relationship considering the phase transition effect is constructed, and the space-time distribution of displacement field and stress field during the whole freeze-thaw cycle is solved; The dimensionless thermal stability index is introduced to quantitatively evaluate the long-term performance of subgrade. The main conclusions are as follows:

(1) During the freeze-thaw cycle, the displacement change curve of key monitoring points of subgrade is highly consistent with the deformation law of foundation characteristic points, showing a typical freeze-thaw cycle, in which the end of November to the beginning of December is the initial stage of freezing, the beginning of December to the middle of January is the rapid development period of freezing, the middle of January to the middle of March is the stable period of freezing, and the end of March to the beginning of May is the development period of thawing settlement, and the thawing settlement rate is greater than the freezing rate.

(2) The frost heave response of subgrade structure has obvious spatial differentiation characteristics. The freeze-thaw deformation response at the slope shoulder is the earliest and the deformation amplitude is the largest. The deformation amplitude at the subgrade center is also small, while the freeze-thaw deformation response at the slope toe is the latest and the deformation amplitude is the smallest.

(3) The stress distribution always maintains good symmetry. In the freezing stage, the subgrade structure presents a tensile stress state as a whole, and the maximum principal stress appears in the central line area; In the melting stage, it changes to the stage dominated by compressive stress, and the maximum principal stress also appears in the central line area. Therefore, in the later study, the subgrade centerline will be determined as the key analysis and monitoring area, in order to accurately capture the evolution of stress field.

(4)The long-term performance of high-speed railway subgrade in seasonally frozen soil area is systematically evaluated by using the subgrade thermal stability index. The results show that the subgrade is in the transition state of thermal stability, and the short-term human interference influence coefficient is less than 0.15; The annual deformation shall be controlled within the allowable range; Maintain good structural integrity. The long-term prediction based on the nonlinear regression model shows that the system will enter an unstable state after 7 years of operation, the annual deformation may increase, and preventive maintenance needs to be started; After 38 years of operation, it will develop into a very unstable state, with the risk of structural damage. In practical engineering, it is recommended to calibrate the model parameters every 5 years.

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