Model and calculation method of frost heaving stress of stagnant water of tunnel in seasonally frozen area

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Abstract

The frost heave caused by the stagnant water may seriously threaten tunnels’ operation safety and service life in seasonally frozen areas. This paper aims to put forward new insights for the accurate evaluation of the frost heaving stress and the prevention of frost damage in seasonally frozen-region tunnels. Firstly, based on the local frost theory and local deformation theory, a new calculation model of the frost heaving stress caused by stagnant water is established. In this model, the space of stagnant water is simplified as the three-axis semi-ellipsoid, which is more in line with the actual situation. Then, the rationality of the new calculation model was verified by comparing it with the results of numerical analysis and previous studies. Finally, the effects of the crucial parameters in the calculation model were also conducted by the univariate method. The results show that the theoretical model is in good agreement with the numerical simulation. The theoretical analysis exhibits the more conservative results, which may provide a practical approach for damage assessments and frost preventions in the case of a lack of observed in-site data. Besides, some significant suggestions about the construction and design of seasonally frozen-region tunnels are obtained.

1. Introduction

The seasonally frozen region accounts for about 55% of the total land area in China (Lai et al. 2016). With the rapid development of the transportation networks and infrastructure in northeastern and northwestern China, a large number of tunnels, gas pipelines, underground storages were built in cold-region and seasonally frozen areas. In recent years, however, numerical frost damages were observed in these tunnels, including lining cracks, ice hanging in the tunnel, lining collapses, and so on (Lai et al. 2000, 2005). These damages may seriously threaten driving safety and shorten the service life of tunnels, and some tunnels need to be maintained and suspended in less than a year. Therefore, accurate evaluation of frost heave and frost-
damage proof plays a significant role in designing and constructing seasonally frozen-region tunnels.

To date, numerous researches were conducted to investigate the frost heave in the cold- and seasonally frozen-tunnels. Considering the non-uniform characteristic of the frost heave, Han et al. (2015) and Huang et al. (2016) derived a theoretical analytical method of frost heave load of circular tunnels and curved-wall tunnels, and explored the influence of the rock mass, lining forms, and buried depth by using finite element method (FEM). According to the continuous condition of displacement, Zhang et al. (2017) established a frost heaving model in a broken freeze-thaw circle and deduced a frost heaving calculation equation, the relation between the frost heave and influence factors were also analyzed by the partial correlation method. Based on the transient heat transfer theory with phase transition, Cheng et al. (2018) simulated the distribution law of temperature fields of surrounding rocks, internal force, and deformation of tunnel linings by using ABAQUS software. By performing the laboratory model test, Hu et al. (2018) investigated the distribution law of frost heaving force of the lining structure of the steep tunnel in cold areas. Liu et al. (2018) established a new calculation model that considers the non-uniform frost heave effect and investigated the relationship between the frost heave force and plastic damages. Combining with the lame solution of the elastic theory, the complex analysis, and Mohr-Coulomb yield criterion, Qin and Luo (2018) studied the plastic area of surrounding rocks and deduced the elastic-plasticity explicit solutions for frost heaving force and stress. Xia et al. (2018) proposed that the surrounding rock in the cold-region tunnel has a non-uniform frost heave under unidirectional freezing conditions and conducted a series of frost tests to the relationship between frost heaving deformation of surrounding rock and temperature. Based on the Drucker-Prager criteria (D-P criteria), Feng et al. (2019) derived the analytical elastoplastic solutions of the stress and deformation in the surrounding rock. Considering the combined effect of the rock elastic modulus and the void ratio, Liu et al. (2019) proposed a damage model for frost heaving pressure of tunnel linings. More relevant studies could be found in the works of Lv et al. (2019), Yan et al. (2019), Zhang et al. (2019), Guo et al. (2020), Huang et al. (2020) and Zhao et al. (2020).

The above studies have provided a good reference for calculating frost heave force and design of anti-frost damage in the cold- or seasonally frozen areas. Generally, the theoretical model of the frost heave force is mainly based on three theories: local frost heave theory, hydrous weathering lay and, integral frost heave theory (Liu et al. 2018; Xia et al. 2020). Currently, the frost heave based on the integral frost heave theory has been comprehensively conducted, and scholars had proposed numerous calculation models by using the integral frost heave theory (Cui et al. 2021). However, calculation models and analysis methods of the hydrous weathering lay and local frost heave theory are rarely mentioned, and the application scenarios of existing models are limited.

In addition, the construction defects always result in the space of stagnant water between the tunnel lining and the surrounding rock, including the construction collapse, over-excavation, and uncompacted backfilling. When water flows and fills the space, it freezes into ice at low temperatures. In water freezing, volume expansion
produces local frost stress, which causes severe damages to the tunnel lining. Therefore, the frost heaving stress of stagnant water is one of the critical technical problems that need to be solved; how to accurately evaluate frost heaving stress is of great significance in the anti-freezing design of seasonally frozen-region tunnels.

Wang and Hu (2004) proposed the conception of the frost heaving model of stagnant water, they simplified the space of stagnant water into triangles and derived the formula for calculating the frost heaving stress in a two-dimensional space. This model could better explain the frost heaving stress of stagnant water in practical engineering due to construction defects and provides a theoretical basis for subsequent studies. Considering that ice is an elastomer after the phase transformation of water at low temperature, Fan et al. (2007) improved the calculation model of Wang and Hu (2004) and proposed an equivalent elastic coefficient method, which makes the deduction process of frost heaving stress clearer and more straightforward. However, in the above research, the plane shape of the space of stagnant water is assumed to be triangular and evenly distributed along the longitudinal direction of the tunnel. Also, these calculation formulas of the frost heaving stress are derived under the two-dimensional condition. Although a reduction factor was proposed to convert from two-dimensional to three-dimensional analysis, the results are inaccurate. Hence, Deng et al. (2010) proposed a constrained model of frost heaving of stagnant water from a three-dimensional spatial perspective referring to that of gas pressure. They proposed that the frost force is generated on the premise that the water is confined in a specific space. Once there is no restriction in any direction, the frost heaving pressure will be released, and local frost heaving will not occur. Compared with the two-dimensional model, the theoretical derivation process is more rigorous. However, this model assumes that the dead water space is a tetrahedron, quite different from the actual situation.

To sum up, the research on the frost heaving theory of stagnant water is relatively less, and each has advantages and disadvantages. This paper aims to put forward new insights for the accurate evaluation of the frost heaving stress and the prevention of frost damage in seasonally frozen-region tunnels. Firstly, based on the local frost theory and local deformation theory, a new calculation model of the frost heaving stress due to the stagnant water is established. The space of stagnant water is simplified as the three-axis semi-ellipsoid in this kind of model, which is more in line with the actual situation. Then, the rationality of the new calculation model was verified by comparing it with the results of numerical analysis and previous studies. Finally, the parameter sensitivity analysis of the new calculation model by using the univariate method was conducted, followed by some scientific suggestions. The research results can provide a theoretical reference for calculating the frost heaving stress of stagnant water in seasonally frozen-region tunnels.

2. Calculation method of frost heaving stress of stagnant water

2.1. Basic assumption and calculation model

The following assumptions were conducted to analyze the frost heaving stress of stagnant water in seasonally frozen-region tunnels (Wang et al. 2020):
1. The surrounding rock and tunnel lining are homogeneous and isotropic materials, and their weights are not considered in this model.
2. The space shape of the stagnant water between surrounding rocks and tunnel lining is three-axis semi-ellipsoid, and the frost heaving ratio is equal in all directions.
3. The stagnant water is in plane contact with the lining, and the direction of frost heaving stress is perpendicular to the linings.
4. The frost heaving stress is wholly caused by the volume expansion when water freezes into ice under low temperatures.

The three-dimension model of frost heaving stress of stagnant water was established (see Figure 1), in which the circumferential length of the ice is expressed as $l$, the longitudinal length of the ice is represented as $B$, and the depth of ice accretion is expressed as $t$. The distribution of frost heaving stress is shown in Figure 2. In this mechanical model, three springs in series are used to simulate the deformation and stress of frozen surrounding rock, ice, and tunnel lining (see Figure 3). In the calculation, it is assumed that the deformation of surrounding rock, ice, and tunnel lining meet certain conditions, that is, at the contact point of surrounding rock and ice (Point A), the deformation displacement of the surrounding rock and ice is equal, and at the contact point of ice and lining (Point B), the deformation displacement of ice and lining is equal.

### 2.2. Formula derivation

Based on the local deformation theory, the elastic resistance of surrounding rocks is in direct proportion to the displacement, gives
\[ \sigma_i = K \delta_i \]  

where \( \delta_i \) is the displacement of point \( i \) on the surface of surrounding rocks (m); \( \sigma_i \) is the elastic resistance of point \( i \) (MPa); \( K \) is the elastic-resistance coefficient of surrounding rocks (MPa/m).

Then, the deformation of surrounding rocks under the frost heaving stress action gives

\[ \delta = \frac{P}{K_r + K_i} \]  

where \( P \) is the frost heaving stress (MPa); \( K_r, K_i, \) and \( K_l \) are the elastic-resistance coefficients of surrounding rock, ice and lining, respectively.

Similarly, the deformation of tunnel lining is

\[ \Delta = \frac{P}{K_i + K_l} \]
Therefore, the frost heaving stress can be expressed as

$$P = \delta (K_r + K_i) = \Delta (K_i + K_l)$$  \hspace{1cm} (4)

Let

$$\mu = \frac{K_r + K_i}{K_i + K_l}$$  \hspace{1cm} (5)

Then

$$\Delta = \mu \delta = \frac{K_r + K_i}{K_i + K_l} \delta$$  \hspace{1cm} (6)

The volume of the ice can be given as:

$$V = \frac{1}{6} \times \frac{4}{3} \pi \times t \times \frac{l}{2} \times \frac{B}{2} = \frac{1}{6} \pi tlB$$  \hspace{1cm} (7)

When the space of three-axis semi-ellipsoid is filled with stagnant water and frozen at low temperature, the volume expansion of the ice is given as:

$$V_i = \frac{1}{6} \pi xtlB$$  \hspace{1cm} (8)

where $x$ represents the frost heaving ratio of ice. Therefore, the volume change of surrounding rock is given as:

$$V_r = \frac{1}{2} \times \frac{4}{3} \pi \times (t + \delta) \times \left(\frac{l}{2} + \frac{l}{2t} \delta\right) \times \left(\frac{1}{2} B + \frac{B}{2t} \delta\right) - \frac{1}{6} \pi tlB$$  \hspace{1cm} (9)

The volume change of the lining is written as:

$$V_l = \pi \frac{l B}{2} \Delta$$  \hspace{1cm} (10)

Since the volume expansion of the three-axis semi-ellipsoid space is equal to the volume changes of surrounding rock and lining, which can be given as:

$$V_i = V_r + V_l$$  \hspace{1cm} (11)

Therefore, substitute Equations (8)–(10) into Equation (11), gives:

$$\frac{1}{6} \pi xtlB = \frac{1}{2} \times \frac{4}{3} \pi(t + \delta) \times \left(\frac{l}{2} + \frac{l}{2t} \delta\right) \times \left(\frac{1}{2} B + \frac{B}{2t} \delta\right) - \frac{1}{6} \pi tlB + \pi \frac{l B}{2} \Delta$$  \hspace{1cm} (12)
Through mathematical calculation:

\[ xt = t \left(1 + \frac{\delta}{t}\right)^3 - t + \frac{3}{2} \Delta \]  

(13)

Divide the left and right sides of the Equation (13) by \( t \) \((t \neq 0)\):

\[ x = \left(1 + \frac{\delta}{t}\right)^3 - 1 + \frac{3\Delta}{2t} \]  

(14)

To simplify the calculation process, let

\[ \lambda = \frac{\delta}{t} \]  

(15)

Combining with the formula (5), formula (14) can be written as:

\[ x = (1 + \lambda)^3 - 1 + \frac{3\delta}{2t} \mu \]  

(16)

So

\[ x = (1 + \lambda)^3 - 1 + \frac{3}{2} \mu \lambda \]  

(17)

Through the mathematical calculation:

\[(1 + \lambda)^3 + \frac{3}{2} \mu \lambda - (x + 1) = 0\]  

(18)

To simplify the calculation process, let

\[ 1 + \lambda = \theta \]  

(19)

So

\[ \theta^3 + \frac{3}{2} \mu (\theta - 1) - (x + 1) = 0 \]  

(20)

Through the mathematical calculation, it can be written as:

\[ \theta^3 + \frac{3}{2} \mu \theta - \left(\frac{3}{2} \mu + x + 1\right) = 0 \]  

(21)

According to the research of Wei and Yuan (2000), the solution of \( x^3 + px + q = 0 (p, q \in R) \) can be given as:
\[
x_1 = 3 \sqrt{-\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}} + \sqrt{-\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}}
\]
\[
x_2 = \omega^3 \sqrt{-\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} + \omega^2 \sqrt{-\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}}}
\]
\[
x_3 = \omega^2 \sqrt{-\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3} + \omega \sqrt{-\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}}}
\]

Equation (22)

Therefore, the solution of Equation (21) is written as:

\[
\theta = \frac{1}{2} \left(\frac{3}{2} \mu + \alpha + 1\right) + \sqrt{\frac{1}{8} \mu^3 + \frac{1}{4} \left(\frac{3}{2} \mu + \alpha + 1\right)^2}
\]
\[
+ \sqrt{\frac{1}{2} \left(\frac{3}{2} \mu + \alpha + 1\right) - \frac{1}{8} \mu^3 + \frac{1}{4} \left(\frac{3}{2} \mu + \alpha + 1\right)^2}
\]

Equation (23)

Substitute formula (5) to formula (23), \(\theta\) can be written as:

\[
\theta = \frac{1}{2} \left(\frac{3}{2} K_r + K_i + \alpha + 1\right)
\]
\[
+ \frac{1}{8} \left(\frac{K_r + K_i}{K_i + K_i}\right)^3 + \frac{1}{4} \left(\frac{3}{2} K_r + K_i + \alpha + 1\right)
\]
\[
- \frac{1}{8} \left(\frac{K_r + K_i}{K_i + K_i}\right)^3 + \frac{1}{4} \left(\frac{3}{2} K_r + K_i + \alpha + 1\right)^2
\]

Equation (24)

Referring to formulas (4, 15) and (19), the \(P\) can be given as:

\[
P = t(K_r + K_i)\lambda = t(K_r + K_i)(\theta - 1)
\]

Equation (25)

Substitute formula (24) into formula (25), the frost heaving stress can be written as:
\[ P = t(K_r + K_i) \]

where \( t \) represents the depth of ice accretion (m), \( K_r \) represents the elastic-resistance coefficient of the surrounding rock (MPa/m), \( K_i \) represents the elastic-resistance coefficient of the ice (MPa/m), \( K_l \) represents the elastic-resistance coefficient of the lining (MPa/m), and \( \alpha \) represents the frost heaving ratio of ice.

In this paper, the frost heaving ratio of ice is taken as 9%. Referring to the related Chinese code (MOHURD 2011; China. RTSotPsRo 2017), the elastic-resistance coefficients of the rocks were determined. In general, the elastic-resistance coefficients of linings and ice should be derived by indoor tests. Also, the practical value is an acceptable choice for the calculation when indoor tests are not available. For example, referring to the research results of Zhang and Wang (2004), the elastic-resistance coefficients of the tunnel lining and the ice are chosen as 75 MPa/m and 50 MPa/m, respectively.

2.3. Formula simplification

In the present study, the frost heaving ratio of ice was selected as 9%, referring to related previous studies. The relationship between the \( \lambda \) and \( \mu \) was fitted by a large number of trial calculations of the SPSS software. The calculation results show a power function between \( \lambda \) and \( \mu \) under the fitting accuracy of 0.986. However, it was found that the frost heaving stress obtained by the fitting method had a significant calculation error when the grades of the surrounding rock are level I or V. Therefore, to improve the fitting accuracy and reduce the calculation error, the fitting processes of each rock grades were conducted respectively, and the calculation results are listed in Equation (27)–(31).

\[ \lambda_I = 0.039 \left( \frac{K_r + K_i}{K_i + K_l} \right)^{-0.889} \]

\[ \lambda_{II} = 0.034 \left( \frac{K_r + K_i}{K_i + K_l} \right)^{-0.84} \]
where the subscripts I, II, III, IV, and V represent the rock grades, and the corresponding coefficients of determination ($R^2$) are $0.999$, $0.999$, $0.997$, $0.992$ and $0.991$, respectively (from I to V). Due to the poor lithology of the grade VI rock, it is difficult to form a space of stagnant water between the surrounding rock and the lining, hence, the analysis of this grade rock is not discussed in this paper.

Based on the above analyses, the formula of frost heaving stress generated by stagnant water is written as:

$$P = a \left( \frac{K_r + K_i}{K_i + K_t} \right)^{-b} t(K_r + K_i)$$

(32)

where $t$ represents the depth of ice accretion (m), $K_r$ represents the elastic-resistance coefficient of the surrounding rock (MPa/m), $K_i$ represents the elastic-resistance coefficient of the ice (MPa/m), $K_l$ represents the elastic-resistance coefficient of the lining (MPa/m), and $a$ and $b$ represent the influence coefficients of surrounding rock, which are given in Table 1.

### 2.4. Rationality verification

The rationality of the proposed equation was verified through a large number of numerical analyses. Also, the influence of the frost heaving stress on tunnel safety was derived. The schematic diagram of the three-dimensional calculation model is depicted in Figure 4. The tunnel’s horizontal, vertical, and longitudinal direction corresponds to the X-, Y-, and Z-axis, respectively. The longitudinal depth, width, and height of the model are 20 m, 50 m, and 80 m. The ice’s circumferential length, longitudinal length, and depth are 0.4 m, 0.4 m, and 0.2 m, respectively. The numerical analysis of the model is based on the following assumption:
1. The surrounding rock and tunnel lining are homogeneous and isotropic materials.
2. The frost heaving stress is entirely caused by the volume expansion when water freezes into ice.
3. The frost heaving ratio is equal in all directions.

The lining material is C30 concrete, commonly used in tunnel engineering, and the thickness of the concrete is set as 40 cm. Referring to the Chinese code (MOHURD 2011), its elastic-resistance coefficient is 75 MPa/m. The material properties of surrounding rock are determined according to the Chinese tunnel code (China. RTSotPsRo 2017), as listed in Table 2. For the simulation of frost heaving stress, the linear expansion coefficient of the ice body and the temperature load is set to reproduce the volume expansion of ice. The grade-I rock model is chosen as an example to present the simulation process. Firstly, the radial stress of the tunnel lining in the static state was determined when no frost heaving had occurred. Then, the ice part was activated and the temperature load was applied to calculate the radial stress of the tunnel lining under the frost heaving action. In theory, frost heaving stress could be derived by calculating the difference between the nephograms.

The nephograms of the tunneling before and after frost actions are plotted in Figures 5 and 6, taking the grade-I rock model as an example for illustrating. It could be found that the maximum frost heaving stress is 1.30 MPa, and it occurs at the vault where the deepest ice accretion is located. In the same way, the frost heaving stress under the surrounding rock of grades II, III, IV, and V could be determined, and the corresponding radial stress nephogram of tunnel lining after frost heaving action is shown in Figure 7. The frost heaving stresses of the theoretical analysis, the numerical analysis in this paper, and previous research under the same condition are
calculated in Table 3 and Figure 8. It should be noted that the frost heaving stress of theoretical calculation in this paper is in good agreement with the numerical simulation; the difference between numerical and theoretical analysis is 1.57%-10.94%. The rationality of the theoretical analysis in this paper could be well verified. In addition,
Figure 7. Radial stress nephogram of lining after frost heaving under different grades of surrounding rock.
compared with the previous study, the frost-heaving stress calculated in this paper is more conservative, hence, in the case of lack of observed in-site data, the theoretical analysis may provide an effective approach for damage assessments and frost preventions in cold areas.

3. Sensitivity analysis of frost heaving stress

Based on the derivation process described above, totally five factors affect the development of the frost heaving stress of stagnant water in the seasonally frozen tunnel, including the depth of ice accretion, the elastic-resistance coefficients of the surrounding rock, lining, and ice, and the frost heaving ratio of the ice. In the actual simulation, the elastic-resistance coefficient and the frost-heaving ratio of ice are always considered as constant. Therefore, in this section, the influence of the rest factors (i.e. depth of ice accretion, the elastic-resistance coefficient of the surrounding rock, and the elastic-resistance coefficient of the lining) on the frost heaving stress of stagnant water is investigated.

3.1. The depth of ice accretion

Take the elastic-resistance coefficient of surrounding rock of 1500 MPa/m as an example, the frost heaving stress in different ice accretion depths is plotted in Figure 9. Overall, the magnitude of the frost heaving stress is positively correlated with the depth of ice accretion and increases linearly as the depth of ice accretion increases. In the actual situation, the stagnant water between tunnel lining and surrounding rock
forms mainly due to construction defects such as the construction collapse, over-exca-
vation, and uncompacted backfill. The greater the depth of ice accretion is, the
greater the frost heaving stress acting on the tunnel lining is. Therefore, in tunnel
construction, the appropriate excavation methods should be selected to ensure tight-
ness between the tunnel lining and surrounding rock. If there is any construction
defect, the concrete materials with similar properties as the tunnel lining can be used
for dense backfilling, and space between surrounding rock and lining shall not be
reserved as far as possible.

3.2. The grade of surrounding rock

Take the elastic-resistance coefficient of the lining as 75 MPa/m as an example, the
frost heaving stress under different grades of surrounding rock is shown in Figure 10.
Overall, the frost heaving stress gradually increases as the elastic-resistance coefficient
of the surrounding rock increases. The frost heaving stress reaches the maximum and
minimum when the surrounding rock is the grade I and V. Theoretically, as the rock
grade increases, the rock mass becomes rigid and intact, and the space of stagnant
water between the surrounding rock and the lining is more closed, which leads to the
growth of the frost heaving stress. In addition, with the decrease of the elastic-resist-
ance coefficient of the surrounding rock, the rock mass becomes more broken. At
this time, the constraint of ice storage space decreases, resulting in the release of part
of the frost heaving force from the cracks. Therefore, under the same conditions, the
better the surrounding rock property is, the greater the frost heaving stress is.

3.3. Material properties of the lining

The magnitude of the frost heaving stress under the condition of various elastic-
resistance coefficients of the lining is derived in Figure 11, taking the depth of ice
accretion as 75 MPa/m for illustrating. In general, it can be observed that the frost
heaving stress increases with the increase of the elastic-resistance coefficient of the
lining. Therefore, in the design of tunnel lining in seasonally frozen areas, the lining
should be flexible materials rather than rigid materials; for example, fiber reinforced.
concrete (FRC) and hybrid fiber reinforced concrete (HFRC) may be a considerable choice.

4. Discussion and conclusions

To put forward new insights for the accurate evaluation of the frost heaving stress and the prevention of frost damages in seasonally frozen tunnels, based on the local frost theory and local deformation theory, a new calculation model of the frost heaving stress caused by the stagnant water is established. Unlike the previous study, the space of stagnant water is simplified as the three-axis semi-ellipsoid in this model, which is more in line with the actual situation. First, the equation of the frost heaving stress was derived, and the rationality was verified. Then, the rationality of the new calculation model was verified by comparing it with the results of numerical analysis and previous studies. Finally, the effects of the critical parameters in the calculation
model were also conducted by the univariate method, followed by some suggestions for designing and constructing the seasonally frozen tunnels. Due to monitoring and measurement technology limitations, it is impossible to accurately measure the local frost heave stress in the prototype tunnel or reproduce the local frost heave stress through the model test. Therefore, the results in this paper cannot be compared with prototype engineering and model tests, which need to be further studied in the future. Even so, some essential conclusions can be drawn:

1. The new model, which adopts a three-axis semi-ellipsoid shape of the stagnant water, is more in line with the actual situation and presents a good agreement with the numerical analysis and the previous study. This theoretical model exhibits the more conservative results, which may provide an effective approach for damage assessments and frost preventions in the case of lack of observed in-site data.

2. The frost heaving stress of stagnant water in seasonally frozen-region tunnels is mainly related to the depth of ice accretion, the elastic-resistance coefficients of the surrounding rock and the lining. The frost heave stress increases with the increase of the ice depth, the elastic resistance coefficient of surrounding rock and lining.

3. The construction defect that may cause the stagnant water should be avoided in the construction process, including the construction collapse, the over-excavation, and the uncompacted backfill. In addition, in the design of tunnel lining in seasonally frozen areas, the lining should be flexible materials rather than rigid materials; for example, the fiber reinforced concrete (FRC) and the hybrid fiber reinforced concrete (HFRC) may be a reasonable choice. Last but not least, more attention should be paid to the frost heaving phenomenon of stagnant water in tunnels with hard rock and reasonable coldproof measures should be taken.

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