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Analysis of the Influencing Factors of Frost Damage in Cold Region Tunnels with High Altitude

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Abstract

As China's transport infrastructure projects are in full swing, road and railway tunnels are becoming more and more common in low temperature and high altitude areas. The occurrence of frost damage in cold region tunnels with high altitude is also increasing, so it is important to classify tunnels for frost damage. At present, there is no good explanation for the phenomenon of why frost damage occurs in tunnels in cold regions. The factors influencing frost damage in tunnels are described: groundwater, temperature and the properties of the surrounding rock. A rational explanation is given for the mechanism of frost damage in cold region tunnels with high altitude and The severity of frost damage in cold region tunnels with high altitude has been graded according to the severity of the factors that produce frost damage.

Keywords

Tunnels in Cold Region; Frost Damage; Mechanism of Formation; Influencing Factors.

1. Introduction

In order to reduce or prevent the occurrence of frost damage in tunnels, an objective and effective evaluation of the frost damage in tunnels from a scientific point of view is required in order to propose appropriate management solutions and frost protection measures. As part of the scientific evaluation of the frost damage in tunnels, the classification of the frost damage in tunnels is of great significance, as it is necessary to complete a reasonable classification of the frost damage in tunnels before a comprehensive evaluation of the frost damage in tunnels can be carried out. At present, scholars at home and abroad have conducted a lot of research on the classification of frost damage in tunnels and have proposed their own criteria for the classification of frost damage in conjunction with engineering practice. For example, Japanese scholars[1~3] have observed the lining structure of many tunnels in Hokkaido and other areas, and found that the lining structure will deform, deteriorate and spall at low temperatures, and through experimental analysis of numerous studies, Japanese scholars have proposed corresponding evaluation criteria for tunnel frost damage. The relevant railway departments in China, after observation and research of many tunnels, in 1997 the Ministry of Railways promulgated the industry standard "Criteria for assessing the deterioration of railway bridge and tunnel buildings - tunnels" (T2820.2 -1997), for the phenomenon of frost damage the corresponding rating criteria are given for the degree of hazard affecting the operational function of the tunnel. Professor Chen Jianxun of Chang'an University[4] summarised and absorbed the experience of his predecessors and, in view of the actual situation of tunnel construction projects in China at the time, proposed a qualitative description of the main factors and quantitative indicators of the deformation rate of the headroom displacement measurement, and proposed criteria for evaluating the degree of frost damage in road tunnels that are compatible with China's tunnel projects, and classified the degree of frost damage affecting the function of road tunnels into five levels. Huang Xiaoming[5] also

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proposed to use groundwater and temperature as assessment indicators to give the evaluation criteria for the level of frost damage in tunnels.

In general, the relevant regulations on the classification of frost damage in tunnel engineering in China mainly rely on information from Japanese research on tunnel lining variation and deterioration, coupled with the fact that the regulations are mostly qualitative descriptions, with different interpretations by design and construction personnel, making it difficult to unify opinions and bringing inconvenience to engineering applications. Due to the many factors affecting tunnel frost damage, subsequent scholars have simply proposed to evaluate the degree of tunnel frost damage by a single or double indicator: deformation rate measured by headroom displacement, groundwater and temperature, which cannot meet the purpose of a comprehensive coincidence of the current state of tunnel frost damage.This paper summarises previous research on the classification of frost damage, outlines the mechanisms of frost damage in tunnels, and considers the effects of groundwater, temperature and rock properties on frost damage in tunnels.

2. Mechanisms of Frost Damage in Cold Region Tunnels

Before the cold region tunnels was opened, some cracking of the tunnel lining and water seepage from the tunnel had already occurred in the cavern section, obviously, at this time, neither the surrounding rock nor the lining had been frost damaged, and it was not the tunnel lining that had cracked and leaked due to icing and freezing, but on the contrary, this structural cracking and water seepage was a prelude to the occurrence of frost damage, and the possibility of icing and freezing of the tunnel lining in the future winter was very high. From Song Shunde's[6] research on frost damage in tunnels, it appears that frost damage in tunnels actually manifests itself mainly in the form of frozen drains in the cavern and water leakage from the vaults in winter. For non-permafrost tunnels, the temperature inside the tunnel is lower than the temperature of the surrounding rock, which is the first to freeze, even though the surrounding rock behind the lining may not freeze in winter. An inspection of the disease characteristics of the Tai Ban Shan tunnel in 2009 revealed serious water leakage and frost heaving in the tunnel lining structure. The water leakage inspection of the lining revealed a total of 86 water leaks in the tunnel cavern and in the cavern sections at both ends, mostly in the tunnel arch waist and vaults, and forming ice cones at low temperatures. Similarly, the Ladder Ridge Tunnel, the Ridge Top Tunnel of the Yalin Line, the Xinjiang Yushimole Tunnel and the Kunlun Mountain Tunnel all had tunnel frost damage problems accompanied by leakage phenomena, such as icing of the road surface, ice hanging from the roof of the tunnel and lining cracks. In other words, when icing occurs inside the tunnel, the surrounding rock at the periphery of the tunnel lining is not iced.

The comprehensive phenomenon of freezing damage to tunnels in cold region in China shows that: (1)The freezing phenomenon of freezing damage to tunnels in cold region in China mostly occurs after events such as water leakage and water surges in tunnels; (2) From the water leakage in Dasanshan Tunnel, Kunlun Mountain Tunnel and Laji Mountain Tunnel, where water leakage or freezing damage occurs in more serious sections, it is generally a section with poor surrounding rock conditions and frequent collapses and cave-ins during the construction process.

Frost heaving is an important part of the problem of freezing in cold region tunnels, but it should not be the whole story. For there is one issue that is probably more important, namely the phenomenon of icing. The icing characteristics exhibited by freezing damage in tunnels in cold region of China are not accidental. The entrance and exit sections of tunnels or shallowly buried sections (such as the Kunlun Mountain Tunnel on the Qinghai-Tibet Line) are extremely susceptible to icing and subsequent frost damage due to climate, depth of burial, construction techniques, etc. The structural layer of the tunnel entrance is easily damaged, including the destruction of the tunnel waterproofing layer and the cracking of the tunnel lining layer, after the destruction of the tunnel structure, followed by water leakage from the lining structure, in winter, the water leakage phenomenon will gradually evolve and advance from the ice inside the cavern to the ice on the outer surrounding rock of the lining, in this process, the freezing effect will destroy the insulation layer of the tunnel lining, the

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failure of the insulation layer will accelerate the ice layer from the inside to the outside, lining cracks When the freezing layer in the lining and the surrounding rock on the outside of the lining melts, it will inevitably lead to a further expansion of the tunnel lining leakage and a further increase in the amount of water leaking through the lining, which will worsen when a new cold season arrives.

Therefore, from the whole process of the generation and evolution of freezing damage in cold region tunnels, freezing damage in cold region tunnels should involve three major factors such as structural damage, water seepage and freeze-thaw cycles, the interaction and influence relationship of these three factors is shown in Figure 1.

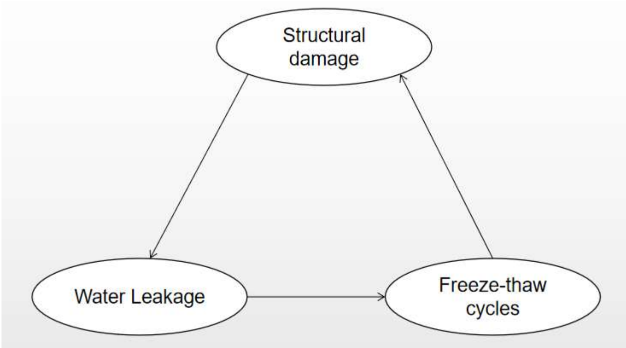

Figure 1. Frost ring mechanism

Figure 1 shows the freeze damage ring needs activation mechanism, from the analysis of the investigation of freeze damage in China, the damage of the tunnel structure layer should be the activation factor, including the damage of the tunnel waterproofing layer and the damage of the structural lining layer. Once the frost ring has been activated, the resulting freezing of water leaks at low temperatures produces a 'freezing swell' phenomenon that promotes and exacerbates the destruction of the lining structure, which in turn accelerates and worsens the leakage of water through the lining, thus forming a complete and gradually accelerating vicious cycle chain. Frost damage is the product of a certain stage in the evolution of the frost ring and is a description of the "frost damage" stage in the evolution of the tunnel frost ring. Therefore, the study of freezing damage mechanisms in cold tunnels should not only focus on the mechanism of freezing and swelling of the tunnel surrounding rock and lining, and the deterioration mechanism of the freeze-thaw cycle, but also on the activation factor of the freezing damage, i.e. the destruction of the tunnel waterproofing and lining layers.

3. Influencing Factors of the Classification of Frost Damage

Engineering practice has proven that conditions are needed for frost damage to occur in tunnels. Firstly, the temperature needs to be below 0°C and the duration of low temperature should be long enough; Secondly, there should be water, the party when the surrounding rock is in a dry state, frost damage will not occur; the nature of the tunnel surrounding rock itself is also very important, the higher the sensitivity of the surrounding rock to frost expansion, the greater the degree of frost damage.

3.1 The Effect of Groundwater on Frost Damage in Tunnels

3.1.1 Groundwater Availability and Recharge Conditions

Groundwater can be divided into:overlying stagnant water, submerged water and interstratified water, depending on the burial conditions. Based on the nature of the aquifer it can be classified as: pore water, fracture water and karst water.

Groundwater recharge conditions are in general a description of the different forms in which external water converges and flows into the subsurface fugitive water system. The main sources of recharge are the following: surface water seepage, atmospheric precipitation, artificial precipitation, recharge between aquifers, etc.

3.1.2 Groundwater Infiltration into the Tunnel

Water leakage in existing tunnels can be divided into several forms: tunnel leaks, gushing water, water pooling around the lining, submerged scouring, erosion and scouring of the lining by erosive water, etc. The risks of water leakage in tunnels are mainly in the following three areas.

(1) Impact of water leakage on the operating environment of the tunnel: comfort of the operating environment, icing in the cavern, spalling of the lining, damage to the road surface, etc.

(2) Influence of water seepage on the stability of the tunnel surrounding rock: When there is a soft structural surface in the surrounding rock, under the action of dynamic water pressure due to the flow of groundwater, the filling in the structural surface is washed and dissolved away, forming an internal hollow state, thus aggravating the influence of the surrounding rock on the overall strength and stability.

(3) The impact of water leakage on tunnel maintenance costs: in general, once a leak has been detected, measures should be taken to repair it promptly; if not dealt with promptly, the cost of repair becomes greater and greater with time.

3.1.3 Groundwater Infiltration into the Tunnel

Groundwater is a mixture of many components in a solution with many elements and a complex composition. The main types of erosive groundwater are the following: sulphide, sulphate, chloride, carbonate and a combination.

3.1.4 Grading the Extent of Groundwater Impact on Tunnel Frost Damage

From these three perspectives, the degree of groundwater impact on tunnel frost damage is graded in Table 1 below.

Table 1. Influence of groundwater on the frostiness of the tunnel envelope

Groundwater conditions			
Groundwater availability and recharge conditions	Groundwater corrosion	Groundwater infiltration into the tunnel	Level of impact
Drying tunnels	Non-corrosive	No water penetration	No impact
Contains a small amount of water tunnel, no recharge	Slightly corrosive	A little water seepage and dripping	Slight impact
Water-bearing tunnel, no recharge	Corrosive	Dripping or linear running water	Impact
Water-bearing tunnels with small amounts of recharge	Severe corrosive	Rain-like water flow	Severe impact
Water-bearing tunnels, well recharged	Extremely corrosive	Perennial gushing water	Extremely serious implications

3.2 The Effect of Temperature on Frost Damage in Tunnels

The coldest monthly mean air temperature and the freezing depth are used as the two indicators for grading the degree of temperature influence on the freezing damage of the tunnel. Luo Yanbin[7] proposed a formula for calculating the coldest monthly mean temperature in the tunnel by modifying the Kriging method formula, and proposed a formula for calculating the freezing depth by linear fitting. It is generally accepted that freezing damage can only occur when the coldest monthly mean temperature is below 0°C, i.e. when the freezing depth is greater than 1.5m. The coldest monthly mean air temperature is divided into five levels according to 6°C, and the corresponding freezing

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depth values are used as indicators to evaluate the influence of temperature on the degree of freezing damage in the tunnel.

Table 2. Extent of temperature effects on frost heave in the tunnel envelope

Level of impact	Coldest monthly average temperature	Freezing depth
Slightly cold	0 to -6	0.16 to 0.82
Cold	-6 to -12	0.82 to 1.48
Heavy cold	-12 to -18	1.48 to 2.14
Severe cold	-18 to -30	2.14 to 3.46
Extreme cold	<-30	>3.46

3.3 Influence of Envelope Properties on Frost Damage in Tunnels

3.3.1 Sensitivity of Fissure Fillers

As a combination of rock and fissure fill, the frost sensitivity of the surrounding rock is determined in two parts, partly by the frost sensitivity of the rock and partly by the sensitivity of the fissure fill, one cannot be separated from the other. The sensitivity of the fissure fill can be graded by reference to the Code for Geological Investigation of Permafrost Engineering, which classifies the sensitivity of the fissure fill into five levels: no sensitivity, weak sensitivity, sensitivity, strong sensitivity and very strong sensitivity, based on the grade of the surrounding rock, degree of integrity, degree of structural surface development, fissure opening and average fissure rate. The grading method is shown in Table 3 below.

Table 3. Fracture frost heave sensitivity classification

Enclosure rock level	Completeness	Degree of structural surface development		Openness			Average fracture rate	Frost swelling sensitivity
		Number of groups	Average spacing	Closure	Microtab	Open up		
I	Complete	1 to 2	>1.0	<1	2	--	0.2	No frost heave sensitivity
II	Complete	1 to 2	>1.0	<1	2	--	0.35	No frost heave sensitivity
	More complete	1 to 2	>1.0	--	2	>3		Weak frost heave sensitivity
III	More complete	2 to 3	1.0 to 0.4	<1	2	>3	2.23	Frost swelling sensitivity
	More broken	2 to 3	1.0 to 0.4	--	2	>3		
IV	More broken	>3	0.4 to 0.2	<1	2	>3	2.63	Strong freeze swelling sensitivity
	Shattered	>3	0.4 to 0.2	--	2	>3		
V	Shattered	>3	<0.2	--	2	>3	6.00	Extremely sensitive to freezing and swelling

3.3.2 Rock Sensitivity

The susceptibility of rocks to frost heave can be judged not only by water absorption, uniaxial compressive strength and saturated water content, but also by elastic wave velocity. Current studies of rock sensitivity classification have considered both elastic wave velocity and density. In this case, the elastic wave velocity P-value is used to classify rocks with a saturated relative density <2.1 g/cm3 into five classes: no sensitivity, weak sensitivity, sensitivity, strong sensitivity and very strong sensitivity. The grading method is shown in Table 4 below.

Table 4. Rock frost heave sensitivity classification

Rock sensitivity classification	No frost heave sensitivity	Weak frost heave sensitivity	Frost swelling sensitivity	Strong freeze swelling sensitivity	Extremely sensitive to freezing and swelling
Elastic wave speed P (km/s)	>2.5	2.5 to 2.0	2.0 to 1.5	1.5 to 1.0	<1.0

4. Conclusion

(1) The influence of groundwater, temperature and rock properties on the degree of frost damage in the tunnel is taken into account and a comprehensive evaluation method is used to classify the level of frost damage in the tunnel.

(2) For tunnels in permafrost zones, the influence of surrounding rock properties on tunnel frost damage is not considered, only the influence of groundwater and temperature.

(3) By reviewing the causes of frost damage in a number of tunnels in China, a frost ring mechanism is proposed for the generation of frost damage in tunnels.

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