Prevention of Frost Heave in the Surrounding Rocks of Tunnel for Ski Resorts

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Abstract. Taking the four-season ski resort in Jilin Beishan as an example, this paper analyses the temperature field of surrounding rocks by applying the theory of transient thermal conductivity of semi-infinite large objects, and explains the necessity of insulation isolation layer and heating system setting. The structure and insulation performance of the insulation isolation layer are specified, and the flat wall steady-state thermal conductivity theory is used to calculate that the heat transfer on both sides of the insulation layer is about 29.66kW. This heat is not only a part of the cooling load of the snow resort refrigeration system, but also a part of the heat load of the wall heating system. For the refrigeration system, the COP value of the chiller is 2.5kW/kW. Even excluding the energy consumption of the transmission and distribution process, the annual power consumption of the cooling load alone is about 104,000 KWH, which explains the importance of the temperature control system and insulation layer. The heat source of the heating system of this project innovatively adopts the waste heat of cooling generated in the refrigeration process. This measure makes the heating source of this project no longer consume fossil energy, resulting in significant energy saving and emission reduction benefits. As described, a tunnel ski resort similar to a new or rebuild one can be used as a reference. Some of the results can be applied to prevention of frost heave of traffic tunnels in high-cold and high-latitude areas.

1. Introduction
In recent years, taking Beijing's successful bid for the Winter Olympics as an opportunity, China has increased its investment in popularizing ice and snow sports, developing ice and snow industries, and realizing the leapfrog development of ice and snow sports, and invested in the construction of a large number of indoor sports venues in the ice and snow category. Cross-country skiing is the official winter Olympic Games event, known as the "snow marathon" title. The cross-country ski area is dominated by snow tracks, which should be no less than 4 meters wide and not less than 1000 meters long. According to the above characteristics, if the construction of indoor cross-country ski resort, its construction form and tunnel is very similar. There are currently four tunnel ski resorts built internationally, namely the Voukatti And Torsby Ski Tunnels in Finland, the "Central 365" Ski Tunnel in Sweden and the Four Seasons Cross-Country Ski Resort in Jilin North Mountain, China. The thermal environment of the ski tunnel is similar to that of the tunnel in the high cold area, and the water vapor contained in the surrounding rock behind the lining is prone to freezing, which exerts a freezing force on the tunnel.
support structure. This paper discusses the impact of the frozen rock expansion on the tunnel support structure system by summarizing the construction experience of the four-season cross-country ski resort in Jilin Beishan, and briefly describes the countermeasures taken by this project, namely, the set-up scheme of the wall heating system.

2. Introduction to the project
Jilin Beishan Four Seasons Cross-Country Ski Resort Project is the National Sports Administration Winter Sports Management Center led the project, Jilin Provincial Sports Bureau and Jilin Municipal Government jointly built an indoor and outdoor integrated cross-country ski training ground. It consists mainly of outdoor snow tracks, professional snow tracks and popular snow tracks (see Figure 1). Professional snow track and people snow track for indoor venues, venues before the renovation for human defense works, located in Jilin City, Beishan Park mountain, the original cave area of 19751m², the total construction area after the expansion of 27009m², snow track use area of 17158m², the total length of the snow track 1.7km (of which the professional part of the total length of 1318m). Professional snow track for the four-season cross-country ski resort, the public part of the snow ice sculpture experience area. The cave-proof chamber is deep into the lowest part of the mountain and the outdoor space height difference of more than 100m, the mountain forms a natural "insulation layer", effectively reducing the operating energy consumption of the ski resort. The project is built to meet the training needs of the national team preparing for the 2022 Winter Olympics, and the stadium is running non-stop all year round, completely solving the problem of the inability to conduct cross-country skiing training in the summer in China and even in Asia, and greatly improving the training efficiency of athletes.

![Figure 1. Ski resort floor plan.](image)

3. Safety analysis of tunnel lining structures
After the tunnel excavation in the cold area and plateau area, the original stable thermal conditions of the tunnel surrounding rock were damaged by the air flow and other factors. Especially for motor vehicles and trains to pass the tunnel, because of the traffic vehicle pass on the air flow disturbance of the enhanced role, so that the tunnel lining and the surrounding air convection heat exchange is enhanced. At this time, the surrounding rock behind the lining forms a seasonal melting ring, which exerts repeated freezing and expansion force on the tunnel support structure. The freezing force and other forces act together on the tunnel lining may cause the tunnel to crack and peel off, causing the tunnel to leak, freeze, hanging ice and other frost damage, threatening the normal operation of the tunnel. There are 33 railway tunnels in northeast and northwest China, all of which have varying degrees of frost damage due to their
location in the cold zone. Some tunnels are unusable for 8 to 9 months of the year due to the effects of frost damage\cite{1}. The original human cave prevention room in Jilin Beishan is different from the above-mentioned traffic tunnel, its main function is the wartime personnel shelter, each exit has strict closure measures, basically isolated from the outdoor environment, after early survey, the temperature inside the cave is maintained year-round at 6 to 8 degrees C. However, after being converted into a four-season ski resort, in order to ensure the requirements of professional snow quality, the temperature in the ski resort needs to be maintained at -6 degrees Celsius all year round. At the same time, there are crack development and water-rich situation in the tunnel rock body, which causes the tunnel surrounding rock and concrete lining to meet three basic freezing and thawing conditions: (1) enough negative temperature environment to make the free water in it freeze; Under the influence of multiple complex environments, it is easy to cause the decrease of the hydraulic properties and the loss of durability of rock, rock and concrete components.

After investigation, the main component of the surrounding rock is granite (containing water), considering that the thermal diffusion rate of water is only 1/10 of the granite, so the influence of water can not be considered for the time being when studying the temperature distribution of the surrounding rock. The surrounding rock plane is analysed as a semi-infinite homogeneous object, and the temperature distribution of the first type of boundary is analysed in the form of a detailed type (1)\cite{2}[3].

$$\theta(x,\tau) = \frac{t - t_w}{t_0 - t_w} = \text{erf}\left(\frac{x}{2\sqrt{\alpha\tau}}\right)$$  \hspace{1cm} (1)

x: calculate the thickness (m) of the rock formation at the location of the point;
\(\tau\): freezing time (h);
\(\theta(x,\tau)\): the excess temperature(K) at which the calculation point is at \(\tau\) time;
\(\theta(x,0)\): calculates the excess temperature(K) at the initial moment of the point;
t: Calculate the real-time temperature of the point (°C);
t_0: Calculate the initial temperature of the point (°C);
t_w: Ambient temperature (°C);
\(\alpha\): Rock formation thermal diffusion rate(m²/h).

The initial temperature of the rock formation \(t_0\) takes the average annual temperature of Jilin City 4.8 degrees C, the ambient temperature \(t_w\) is -6 °C, and the granite thermal diffusion rate \(\alpha\) is 0.0046 m²/h. Bring the above values into the formula (1) and give the specified freezing time to obtain the temperature values of any point. For easy analysis, select the three time states of \(\tau_1=720\)h, \(\tau_2=2160\)h and \(\tau_3=8760\)h, respectively, to plot the temperature distribution in the range of 0 to 15m of rock formations, as detailed in Figure 2.

![Figure 2. A map of the temperature distribution of rock formations.](image-url)
As can be seen from Figure 2, when the rock formations are in an environment of -6 degrees C, the freezing thicknesses of the rock formations of 720h (30 days), 2160h (60 days) and 8760h (365 days) (below 0 °C) are 1.8m, 3.4m and 6.8m, respectively. It can be seen that if the necessary measures are not taken, the tunnel surrounding rock and concrete lining will inevitably freeze, endangering its structural safety.

4. Tunnel lining structure safety measures
In order to eliminate the damage of freezing to the tunnel lining layer, we should start with insulation technology and strengthen waterproofing and drainage measures. Jilin Beishan Four Seasons Cross Country Ski Resort Project has carried out a large number of innovative designs in the maintenance structure. Insulation isolation layer is set between lining and snow track, because the isolation of light steel structure needs to be designed in the tunnel, to solve the insulation, waterproof, fireproofing, but also to solve the feasibility and reliability of reverse construction process. Through unremitting efforts to overcome a number of technical difficulties, access to a number of utility model patents, and finally formed an implementation plan, see Figure 3.

As can be seen in Figure 3, a cavity is formed between the insulation isolation layer and the lining layer, and a wall heating tube is also set up on the lining side to maintain the cavity temperature at 2 degrees C. Such a structure completely isolates the ski slopes from the effects of low temperatures on the lining layer and guarantees the durability of the lining layer. At the same time, it also provides a positive temperature space for drainage, and the rich groundwater in the mountain can be directly imported into the cavity drainage ditch through the ring-to-blind pipe and discharged directly into the outdoor area. In terms of waterproofing, the need for a first-class waterproof level of ski slopes contradicts the waterproofing process of road tunnels that do not have a waterproof rating standard. In the example of highway tunnel engineering, leakage is common. However, the tunnels used for ski resorts must meet the waterproofing and fortification standards of construction projects. The insulation and waterproof isolation of light steel structure is established in the reinforced concrete lining of the tunnel, and the design of "room in room" ensures that the open anti-drainage system is self-contained and does not depend on the quality of tunnel construction.

5. Wall heating system
As mentioned above, it is necessary to set up a wall heating system in the cavity to ensure the integrity and durability of the lining. But the heat that is constantly being delivered to the cavity through the wall
heating system also creates a new air conditioning cooling load inside the snow channel. In cavities and ski slopes on both sides of the insulation isolation layer, the ambient temperature is stable, and this problem can be analyzed using a steady-state thermal conduction method, as detailed in Figure 4.

\[
\Phi = \frac{t_1 - t_2}{\sum_{i=1}^{n} \frac{\delta_i}{h_i}} \cdot A
\]

(2)

Φ: hot flow (w);
t1: cavity side ambient temperature (°C), take t1 as 2°C;
t2: ski resort ambient temperature (°C), take t2 as -6°C;
h1: cavity side convection heat exchange coefficient (w/(m²•k)), taken h1 as 10 (w/(m²•k));
h2: Snow-side convection heat exchange coefficient (w/(m²•k)), h2 as 10 (w/(m²•k));
A: the surface area of the isolation layer (m²), A is the perimeter, the length of the snow track is 17.5x1318=23065m²;
\[\sum \delta i / i\]: Total heat transfer resistance of the isolation layer ((w/(m²•k))), see Table 1 for details.

| Structural materials | Construction layer thickness m | Thermal conductivity w/(m•k) | Thermal resistance (m²•k)/w |
|----------------------|-------------------------------|-------------------------------|-----------------------------|
| Galvanized pressed steel plate | 0.001 | 58.2 | 1.71821E-05 |
| Polyurethane | 0.15 | 0.0324 | 4.6296 |
| Water-repellent inorganic insulation mortar | 0.02 | 0.08 | 0.2500 |
| Cement slurry protection layer | 0.01 | 0.93 | 0.0108 |
| Ultra-fine glass silk plate | 0.05 | 0.045 | 1.1111 |
| Silicate lining | 0.008 | 0.87 | 0.0092 |
| High density silicate colored panels | 0.008 | 0.87 | 0.0092 |
The above values are available in the type (2) and the heat flow from the cavity to the ski slopes is approximately 29.66kW, cavity side design the temperature increases by 12.5% for every increase in heat transfer by 1 degree C. This mode of hot and cold consumption is only a stopgap measure to ensure structural safety, and measures should be adopted to strictly control heat supply. How to make the heating system run at the lowest load all the time, which is the key subject of the wall heating system design under the premise of meeting the structural safety.

Wall heating system adopts the method of regional overall control, sets the self-control temperature control valve of remote control in each water divider backwater main, sets the temperature measurement point in the direction of the snow track, and realizes the remote automatic control through the building automation system. In a wall heating system, each component collector can afford a range of approximately 40m of snow travel direction (see Figure 5). The spacing between the temperature points is set to 80m, the feedback signal for each temperature point corresponds to the temperature control valve on the two adjacent dividers that control the adjacent. Temperature measurement points have been added in several locations where the snow track is deep into the shallower mountains to monitor locations that may be affected by changes in the temperature of the outdoor environment. Each temperature point is set to 4 temperature sensors (see Figure 6 for details), with either sensor return temperature below 2 degrees C as the system start signal, and the sensor returning average temperature greater than 5 degrees C as the system stop signal, which in the event of a conflict is guaranteed to be no less than 2 degrees C. The temperature monitoring system not only acts as the control signal source for the control wall heating system, but also serves as an alarm signal for the freezing of the lining layer.

Figure 5. Wall heating tube expansion surface layout diagram.

Figure 6. Temperature sensor layout diagram at temperature point.
6. Conclusion
(1) The lining of the tunnel ski resort must take protective measures, otherwise it will cause frost heave hazards and affect the safety of the tunnel structure. The practice of insuring the isolation layer has been proven to be effective in practical engineering and can be used in such projects.
(2) In order to reduce the offset effect of wall heating system on the cooling effect of ski resorts, it is necessary to limit it by adopting a reasonable temperature monitoring system. Because the temperature difference between the ski slope and the cavity is small, the energy saving benefit of controlling the ambient temperature in the cavity is more obvious.
(3) Because the composition of tunnel rock body is more diverse, and the material parameters of the mixture are not easy to calculate, so this paper in the process of surrounding rock temperature analysis has been simplified, if the experimental parameters of the relevant substances can be obtained later, the results will be further accurate analysis.

7. References
[1] Zhang Dehua 2003 Effect of frost heaving on tunnel supporting systems of Fenghuoshan railway tunnel (Nanjing: Chinese Journal of Geotechnical Engineering)
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[3] Gu Qinchang 1996 Analysis of unsteady thermal conduction of semi infinite objects(Xi’an: Journal Of Xi’an Mining Institute)