Freezing-resistant and Prevention Technology for Railway Tunnels in Cold Region

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Abstract: The railway tunnels in cold region are a tube-type building with both ends exposed. Due to the influence of air pressure, natural wind and train piston wind, the temperature inside the tunnels is obviously affected by the ambient temperature outside. In the change of temperature and alternation of freezing and thawing, there will be ice hanging on the arch wall and ice deposited at the bottom of the tunnel due to structural water leakage, and the crack of lining due to frost-heaving surrounding rock or cavity water behind the structure, which have become the main issues troubling the tunnel operation in cold region. Therefore, freezing-resistant technology is the key to the railway tunnel construction in cold region. Centering on the characteristics of cold region, the paper systematically discusses the technical characteristics for freezing-resistant design, construction, and operation and maintenance of tunnels, providing a reference for the standardization of tunnel freezing-resistant engineering.

Keywords: railway tunnel; cold region; freezing resistance and prevention; insulation layer; drainage system

1 Introduction

China is with vast territory with its land areas crossing north latitudes of 10° to 50° and the climate showing obvious differences between the north and the south. According to the relevant standards of civil engineering, cold regions generally refer to the regions with the mean air temperatures of the coldest month being below −3℃, among which areas with the air temperatures of −8℃ to −3℃ are the cold areas and the those with the air temperature below −8℃ are the severe

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cold areas. For instance, Dalian is located in north latitude of 40° with the mean air temperature of the coldest month being −5℃ and the winter period as long as approximately 4 months, whereas Mohe is located in north latitude of 52° with the mean air temperature of the coldest month being −28℃ and the winter period as long as approximately 8 months, for which the differences of temperature change and winter period duration with the changes of latitude are utterly obvious. The terrains in China are high in the west and low in the east presenting three levels of steps and with the height difference between steps being at hundreds to thousands of meters. In the high-altitude regions with obvious fluctuation of the terrain height, the vertical differences of climate are very obvious due to the difference of the altitude. Taking the case of the Western Sichuan Plateau located to the east of Qinghai-Tibet Plateau as the example, Kangding is the place with the altitude of 2500 m, for which the mean air temperature of the coldest month is below − 0.5℃ and the winter period is as long as approximately 3 months, whereas Litang is the place with the altitude of 4 500 m, for which the mean air temperature of the coldest month is below −8.9℃ and the winter period is as long as approximately 5 months, with obvious differences of temperature change and winter period duration with the change of altitude.

Therefore, in the light of the different characteristics in terms of high latitude and high altitude, the cold regions in China can be classified into two major categories, i. e. the high-latitude cold region mainly for the northeast region and the high-altitude cold region mainly for the Qinghai-Tibet Plateau region. The technical characteristics for tunnel freezing-resistant and prevention design, construction, and operation and maintenance are hereby expounded centering on the features of cold region.

2 Design Zoning of Freezing Resistance and Prevention for Tunnels in Cold Region

2.1 Tunnels in high-latitude cold region

The high-latitude cold regions are represented by the northern part of the north China and the northeastern China, for which the latitudes are roughly between north latitudes of 40° to 52°, the mean air temperature of the coldest month is between −28℃ and 3℃ and the annual mean air temperature is between −4℃ and 12℃, and the temperature of constant temperature zone near the earth's surface that is not influenced by the ambient temperature is approximately between −1℃ and 15℃. Great part of that region is the seasonal frozen earth and only part of Daxing'anling and Changbai Mountain with the altitude of over 1 200 m is distributed with permafrost. Based on the meteorological characteristics of the areas passed by the railway projects in Heilongjiang Province, Jilin Province, Liaoning Province, middle and eastern parts of Inner Mongolia Autonomous Region, northern part of Shanxi Province and northern part of Hebei Province (including Beijing and Tianjin) and the frost damage of existing tunnel project and technical characteristics of frost resistance and prevention, tunnels in the high-latitude cold region are divided into five zones[1] (refer to Table 1).

2.2 Tunnels in high-altitude cold region

The Qinghai-Tibet Plateau is located deep in inland area with high terrain. The southeastern part of the plateau is with magnificent mountains and deep rivers and the northwestern part of the plateau is with flat terrain, presenting large area of depopulated zone, flat and gentle terrain and wide distribution of seasonal frozen soil. The elevations of permafrost areas are basically kept stable at over 4 500 ~ 5 000 m. For areas with the altitude of over 5 000 m, although the surface soil has frozen and thawed, it is difficult for the temperature in the temperature zone to reach over the freezing point[2]. Therefore, the vertical change of climate with elevation in the high-altitude cold region is obvious and characteristics of the wide distribution of seasonal frozen soil layer and freezing and thawing of continuous permafrost distribution are the important difficulties confronted in the railway engineering freezing protection of Qinghai-Tibet Plateau. The tunnels in the high-altitude cold region are thus classified into six zones[3] in combination with the elevation (refer to Table 2).

It is worth noting that the Mediterranean-Himalayan geothermal belt is the global important geothermal belt and the Qinghai-Tibet Plateau in China goes eastward to Sanjiang (three rivers, i. e. Yangtze River, Yellow River and Lancang River) Area along the Yarlung Zangbo River and then turns southward via Tenchong in Yunnan and goes further southward and leaves the country. Due to the role of geothermal belt, the temperature of the area under the constant temperature zone is made to increase very quickly, for which the temperature of the place with the depth of 1 000 m under the ground surface is basically over 50℃ and partly even up to 70℃; and the temperature of the place with the depth of 2 000 m under the ground surface is at over 70℃ and partly even up to 90℃[6]. Cold on the surface and hot underground is another feature of tunnel engineering in this area.

3 Tunnel Structure Freezing Resistance[7]

3.1 Structure freezing resistance and insulation layer

3.1.1 Purposes of insulation layer setting

Setting insulation layers for insulation is one of the effective means to prevent freezing damage causing to tunnel structure of cold region. Insulation

Table 1 Design Zoning of Railway Tunnel in High-latitude Cold Region

Design zoning	Meteorological characteristic parameter/℃		Surface temperature of constant temperature zone/℃	North latitude/(°)	Representative projects of existing railway
	Mean air temperature in January	Annual mean air temperature			
I	−8 ~ −4	8 ~ 12	11 ~ 15	38.0 ~ 40.5	Yuxian-Yangqu section of Shijiazhuang-Taiyuan HSR, Badaling-zhangjiakou section of BeijingZhangjiakou HSR, Fengcheng-Dandong section of Shenyang-Dandong HSR, Anshan-Pulandian section of Shenyang-Dalian HSR, Zhangjiakou-Xinglong section of Zhangjiakou-Tangshan HSR, etc.
II	−15 ~ −8	4 ~ 8	7 ~ 11	40.5 ~ 43.0	Section in Liaoning of Beijing-Shenyang HSR, Shenyang-Fengcheng section of Shenyang-Dandong HSR, Shenyang-Anshan section of Shenyang-Dalian HSR, Zhangjiakou-Hohhot HSR, Chongli section of Chongli Railway, etc.
III	−20 ~ −15	0 ~ 4	3 ~ 7	43.0 ~ 47.0	Jilin-Yanji section of Jilin-Hunchun HSR, Harbin-Mudanjiang HSR, Mudanjiang-Suifenhe Railway, Harbin-Jiamusi Railway, Changchun-Jilin Intercity Railway, Harbin-Zalantun section of Harbin-Manzhouli Railway, Xilinhaote-Wulanhaote Railway, etc.
IV	−28 ~ −20	−4 ~ 0	−1 ~ 3	47.0 ~ 51.0	Zalantun-Manzhouli section of Harbin-Manzhouli Railway, and Nahe-Linhai section of Fuyu-Xilinji Railway
V	<−28	<−4	<−1	Over 51.0	Gulu-Luoqi Railway, North Linhai of Fuyu-Xilinji Railway, etc.

Table 2 Design Zoning of Railway Tunnel in High-altitude Cold Region

Design zoning	Meteorological characteristic parameter/℃		Surface temperature of constant temperature zone/℃	Altitude/m	Representative projects of existing railway
	Mean air temperature in January	Annual mean air temperature			
I	>−0.5	>8	>11	Below 2500	Minhe-Datong section of Lanzhou-Urumqi HSR, etc.
II	−4.7 ~ −0.5	4 ~ 8	7 ~ 11	2 500 ~ 3 250	Dabanshan Tunnel of Lanzhou-Urumqi HSR, Guanjiao Tunnel of Qinghai-Tibet Railway, Dangjinshan Tunnel of Dunhuang-Germu Railway, etc.
III	−8.9 ~ −4.7	0 ~ 4	3 ~ 7	3 250 ~ 4 000	Qilianshan Tunnel group of Lanzhou-Urumqi HSR, Lhasa-Rikaze Railway, etc.
IV	−13.1 ~ −8.9	−4 ~ 0	−1 ~ 3	4 000 ~ 4 750	Kunlunshan Tunnel and Yangbajing Tunnel group, etc. of Qinghai-Tibet Railway
V	−17.3 ~ −13.1	−8 ~ −4	<−1	4 750 ~ 5 500	Fenghuoshan Tunnel of Qinghai-Tibet Railway, etc.
VI				Over 5500	No railway tunnel project so far

Note: Mean air temperatures in January are computed by referring to appendix A of reference [5]; and there might be certain errors for temperatures of the high-altitude areas with the latitude higher than the Western Sichuan Plateau.

layers are set in the sections of tunnel that are liable to influence by freezing and thawing to slow down the heat exchange of the lining and surrounding rock with the air in the tunnel, avoid the frequent freezing and thawing changes at the back of lining, and realize the purpose of freezing damage prevention.

3.1.2 Comparisons of locations for insulation layer setting

There are generally two ways for

setting insulation layers, of which one is to set the insulation layers directly at the surface of the tunnel secondary lining structure and the other is to set the insulation layers between the tunnel primary support and the secondary lining. For contrasts of their advantages and disadvantages, refer to Table 3.

Table 3 Contrasts of Advantages and Disadvantages for Insulation Layers of Different Location Settings

Locations	Advantages	Disadvantages
Secondary lining surface	Construction techniques are relatively simple and easy for control of quality; and relatively convenient for maintenance	(1) When setting insulation layers, there are great influences on hanging equipment at the lining surface in the tunnel and it is complex for fixing. To meet the demands of operation, special treatment is needed for fire prevention and finishing; (2) Due to the setting of insulation layers at lining surface, occurrences and development of lining surface failure cannot be observed in time when the lining structure deteriorates and it is disadvantageous to the failure prevention and timely addressing; and (3) The frequent changes of train wind and pneumatic load from the operational vehicles in tunnel are liable to causing damages to insulation layers and further endangering traffic safety
Between primary support and secondary lining	No influence for hanging facility and equipment of the lining structure surface	(1) Working procedures of construction are tedious and with low working efficiency; (2) With intersecting operations of multiple working procedures in construction such as excavation and support, waterproofing and lining in the tunnel, there might have high risks of fire accident occurrence due to the low flame retardant property of insulation layers; (3) Insulation layers are liable to dislocation causing local cavitation in the course of concrete placing and vibrating for secondary lining; (4) Due to strength and elastic modulus of insulation layer on the low side, the insulation layers located between the primary support and the secondary lining are liable to damage of deformation because of compression, resulting in reduction of thermal insulation property; and (5) The insulation layers located in sandwich position cannot be maintained and replaced when they become ineffective

The comparisons show that train operates at high speed in the railway tunnel with obvious influence of aerodynamic force on the lining surface due to train wind and pneumatic pressure. In addition, due to the high traffic density and the main structure being designed maintenance-free, the maintenance work can be conducted only during the maintenance window time, and furthermore, due to the poor fire resistance of insulation material, the insulation layers should not be laid on the surface of lining structure. When setting the insulation layers for railway tunnel, they should be placed between the primary support and the secondary lining.

3.1.3 Environmental adaptability of insulation layer

Practical experiences indicate that the key to whether the insulation layers can achieve the heat preservation effect lies in the condition of humidity for the environment of the insulation layer. The degree of dryness and wetness of the material is closely related to the thermal conductivity and limiting moisture content is an important link to ensure the quality of thermal insulation. In the relatively dry environment, the effect of insulation layer is better. Therefore, different forms of permafrost stratum and seasonal frozen soil stratum will have different impacts on the heat preservation effect of insulation layer placed between the primary support and the secondary lining.

(1) For the railway tunnels of permafrost area, the main purpose of setting the insulation layer is to prevent the permafrost around the tunnel from thawing in summer. As the ground water in the permafrost stratum is in solid state, the insulation layers placed between the primary support and the secondary lining can basically be kept in dry state and the heat preservation effect is guaranteed. Therefore, the insulation layers can achieve the purposes of heat preservation and thawing prevention.

(2) For the railway tunnels of seasonal frozen soil area, as the ground water in such stratum is in liquid state, the ground water is easily channeled in the insulation layer due to the influence of gravity and the breakage of waterproof layer and it is difficult for the insulation layers located between the primary support and the secondary lining to be kept dry, thus causing, on the one hand, the heat preservation effect of the insulation layer being greatly decreased and even made ineffective, and, on the other hand, the inevitable occurrence of freezing in the state of low temperature due to failure of timely water drainage from the insulation layer and further leading to damages to the tunnel structure. The seasonal frozen soil area should therefore use the insulation layer carefully. Should it be necessary to set the insulation layers for tunnels of the seasonal frozen soil, it is suggested to develop the heat-insulating materials adaptive to the tunnel structure, construction techniques and hydrophobicity starting from the material

properties of insulation layer.

3.2 Tunnel structure freezing resistance for seasonal frozen soil area

3.2.1 Characteristics of tunnel structure affected by temperature environment

For the seasonal frozen soil area, the lining structure affected by temperature environment during continuous negative temperature has the following characteristics: firstly, when pores, gaps at joint and capillary pores in the tunnel lining concrete contain water or the lining concrete that is not compacted contains water, the negative temperature will lead to tunnel lining subjected to internal frost heave force; secondly, the relevant measured data indicate that temperature in the tunnel is generally maintained at around 15℃ during tunnel construction in cold region, but the temperature of the portal section is approaching the ambient temperature outside the tunnel when in operation and the concrete structure in winter will have significant shrinkage stress; thirdly, surrounding rock of tunnel belongs to silt, clay and other soil layers with strong frost heaving property after containing water or the marl, tuff, basalt and other rock strata with high frost heaving ratio; and fourthly, there are cavities in or behind the lining with concentrated frost heaving force being formed on the lining structure after ponding.

3.2.2 Tunnel structure freezing resistance

(1) Analysis on freezing-resistant performance of primary support. Research results of freezing-resistant tests for shotcrete structure indicate that the surface of shotcrete structure is with serious denudation under the freeze-thaw cyclic action and the indices of mechanical properties such as compression strength and cleavage strength are decreased to certain extent. Moreover, the internal pore content of shotcrete is further increased in the microscopic state, making the hydrates become crisp and be of degradation with increased width of crack and leading to gradual decrease of the structural load carrying capacity. However, the closed spherical bubbles internally formed in the shotcrete structure itself cut off the capillary channels for water seepage in concrete and can effectively alleviate the damages to the hardened cement matrix from frost heave pressure and osmotic pressure. Therefore, the freezing-resistant performance of shotcrete is better than that of the molded concrete. Nevertheless, the reinforced shotcrete is disadvantageous to the freezing resistance of primary support and it is preferable for the tunnels in cold region to decrease appropriately the design rigidity of primary support in the conditions of reinforcing and improving the strata and reducing the ground water infiltration in advance by taking measures such as surrounding rock grouting, reduce the use of mesh reinforcement for shotcrete of the primary support and use the grid steel frame when making design of steel frame.

(2) Freezing-resistant measures for secondary lining. The tunnel portal section of the seasonal frozen soil with obvious influence of ambient temperature should set the freezing-resistant structure, for which the lengths of the section can be determined by taking comprehensive considerations for the factors of influence such as lengths and gradients of tunnel, portal orientation, local mean air temperature of the coldest month, groundwater quantity, internal and external temperatures of tunnel, wind velocity, wind direction, lengths of train, train operation speed and density. In reference to the local mean air temperature of the coldest month and in combination with the categories and effects of conditions for prevention. The lengths of tunnel structure sections set for prevention of seasonal frozen soil area in high-latitude cold region can be determined by referring to Table 4 and those of tunnel structure sections set for prevention of seasonal frozen soil area in high-altitude cold region can be determined by referring to Table 5.

Support structure of freezing-resistant section should meet the following requirements:

(1) The freezing-resistant section should be set to adopt the compound lining of curved wall with inverted arch and use the waterproof reinforced concrete for secondary lining. The impermeability grade of concrete should not be lower than P8 and the indices of freezing resistant performance should not be lower than F300.

Table 4 Length of Tunnel Structure Freezing Resistance for Seasonal Frozen Soil Area in High-latitude Cold Region

Design zoning	Mean air temperature of the coldest month t/℃	Length of freezing-resistant section/m
II	$-15< t \leqslant -8$	500 ~ 1 000
III	$-20< t \leqslant -15$	1 000 ~ 1 500
IV	$-28< t \leqslant -20$	1 500 ~ 2 000
V	$t \leqslant -28$	≥2 000

Table 5 Length of Tunnel Structure Freezing Resistance for Seasonal Frozen Soil Area in High-altitude Cold Region

Design zoning	Mean air temperature of the coldest month t/℃	Length of freezing-resistant section/m
II	$-4.7< t \leqslant -0.5$	500 ~ 1 000
III	$-8.9< t \leqslant -4.7$	1 000 ~ 1 500
IV	$-13.1< t \leqslant -8.9$	1 500 ~ 2 000
V	$-17.3< t \leqslant -13.1$	2 000 ~ 2 500

(2) The structure of freezing-resistant section should be set with expansion joint of temperature, which should be kept away from the concentrated outlet of ground water. According to the requirements of environmental conditions for concrete pouring and curing of tunnel secondary lining, the climatic characteristics of big temperature differences and long freezing period in cold region, and further the distribution of longitudinal temperature field of tunnel in winter being generally in parabolic law of low at both ends and high in the middle, the concrete of the portal section is with obvious shrinkage at low temperature and thus longitudinally the secondary lining structure of the freezing-resistant section needs the setting of expansion joint for temperature to eliminate the temperature stress caused by temperature difference.

(3) The top and bottom of construction joints, expansion joints for temperature, and settlement joints of the arch wall, inverted arch, inverted arch filling and side ditch for freezing-resistant section should be through and aligned to avoid the cracks resulted from inconsistent deformation of upper and lower parts of tunnel structure.

It should be noted that though tiny cracks of tunnel structure do not affect the load carrying capacity of structure, they will have greater impact on waterproofing and durability. With respect to the tunnel design at present, longitudinal reinforcement of lining structure is generally deployed based on the construction with no computing being conducted and spacing of reinforcement being in general 200~300 mm, which is disadvantageous to crack resistance of the structure. It is therefore suggested that longitudinal constructional reinforcement is to be appropriately increased for the density up to 100~150 mm[8].

3.3 Freezing resistance of tunnel structure in permafrost region

3.3.1 Characteristics of tunnel structure under action of environment

The surrounding rock of tunnel for permafrost area is in frozen state throughout the year. The surrounding rock itself possesses good condition of stability and the tunnel building might cause thawing in a certain area around it. In addition to the impact on the frozen soil during construction, the influences of train heat dissipation and ambient temperature during train operation will be for long period of time. After the frozen soil environment around the tunnel is changed, freeze-thaw circle will be formed for the surrounding rock in a certain area around, which will be in an unstable state of freeze-thaw circulation and have adverse impact on the structure with the alternating changes of cold and warm seasons. In natural conditions, the maximum thickness of freeze-thaw circle approaches the top limit of local frozen soil. The greater the area of freeze-thaw circle, the stronger the freeze-thaw action and the greater the impact caused. Therefore, the freeze-thaw circle is the extremely important factor affecting the tunnel structure in the permafrost area and it is the fundamental means to guarantee the stability of structure by reducing the area of freeze-thaw circle, maintaining the heat stability of surrounding rock, and bringing into full play the stability condition of the frozen soil itself.

3.3.2 Freezing resistance of tunnel structure

Heat insulation technology is applied to achieve the purpose of preventing surrounding rock thawing behind the lining and minimizing the freeze-thaw circle. Generally, the insulation layers can be placed between the primary support and the secondary lining to reduce the heat exchanges of the air temperatures inside and outside the tunnel with the surrounding rock.

Considering the tunnels in severe-cold and freeze-thaw environment, primary support can adopt molded concrete and secondary lining use the molded reinforced concrete. The support and lining can both adopt the low-temperature early-strength durable concrete and the linings make full use of the self-waterproofing ability, with the impermeability grade being not lower than P8 and the freezing-resistant grade not lower than F300. The duration requirements can be met by adjusting the concrete mixture ratio, adding composite high-effective admixture, and formulating special construction techniques.

4 Freezing Protection of Tunnel Drainage System

4.1 Utilization of ground temperature in seasonal frozen soil area

In seasonal frozen soil area, the ground temperature of stratum is generally higher than 0℃ under the freezing depth, for which the drainage system will be therefore buried under the freezing depth. Utilization of ground temperature for freezing prevention is the main means for freezing prevention of tunnel drainage system in cold region.

To summarize the railway tunnel engineering practices in northeast China's high-latitude cold region, it is suggested to refer to Table 6 for the lengths of the heat-insulating ditches set in the inverted arch of tunnel in high-latitude cold region and those set under the inverted arch; and refer to Table 7 for the lengths of tunnel heat-insulating and drainage measures set in high-altitude cold region.

4.2 External heating

Freezing resistance by external heating is to prevent the occurrence of frost damage by heating the tunnel drainage system. The modes of arrangement for the heating system mainly include: (1) adoption of tube-type electrical heater; (2) setting of the heating cables in the drainage system in tunnel; (3) utilization of underground hot water or steam for heating ditches.

It is viable for the freezing prevention technology with heating to prevent frost damages at places with partly serious freezing and for the short tunnel with comparatively short period of freezing time. However, it might not be able to achieve the expected results for longer tunnels or

Table 6 Suggested Lengths [1] of Insulation and Drainage Measures for Tunnels in High-latitude Cold Region

Air temperature of tunnel location area/℃		Design zoning	Heat-insulating ditches under the inverted arch				Heat-insulating ditches in the inverted arch			
Mean air temperature of the coldest month t_1	Annual mean air temperature t_0		Shallow drain under the inverted arch	Deep buried drain under the inverted arch	Cold-proof drain tunnel	Length of setting/m	Up setting	Length of setting/m	Down setting or concealed pipe	Length or range of setting/m
−8 ~ −4	8 ~ 12	I	Not necessary	Not necessary	Not necessary		Proper heat insulation for portal section	0~300	Not necessary for heat insulation	
−15 ~ −8	4 ~ 8	II	Setting for portal section	Not necessary	Not necessary	When $L \leqslant -1\,000-200t_1$, $L_1+L_2+L_3=L$; and when $L>-1\,000-200t_1$, $L_1+L_2+L_3=-500-100t_1$	Heat insulation necessary for tunnel portal and body sections	300~1 500	Heat insulation necessary for portal section when heat-insulating ditches are not set under inverted arch	Length of setting can be the same as L_1
−20 ~ −15	0 ~ 4	III	Setting for tunnel body section	Setting for portal section	Not necessary				Heat insulation necessary for tunnel body section	Not necessary when $L \leqslant -1\,000-200t_1$, and necessary for the section when $L> -1\,000-200t_1$ and in the range of $(-500-100t_1)$ ~ $(500-100t_1)$ from the portal
−28 ~ −20	−4 ~ 0	IV	Setting for tunnel body section	Setting for tunnel portal and body sections	Setting for tunnel portal and body sections when the computed ditch burying depth is over 2.5 m					
<−28	<−4	V	Portal section is preferably designed as per the permafrost tunnel design, and body section can be designed as per the design of IV zone							

Note: Tunnel length is L, length of shallow drain under the inverted arch is L_1, length of deep buried drain under the inverted arch is L_2, and length of cold-proof drain tunnel is L_3.

Table 7 Suggested Lengths of Insulation and Drainage Measures for Tunnels in High-altitude Cold Region

Design zoning	Mean air temperature of the coldest month/℃	Length of portal heat insulation and drainage/m
II	−4.7 ~ −0.5	1 000 ~ 1 500
III	−8.9 ~ −4.7	1 500 ~ 2 000
IV	−13.1 ~ −8.9	2 000 ~ 2 500
V	−17.3 ~ −13.1	2 500 ~ 3 000

tunnels with longer period of freezing time. Moreover, there exist disadvantages such as great energy consumption, high operational costs, and difficulties in equipment and facility maintenance for most of the technical measures, which do not comply with the overall requirements for building the energy-saving society as initiated by the country. At present, the freezing prevention technology with electrical heating is mainly adopted in the addressing of freezing damage for railway tunnels. Qinghai-Tibet Plateau has the abundant geothermal resources and tunnel portal freezing prevention by using the high rock temperature and high water temperature in tunnel is a new technology worth exploring and trying.

5 Design and Construction of Freezing Resistance and Prevention for Tunnels in Cold Region

5.1 Design principles [9]

(1) Tunnel position is preferably to choose the sections with low ground water level and with less water storage structure. It is preferable to avoid the shallow burying of long section at the portal and the crossing of large gully in the way of shallow burying for tunnel body.

(2) Tunnel is preferably to choose the strata of low frost-heave sensitivity and it is preferable to avoid crossing the strata of clay soil and mud stone for long section.

(3) Tunnel portal is preferably to choose the position being leeward to the sun, not easy to snow and easy to drain. When the tunnel is located in the mountainous area with heavy snowfall, it is not preferable to place the portal at the positions with the side and steep slopes and being prone to avalanches.

(4) The track longitudinal grade in the tunnel is not preferable to be less than 5% and better to adopt the herringbone slope if possible.

(5) Waterproof and drainage for the cold-proof section follow the principles of "combination of blocking and drainage, suiting measures to local conditions, reliable cold-proof, smooth drainage, convenient construction and easy maintenance". Heat insulation ditch, deep-buried ditch of cold-proof drainage tunnel are adopted based on temperature conditions and heat preservation is preferably adopted for blind drain system.

(6) For the sections of tunnel portal with obvious influence from ambient temperature, reinforced concrete is preferably adopted for the lining and the divisions of sections for the lining are carried out in combination with the influence of temperature stress.

(7) The foundation base of the tunnel structure in the frost-heaving stratum is buried below the freezing line or addressed to eliminate the frost heave by the base.

(8) When the portal or the shallow-buried section are in the surrounding rock section of high frost-heaving sensitivity, it is preferable to give priority to adopting open-cut method for construction and make the backfill with non-frost-heaving materials.

5.2 Insulation and drainage design

The insulation and drainage system of tunnel in cold region mainly include the insulation ditch, central deep-buried trench and cold-proof drainage tunnel (refer to Fig.1–Fig.3). The tunnels in cold region set with the insulation ditch, deep-buried trench or cold-proof drainage tunnel should also be provided with the supporting drainage facilities in the tunnel including insulation manhole, blind drain (ditch), drain hole, and transverse drain.

5.3 Characteristics of construction technologies

(1) Construction of central deep buried ditch. Excavation of groove body for central deep buried ditch is liable to have impact on the stability of primary support for the arch wall part of tunnel, for which mechanical excavation can be adopted in combination with conditions of surrounding rock or mechanical excavation and trenching adopted following pre-splitting and blasting. Prefabricated stamping mould can be adopted to complete the cast-in-situ C20 fine stone concrete base of the central deep-buried pipe and ditch according to the designed longitudinal slope so as to ensure the straightness and stability of pipe and ditch installation. For the schematic diagram of central pipe and ditch base and joint as well as the construction scene, refer to Fig. 4 and Fig. 5 respectively.

(2) Deep-buried circumferential blind drain or side wall crushed stone blind drain. Construction of the deep-buried circumferential blind drain is carried out by chiseling and removing the shotcrete of the primary support, cutting the trench, and then burying the pipe to form a deep-buried circumferential blind drain. Cutting of the trench can be completed by way of controlled blasting or mechanical excavation. If there is steel frame near the place where deep-buried circumferential blind drain is to be set, the longitudinal spacing of the steel frame can be locally adjusted based on the practical conditions of the site. For the schematic diagram of deep-buried circumferential blind drain, refer to Fig. 6.

(3) Cold-proof drainage tunnel. To prevent the construction of drain

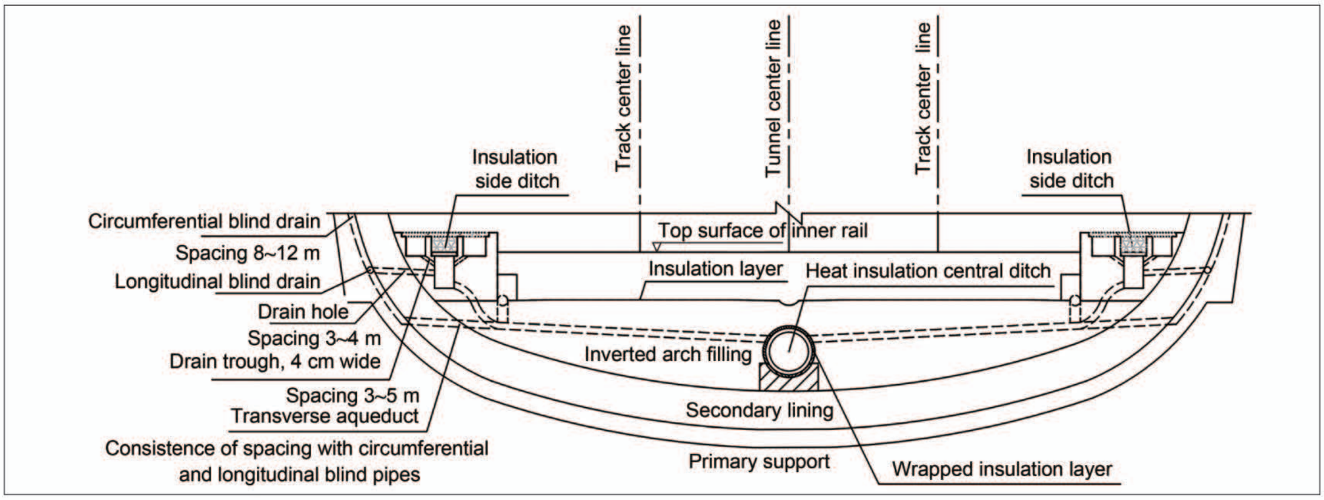


Fig. 1 Schematic diagram of heat insulation ditch

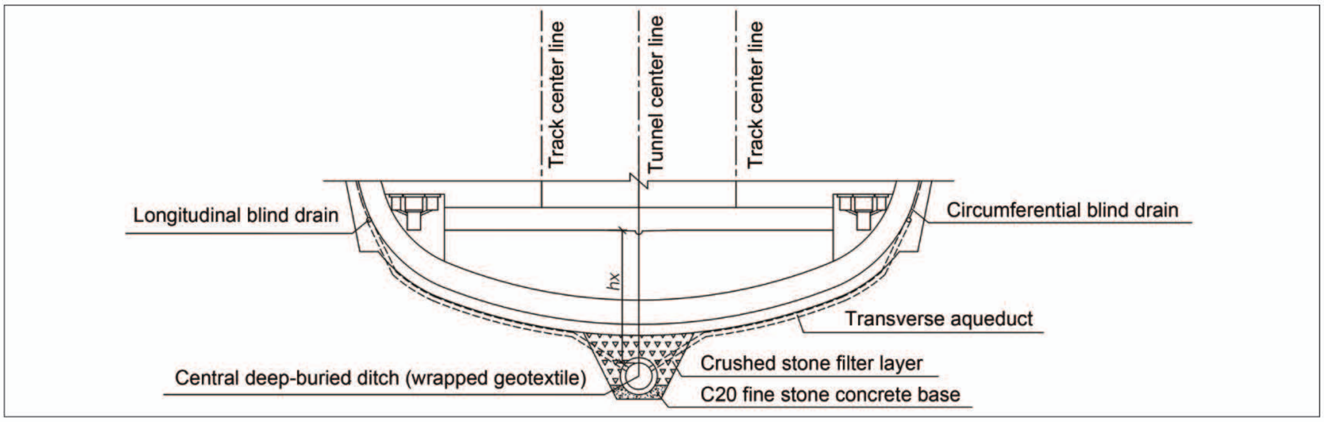


Fig. 2 Schematic diagram of central deep-buried ditch

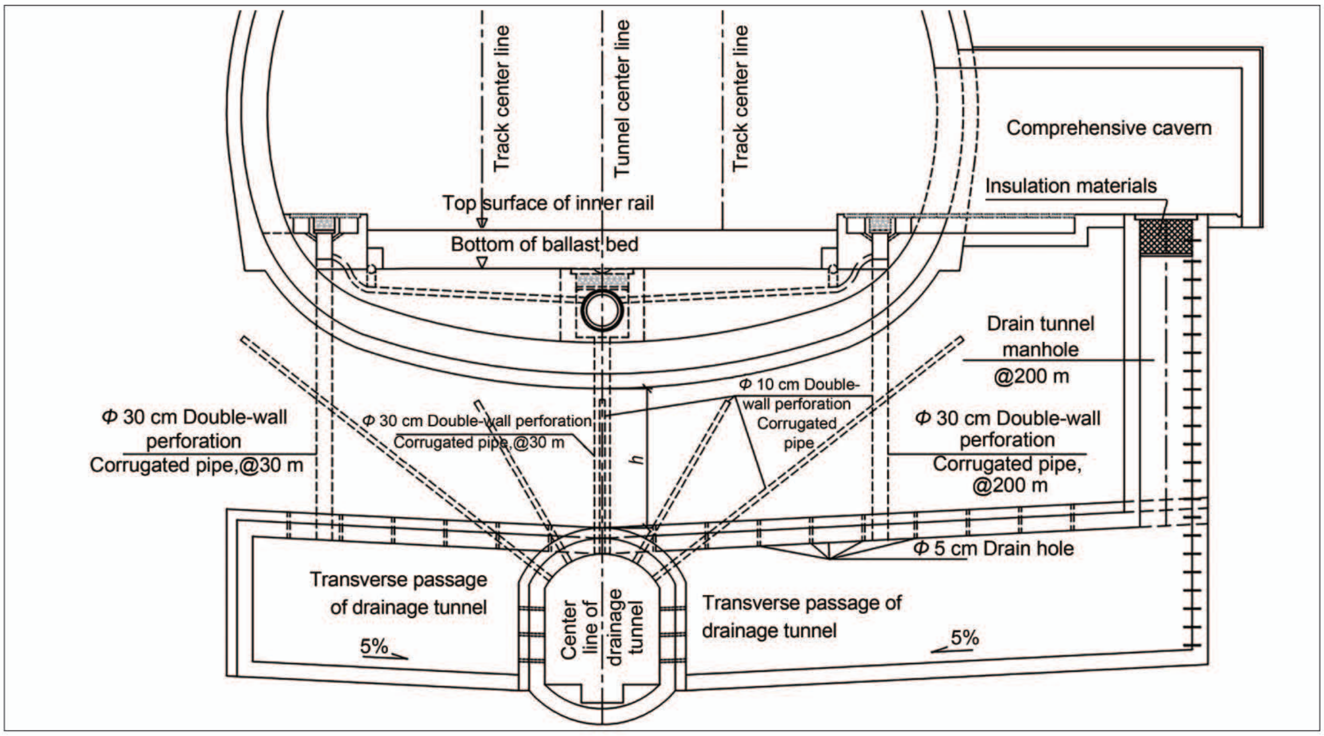


Fig. 3 Schematic diagram of cold-proof drainage tunnel

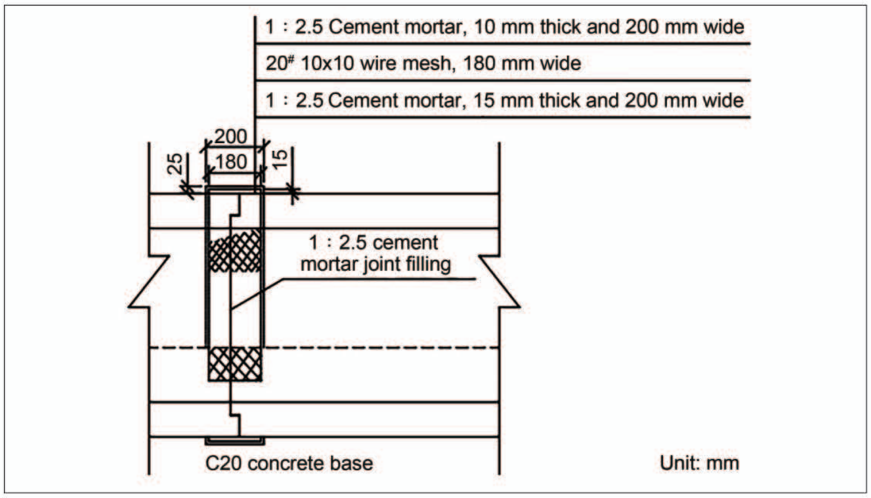


Fig. 4 Schematic diagram of central pipe and ditch base and joint

Fig. 5 Construction scene of central pipe and ditch

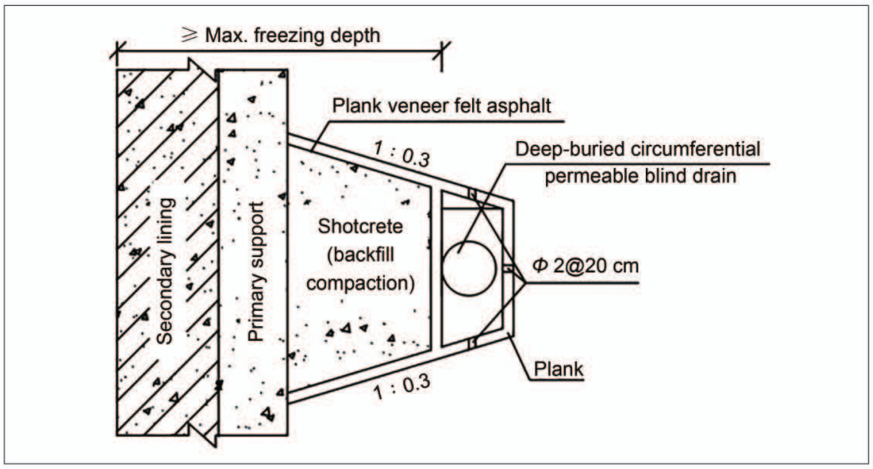
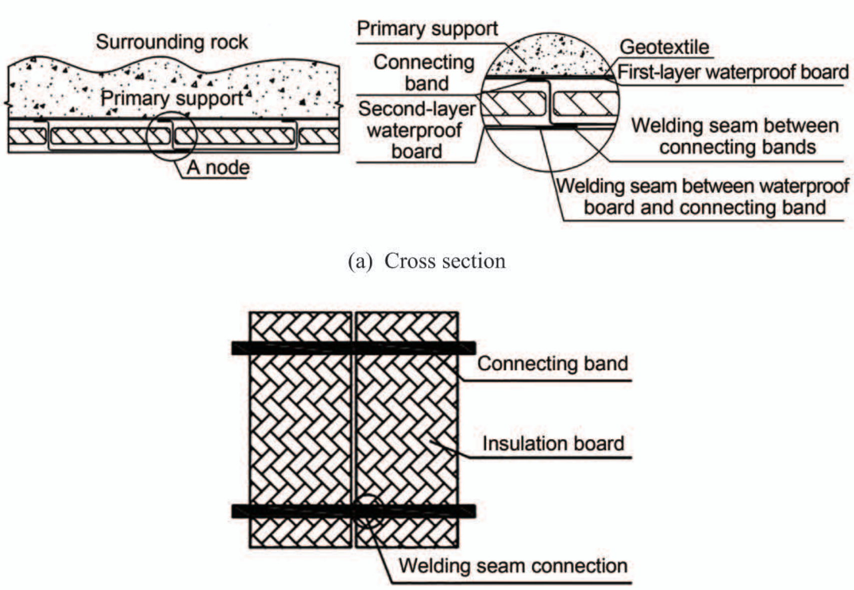


Fig. 6 Schematic diagram of deep-buried circumferential blind drain support

tunnel from affecting the main tunnel, it can be taken in the meantime as the advance pilot tunnel concurrently to predict the engineering geological and hydro-geological conditions of the main tunnel ahead so as to provide appropriate references for the safe construction of the main tunnel. Cold-proof drainage tunnel should generally meet the requirements of advance main tunnel construction and construction of the drainage tunnel can be carried out by adopting drilling and blasting method or tunneling machine method. When the construction is carried out by drilling and blasting method, controlled blasting measures should be taken for both the drainage tunnel and the main tunnel excavations to control the blasting vibration velocity.

(4) Insulation layer construction. At present, the insulation layers of railway tunnel are basically located between the primary support and the secondary lining, for which hanging method is generally adopted for construction. When insulation layers are made by hanging method, the structural form of the insulation board sandwiched between the double-layer waterproof board is generally adopted for the insulation layer and the construction of the waterproof board and the insulation board is carried out by adopting the annular tensioning method of the waterproof board connection point, i. e. welding the first-layer waterproof board with the hot melt gasket for fixing the non-woven fabric by a manual electro-thermal fusion device, and setting the waterproof strip to fix the insulation board and weld it with the second-layer waterproof board so as to ensure the effective connection between the insulation layer and the waterproof board. For the construction techniques of insulation layer, refer to Fig. 7.

(5) Concrete construction in winter. In accordance with the relevant specifications[10], concrete construction should be carried out as in winter when the outdoor daily mean air temperature is below 5℃ or the minimum air temperature is below 0℃ for three consecutive days. Insulation measures should be taken for concrete mixing and transportation and measures for heating and insulation are also re-



(a) Cross section

(b) Plane

Fig. 7 Schematic diagram of construction techniques for insulation layer

quired for the relevant raw materials. Concrete curing following completion of pouring should be enhanced to ensure sufficient humidity for the curing environment and prevent concrete surface cracks caused by too fast moisture loss of concrete. Moreover, the ambient temperature for reinforcement processing should not be below 5℃.

6 Conclusion

(1) Cold regions in China can be classified into high-latitude cold region and high-altitude cold region according to the geographical and topographic characteristics.

(2) Railway tunnel designs in high-latitude cold region can be divided into five zones and those in high-altitude cold region can be divided into six zones.

(3) When the tunnel portal in cold region is obviously affected by temperature, design of freezing resistance is needed for tunnel structure of the portal section and design of thermal insulation is necessary for the drainage system of the portal section.

(4) Heat insulation drain ditches of seasonal frozen soil area in cold region include heat insulation ditches, deeply buried ditches and cold-proof drain tunnels.

(Translated by Zheng Mingda)

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