Active Geotechnical Treatment Technology for Permafrost Embankment of Qinghai-Tibet Railway

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ABSTRACT

Frozen soils occupy most of the area of western China. In order to support the advance of the development of the western region, the Qinghai-Tibet Railway has been basically achieved to overcome the obstacle of the frozen soils, and opened up a new solution to the worldwide problem. In this paper, the Qinghai-Tibet railway was taken as the background; the basic principles of the following 5 main embankment forms were introduced: the block-stone embankment, ventilation pipe embankment, thermal pipe embankment, sunshine-shield embankment, crushed-rock revetment embankment and the development status were analyzed.

KEYWORDS: Frozen soil; Block-stone Embankment; Ventilation pipe; Thermal pipe

INTRODUCTION

Warm permafrost along the Qinghai-Tibet Railway consists of 550 km predominantly continuous permafrost and 82 km discontinuous island permafrost. Warm permafrost (0 ~ -1℃) is extremely sensitive to temperature change with strong instability. High ice content will aggravate its thaw collapse. As for the railways built on the frozen soils, when the railway is running, heat will be transferred down along the embankment; the frozen soils on the active layer will have a thawing and freezing cycle which will lead to embankment deformation and derailment accident will occur easily (Wen, *et al.* 2005; Liu, *et al.* 2006; Niu, *et al.* 2012; Mu, *et al.* 2012) which is harmful to the safe operation of the railway. How to protect the stability of permafrost under the greenhouse effect has become a key issue of the construction of the embankment.

Prior thaw collapse of the frozen soils and heightening the embankment are two traditional ways to increase the stability of the permafrost embankment. The large temperature difference between winter and summer in Tibetan Plateau causes significant heat transfer that includes radiation, convection and conduction. Permafrost embankment of the Qinghai-Tibet Railway has the following characteristics:

① the thickness of permafrost is about ten to a few hundred meters;

② accompanied by a few meters underground ice;

③ the mean annual temperature $T_{CP} > -1.5°$.

Therefore, the traditional approach of permafrost embankment is no longer applicable to the Qinghai-Tibet railway. To keep its stability, we have to control of the heat transfer and look for new initiative permafrost embankment treatment technology (Yang and Jiang 2010; Zhou, *et al.* 2009).

THE BASIC PRINCIPLE OF PERMAFROST EMBANKMENT TREATMENT

The former studies focused on passive protection principles in which the most common is heat insulation method (Wen, *et al.* 2005). In order to reduce artificial thermal disturbance, the heat insulation method has been largely restricted during the construction period. The thermal insulation material can well maintain the upper limit of permafrost, but the heat accumulation under the thermal insulation layer can make the warm permafrost yearly melting. The embankment stability can not be guaranteed when $T_{CP} > -3.84$ ℃. In another hand, when the outside temperature reached the lower limit of permafrost, the heat insulation method is also out of action. Thus, the heat insulation method is limited within a certain range of ground temperature of permafrost.

The Tibetan Plateau has rich ground ice. The upper limit of permafrost with a role of exclusion of water declines with global warming, and the moisture loss which will accelerate the decomposition of grassland and the degradation of biological wreckage. A tremendous increase in the amount of carbon emissions will aggravate the role of climate. So the following active cooling protective measures are applied to the Qinghai-Tibet Railway construction.

For the first time, the application of guiding theory from passive to active in Qinghai-Tibet Railway construction has been fundamentally solved the permafrost troubles, which achieved a better and more efficient cooling effect. The integrated application of the block-stone embankment, the ventilation pipe embankment, the thermal pipe embankment, the sunshine-shield embankment and the crushed-rock-revetment embankment method have taken advantage of the local conditions of Tibetan Plateau such as rich wind power and accumulation of negative temperature to prevent embankment heat input, strengthen the beneficial air convection with the thermal conductivity to promote heat loss and cold energy storage. The use of one-way heat transfer apparatus can make active cooling and remove the threat of imported heat, under the greenhouse effect and intense solar radiation. Meanwhile, natural protective layer which formed by the block-stone revetment and opposite to the thermal conductivity direction has good cooling effect, thereby improving the use conditions of embankment under unfavorable environment.

ACTIVE TREATMENT TECHNOLOGY

Block-stone Embankment

In 1996, Georing and Kumar proposed that the cooling effect of block-stone embankment originated from the larger porosity (Georing and Kumar, 1996; Liu, *et al.* 2006). As shown in Figure 1, in warm season, the density of the heating air in the ballast layer decreases, and the rise direction is opposite to heat transfer direction. It will form a natural heat shield with a small amount of heat conduction. As shown in Figure 2, in cold season, when the outside environment passed cold energy to the embankment, the air in ballast layer will sink, and the hot air is squeezed to shift up which is consistent with heat conduction direction, so that the effective thermal conductivity increases to form a cold and hot convection to protect permafrost embankment.

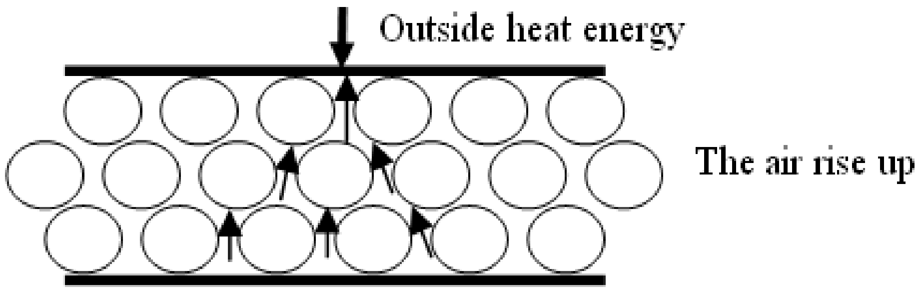

Figure 1: Ballast Layer in Warm Season

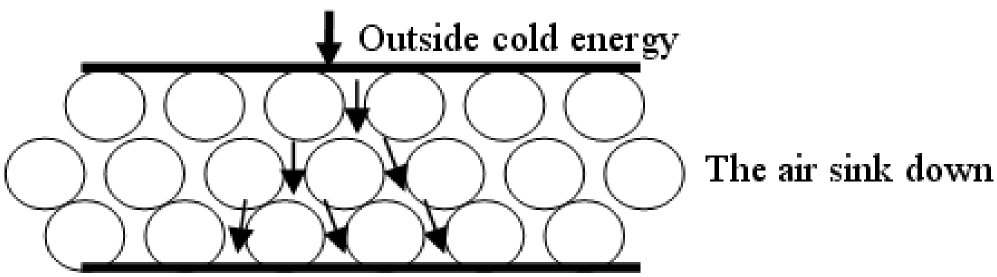

Figure 2: Ballast Layer in Cold Season

Like automatic switches, thermal shielding and cooling effects of the ballast layer forms heat energy positive and negative effects, and to achieve a unidirectional heat conduction of thermal semiconductor insulation materials (Niu, *et al.* 2012; Wu, *et al.* 2005) According to the observations of the Academy of Railway Sciences Northwest Branch: the effective thermal conductivity of the crushed rock layer in winter is as l2.2 times as in the summer, the cold accumulation is significantly greater than the heat in warm and cold seasons, and the natural convection significantly increases cold energy storage. On the Tibetan Plateau, 75% of the strong wind occurs in the winter with high average speed, the refrigeration effect of forced convection between the air in the ballast layer and the outside air by wind action is doubling increase, which can effectively increase the permafrost upper limit under the day and night, summer and winter temperature alternating.

Ventilation Pipe Embankment

Based on the observation of the residence house on the Tibetan Plateau, we can get that each house has a ventilation pipe; the wall above ventilation pipe of which the nozzle is blocked by soil will appear long cracks. Engineers learn the methods to expand research on the ventilation pipe embankment, as shown in Figure 3 (Yang and Jiang 2010; Sun, *et al*. 2011). In cold season, the hot air is extruded from the tube by cold air deadweight and wind effects to consume the thermal radiation of the embankment surface and take the heat of the tube wall surrounding soil away. Ventilation pipe increases the interface of the external environment and the embankment, promotes convection and accelerates cold transmission by wind motivation, and takes full advantage of the characteristic of negative accumulated temperature is much greater than the positive accumulated temperature in Tibetan Plateau (Zhou, *et al.* 2009); the thermal conductivity of the air in the tube is less than in the soil which provides relative insulation to reduce heat into the soil. Some data indicates that: compared with the annual average temperature, the embankment surface temperature is 4℃ higher, while the temperature inside the ventilation pipe is only 1.6 -1.8℃ higher than the outside world. The negative accumulated wall temperature is 2 to 4 times as positive accumulated temperature; the ordinary embankment is only 0.2 to 0.6 times (Yang and Jiang 2010; Wu, *et al.* 2004). There is a considerable space to increase the upper limit artificially.

Figure 3: Ventilation Pipe Embankments

Currently, there are two kinds of ventilation pipe embankments: the automatic temperature control type and the embankment with porous ventilated tubes. As for the automatic temperature control ventiduct, namely installed a memory alloy in the nozzle to control the opening and closing of the nozzle baffle automatically according to the temperature changes, absorb cold air in winter and prevent hot air in summer. Tests has shown that the temperature of automatic temperature control ventiduct wall is 1℃ lower than the traditional ventilation pipe, T_{CP} of the levee foundation at 3.5 m is also 0.45℃ lower than the general ventilation tube. The perforated ventilation pipe (Sun, *et al.* 2012) has apertures in the wall to keep the soil dry and improve the cooling efficiency by using water evaporation and the heat exchange between air in the tube and the surrounding soil. During the thawing period, water evaporation of the soil surrounding the apertures is very strong, that can counteract part of the convection caused by the warming effect, to make up for the disadvantage of the ventilation pipe without apertures only has warming effect in the warm season.

Thermal Pipe Embankment

Thermal pipe (Zhou, *et al.* 2009; Guo, *et al.* 2009) is a kind of heat transfer devices sealed with gas-liquid circulative convection, filled with liquid ammonia of low boiling point and other refrigerants. The upper end is condensing section and the lower end is evaporating section. In cold season, after the evaporator section refrigerant absorbing permafrost heat to have a vaporization, it will shift up to the condensing section along the tube cavity due to pressure difference, then liquefy and release heat through the heat fin, the liquid reflux along the wall to the evaporator section and cyclical transfer by deadweight until the external temperature is higher than the temperature of the embankment can stop working. Thermal pipe has a one-way heat transfer characteristics which is a controllable heat transfer of efficient thermal conductivity device. Copper and silver have the strongest thermal conductivity, while thermal conductivity of thermal pipe is l000 times higher. The researches show that: the maximum vertical rise of the permafrost upper limit is over 1.5m by using thermal pipe embankment, as shown in Figure 4 (Zhou, *et al.* 2009).

Figure 4: Thermal Pipe Embankments

Except for the upgrade of embankment, the core thermal pipe has been improved from coreless pipe. Core thermal pipe uses tube core with porous materials, and steam under small pressure flows to the condensation section and liquefies, then use the capillary pumping ability of the core pipe to force the liquid to overcome the deadweight back flow to the evaporator section, thus expand the application surface.

Sunshine-shield Embankment

Currently, sunshine-shield protection on the permafrost are most applied in Russia and the Alaska areas in the United States, Kondratjev (1996) proposed a new way to strengthen the embankment on the ice-rich permafrost in which the superiority of the sunshine-shield embankment was proposed. Experimental investigation was taken on Fenghuoshan Basin of the

Qinghai-Tibet Railway by Academy of Railway Sciences Northwest Branch, relative experiments and researches have been taken by Cold and Arid Regions Environmental and Engineering Research Institute of Chinese Academy of Science, which have provided many theoretical basis and practical foundation for the Qinghai-Tibet railway construction and later maintenance, and also for the highway construction in western permafrost areas.

Since Tibetan Plateau is located in the medium and low latitudes, and with high altitude, the solar radiation is very strong. Embankment built has changed the traits of the ground and increased the amount of direct sun radiation which would cause the melting of the permafrost foundation. Therefore, use of the sunshine-shield to block the strong direct radiation of the sun on the embankment can reduce the temperature of the surface of the embankment and to reduce the amount of heat transferred to permafrost foundation. Sunshine-shield is a kind of low shielding structures set on the slope consisting of a pile and composite panels. In order to increase the reflectance, the plate can be coated into a light color [13], as shown in Figure 5.

Figure 5: Thermal Pipe Embankments

The trial of the Qinghai-Tibet Railway (Niu, *et al.* 2010) has shown that: the average temperature of the slope under the sunshine-shield is 3.2 ℃ lower than the outside, and the maximum can be a difference of 4.2℃. As for the loose embankment formed by repeated freezing and thawing, the sunshine-shield can keep out wind and rain, not only effectively reduce the embankment deflation and water erosion, but also prevent sand entering the pore on the block-stone layer to ensure the cooling effect of convection.

Crushed-rock-revetment Embankment

Crushed-rock-revetment embankment (Sun, *et al.* 2007) is built to protect the underlying permafrost and ensure the thermal stability of embankment by the characteristics of the thermal conductivity of the gravel layer through laying a certain thickness of the gravel on both sides of the embankment in permafrost regions. Crushed-rock-revetment embankment is generally applied in high temperature and high ice content permafrost region. Relevant data show that the equivalent thermal conductivity of the gravel layer in the cold season is 5 to 10 times or more as in warm season, which also has a thermal diode effect and shading effects. The combined effect of the two effects can reduce the permafrost temperature, and effectively improve the embankment under the foundation of the regenerator to protect the permafrost foundation. In the construction of the embankment in permafrost regions, crushed-rock-revetment embankment is one of the most effective methods to protect permafrost.

The embankment structure development trends to have a diversification and the crushed-rock-revetment embankment type have also been improved. The Qinghai-Tibet Railway has applied a U-type rubble embankment (Cheng, *et al.* 2009). The cooling principle of U-type rubble embankment is similar to the block-stone embankment, and both of their cooling effect is by the negative impact of the thickness of the casing soil. Under the plateau condition of high altitude and thin air, U-type rubble embankment has good application. But the natural convection in the block-stone embankment is relatively weak with higher cost. In addition, the biggest difference is that the U-type rubble embankment increases optimization of shady and sunny slope embankment. Qinghai-Tibet Plateau has an asymmetry of thermal field (Song, *et al.* 2006) caused by incident angle of sunlight, the radiation absorbed on both sides of embankment are different.

What's more, the Tibetan Plateau solar radiation is very strong, so the thermal difference is quite large between both sides of embankment, and it will lead to some problems such as cracks in a sunny slope embankment, which can easily affect the stability of the embankment. Therefore, as shown in Figure 6, this U-type rubble embankment adjusts the thickness of the embankment on both sides to regulate the shady and sunny slope embankment absorption of solar radiation, balance transverse temperature field and eliminate uneven deformation. The base stone also can in a timely manner exclude melt water to consolidate soil which has higher stability than block-stone embankment.

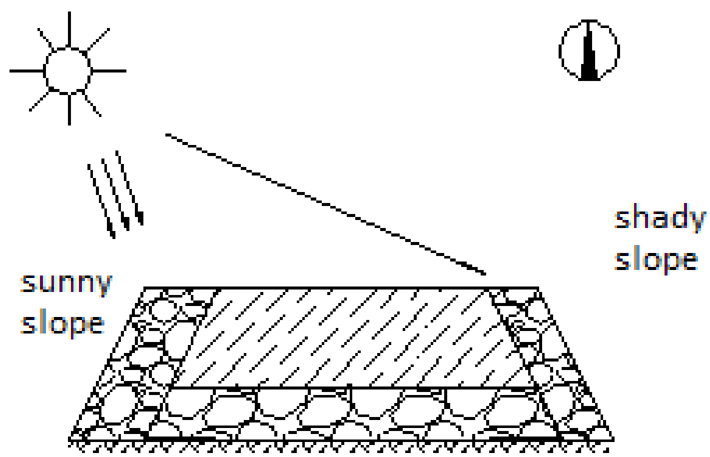

Figure 6: U-type Rubble Embankments

The above 5 types of embankment are main active geotechnical treatment technologies for permafrost embankment of Qinghai-Tibet Railway, and the applications or testing in the Qinghai-Tibet Railway are shown in Table 1.

Table 1: Embankment Locations of the Application /Testing in the Qinghai-Tibet Railway

Embankment type	Applying location	Reference
block-stone embankment	Southwestern Basin, Hoh Xil Basin and Fenghuoshan Basin	[9]
ventilation pipe embankment	Qingfeng Rivier and Beiluhe	[10]
thermal pipe embankment	Fenghuoshan Basin and Qingfeng Rivier	[11]
sunshine-shield embankment	Tangguala area and Qumar River	[14]
crushed-rock-revetment embankment	Qumar River and Beiluhe	[15], 17]

CONCLUSIONS

The embankment construction in warm permafrost area is an important component of the frozen soil engineering with challenging and variability. We should not only ensure safe and reliable engineering but also have to pay attention to the reaction of the environment. There will be more problems for improvement in the future demand of the railway speed, and the embankment structure of the Qinghai-Tibet Railway have a large number of experiments to prove its good cooling effect and provides a valuable reference and practical experience.

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