Cooling Effects and Characteristics of Crushed Rock Embankments with Different Structures in a Warm Permafrost Region

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Abstract **— Crushed rock embankment, as a typical technique to cool roadbeds, is widely used in the embankment engineering of the Qinghai-Tibet Railway (QTR) in permafrost regions. Its cooling effect has been paid special attention under a climate warming scenario and the warm and ice-rich permafrost. Ground temperatures of three kinds of crushed rock embankments along the QTR were measured for ten years (2003-2013), in Chuma'er High Plain where the permafrost is warm (> −1.0℃), to determine their cooling effects and characterize thermal differences among each embankment structure. The results show that all the three kinds of embankments have active cooling effects on the underlying permafrost but the cooling characteristics vary significantly with different embankment structures. Obvious asymmetries existed in the ground temperature field within the crushed rock basement embankment (CRBE), indicating thermal regime of this structure was disadvantageous for its thermal stability. In contrast, the ground temperature fields of both the crushed rock sloped embankment (CRSE) and the U-shaped crushed rock embankment (UCRE) were well symmetrical. However, the UCRE gave better thermal stability because slow warming of deep permafrost was observed under the CRSE. Generally, the UCRE structure can be very advantageous to its long-term thermal stability, even in a warm permafrost region. It is helpful in providing references for future's improved engineering design and maintenance of roadbeds in permafrost regions.**

Keywords - Qinghai-Tibet Railway; crushed rock embankments; cooling characteristics; permafrost; embankment structures

I. INTRODUCTION

The physical and mechanical properties of permafrost are highly variable and extremely sensitive to temperature changes due to existence of ground ice [1]. Therefore, permafrost temperature is considered as one of the key parameters in controlling the stability of permafrost engineering [2]. In order to reduce the risk of a structure failure in a permafrost environment, a guarantee of the ground thermal stability has to be the main goal [3]. Road construction always inevitably disturbs the original energy balance of the ground surface because of the built of roadbeds [4], and might cause the underlying permafrost warming and thawing. Melting of ground ice leads to uneven thaw settlement, producing a great threat to constructions over it [5]. Though road construction over permafrost has more than 100 years of history, permafrost-related engineering problems still exist, and there has been a damage rate of about 30% existing in the currently operational roads in permafrost regions [6].

The Qinghai-Tibet Railway (QTR), as the world's highest and longest plateau railroad, is 1,142 km in length, crossing approximately 550 km of the continuous permafrost regions. About 50% of the permafrost area traversed by the QTR is warm permafrost with a mean annual ground temperature (MAGT) of −1 to 0 °C, and around 40% is ice-rich permafrost [6]. Under climate warming and regional permafrost degradation on the Qinghai-Tibet Plateau (QTP) [7-8], thermal regime and changes of the underlying permafrost are well related to the roadbed stability and its long-term safe operation [9]. To overcome the engineering problems caused by permafrost changes and ensure the roadbed stability, an active-cooling principle had been proposed in period of construction of the QTR [10], and various cooling measures, including crushed rock embankment (CRE), duct-ventilated embankment, sun-shading embankment and thermosyphon embankment, have been tested and applied in the QTR [11].

A crushed rock layer, which was acted as thermal semi-conductor, has a cooling effect during winter time and heat insulation effect during summer time, which can be demonstrated by Rayleigh–Bénard convection [12]. Although early studies have discussed its cooling effects, their works were based on short-term field monitoring data [11-15]. There is no new report on long-term thermal regimes of the embankments based on time series up to 10 years, and the comparative analysis on different-structured embankments in the same warm permafrost region was less. Now the QTR has been serving with a train-speed of up to 100 km/h (one of the designed requirements), and it has been 10 years since the roadbeds were constructed. And also, this railway is expected to operate for more than 100 years. The status of the crushed rock embankments in permafrost regions, particularly warm permafrost, has been attracting much attention since the QTR was opened to serve on July 1, 2006. Thus an analysis of their long-term cooling characteristics is very necessary.

In this paper, we chose 3 types crushed rock embankments built in Chuma'er region (where permafrost is warm and ice-rich) along the QTR to analyze their long-term cooling effects and characteristics, based on 10 years' ground temperature data monitored since 2003, just when the embankments were constructed. The purpose of the paper is to evaluate the cooling effects and characteristics of different-structured crushed rock embankments in warm permafrost regions, and enhance the understanding of the effects of the cooling principle for permafrost roadbed constructions and maintenances.

II. STUDY SITE

A. Study Site and Permafrost Conditions

The three chosen monitoring section for different structures installed along the QTR were located in the Chuma'er High Plain, the hinterland of the QTP. This region is characterized by flat topography and widely distributed thermokarst lakes. The basic environment is very high elevation, cold and dry climate, and as a result, the soil types are mainly alpine grassland soil and alpine meadow soil in most areas. The average elevation of the site is over 4,500 m. The mean annual air temperature (MAAT) is around −4.5°C, and the frozen period is from September to April.

There is sparse vegetation in this region, with a surface vegetation cover less than 35%. According to the geologic drilling data, permafrost under the monitored embankments are typically warm and ice-rich, with a MAGT of −0.9 to −0.7°C; the permafrost table ranges from 2.0 to 2.8 m in buried depth, and the volumetric ice content is about 40% at the depth from 2.8 to 6.0 m. Thus, this region of the monitoring sections located is a representative of warm and ice-rich permafrost of the QTP.

B. Crushed Rock Embankments Structures

As a representative measure of adjusting heat conductivity and convection, the CRE has been widely applied in the QTR construction, for reasons of easy to construct and low-cost [11-13]. This type of embankment can be classified into three different structures: crushed rock basement embankment (CRBE), crushed rock sloped embankment (CRSE), and U-shaped crushed rock embankment (UCRE), as shown in Figure. (1). The CRE stands for the major cooling measure applied in QTR in permafrost regions and therefore their long-term cooling effects and characteristics are very necessary to be concerned, when the roadbed stability of the railway is mentioned.

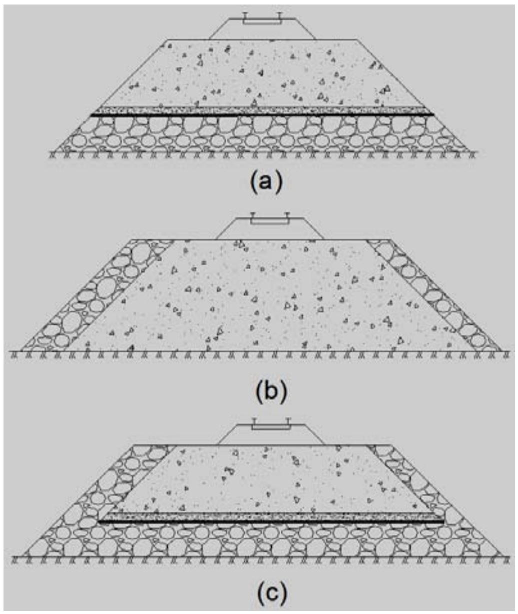

Figure 1. Structural diagrams of three types of crushed rock embankments. (a) CRBE; (b) CRSE; (c) UCRE;

III. MORNITORING METHOD

Between July and September 2003, four boreholes with a depth of 16 m were drilled at the two shoulders and the two slope toes of each railway embankments monitored, and a borehole with a depth of 16 m was also drilled in the undisturbed natural ground as a reference of permafrost thermal status without disturbance, which is 10 m away from the embankment toe, as shown in Figure. (2).

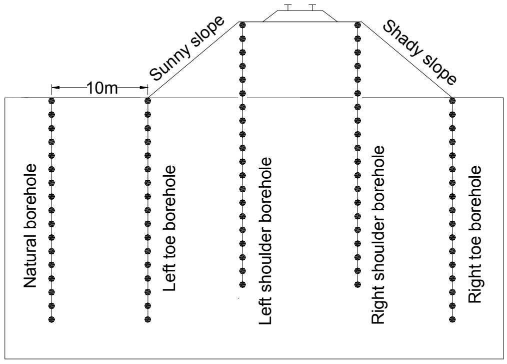

Figure 2. Location of temperature observation boreholes

A thermistor cable, with 33 thermistors at 0.5 m intervals from the surface down to 16 m, was installed into each borehole to monitor the soil temperature. The thermistors, with a precision of ±0.05°C, were manufactured and assembled by the State Key Laboratory of Frozen Soil Engineering, in China. The tube was sealed at the bottom and top once the cables had been inserted, preventing moisture from entering the sensors and reducing the air convection. The boreholes were filled with dry sand and

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packed with a long rod, in order to provide tight contact between the tube and the ground. The ground temperature data were collected manually by a CR3000 data logger semimonthly. The monitoring work was started in October 2003, just after the roadbeds were constructed.

IV. Monitoring Results

A. *Ground Temperature Fields Beneath the Embankments*

Figure.(3) shows the ground temperature fields of the CRBE when the maximum seasonal thawing depth occurred in the year of 2003, 2006, 2010 and 2013. As shown, the temperature field and the permafrost table (0°C isotherm) were both basically symmetrical in 2003. However, the marked asymmetry of temperature field was occurred in the CRBE after 2003. The −0.5°C isotherm under the left part of the embankment deepened evidently, meaning that the temperature of this part was steadily increasing and that the asymmetry of the embankment temperature distribution was intensifying gradually. Up to 2013, the −0.5°C isotherm under the left part descended to the depth of −8.0 m below the ground surface, while that under the right part kept approximately constant. The asymmetry characteristic of the temperature distribution within and beneath the embankment was mainly caused by the solar radiation-induced thermal difference between the sunny and shady slopes, but the surface water occurred near the left embankment toe since 2009 may be another reason, which led to an obvious temperature rising of the left toe and thus intensified the asymmetry of temperature field. The obviously asymmetrical ground temperature field of the CRBE might cause uneven deformation of the roadbed.

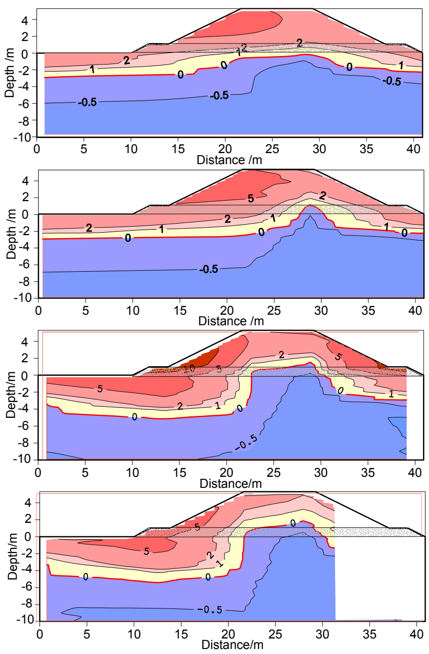

Figure 3. Temperature fields of the CRBE in october at different years as (a) 2003, (b) 2006, (c) 2010, and (d) 2013.

In contrast, the most remarkable characteristic of the temperature distribution in the CRSE was well symmetry. By 2006, the permafrost table under the embankment had uplifted to the original ground surface. Meanwhile, the symmetry of the temperature field was improved obviously in a comparison with that in 2003.Then the symmetry of temperature distribution and the stability of the permafrost table continued till 2013. All these characteristics proved that different thickness of the crushed rock layers on the two slopes have performed satisfactorily in improving the symmetry of the ground temperature distribution. Meanwhile, the temperature of shallow ground (with a depth from −3 to −5 m) under the embankment decreased gradually. However, it should be noted that the deep permafrost was in a slow warming trend, shown by the disappearance of the −1°C isotherm.

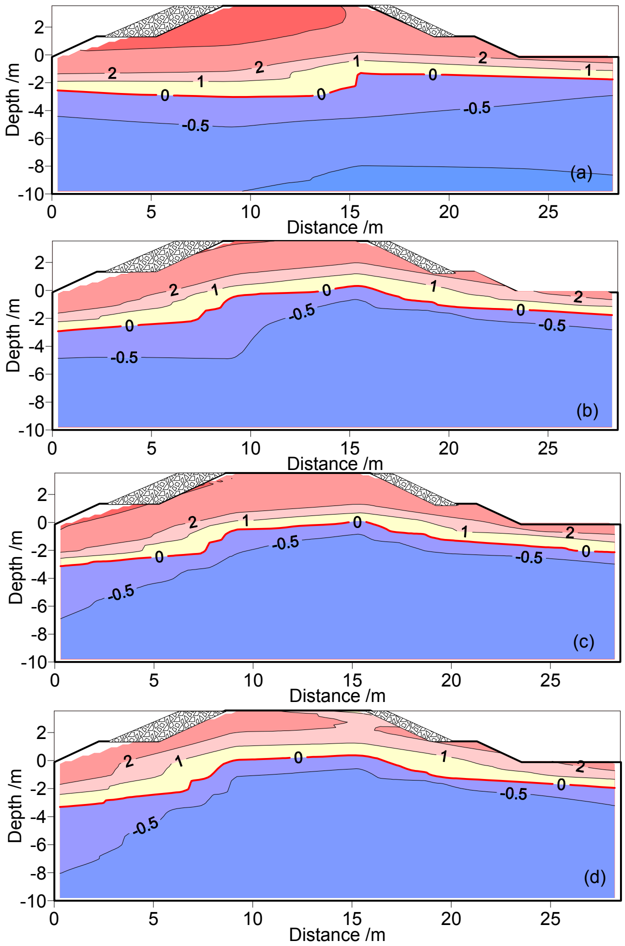

Figure 4. Temperature fields of the CRSE in october at different years as (a) 2003, (b) 2006, (c) 2010, and (d) 2013.

For the UCRE, as shown in Fig. (5), the ground temperature field had been basically symmetrical by 2004, and the permafrost table had been elevated to the original ground surface. This thermal condition has been maintaining up to 2013. Moreover, what differentiates the temperature field of the UCRE from the CRBE and CRSE is that there was a core with temperature lower than −1°C occurred in the shallow permafrost under the right shoulder of the embankment in 2006. Then this "cold core" developed and its extent expanded steadily, covering most part under the embankment except that under the left part horizontally, in 2013. Such characteristics proved that the UCRE not only has remarkable effects in adjusting symmetry of the permafrost table and the temperature field, but also take a very positive action in decreasing the underlying permafrost temperature. Therefore, the UCRE has the most efficient "active cooling" effects.

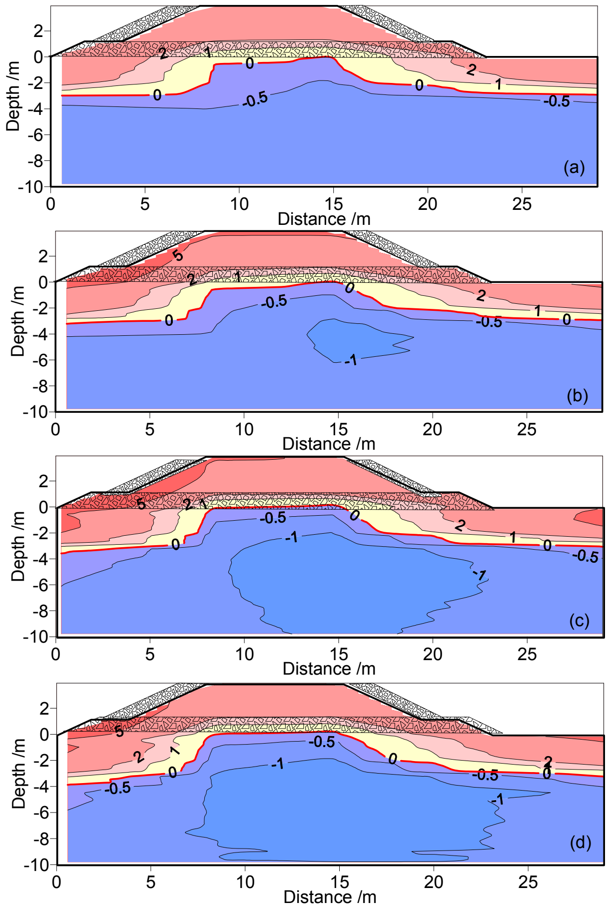

Figure 5. Temperature fields of the UCRE in october at different years as (a) 2004, (b) 2006, (c) 2010, and (d) 2013.

For further investigation of dynamic variation of permafrost temperatures, Fig. (6) was drawn to show permafrost temperatures variations with depths of 5 m and 10 m beneath left shoulders and right shoulders of different structures. The depths labeled in the figures were measured from the original ground surface, which represented the shallow and deep permafrost, respectively. As shown, there were significant differences in permafrost temperature variations under different embankment structures.

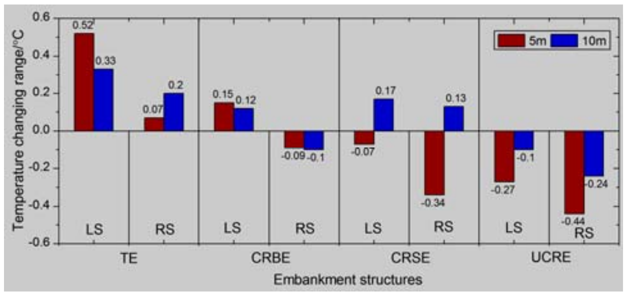

Figure 6. Variation range of permafrost temperatures at 5 m and 10 m under the two shoulders with different structures. (LS-left shoulder; RS-right shoulder).

For the CRBE, permafrost temperatures at depths of 5 m and 10 m were in a warming trend under the left shoulder but in a cooling process under the right shoulder, and this could explain the serious asymmetry of temperature distributions within and beneath the CRBE. For the CRSE, permafrost at 5 m depth experienced a cooling process. However, deep permafrost temperatures at depth of 10 m under both shoulders were rising slowly, with increases of 0.17 °C and 0.13 °C, respectively. It can be inferred that the CRSE could not produce cooling effects strong enough on the deeper permafrost. For the UCRE, the ground, including the shallow and deep permafrost, under the two shoulders all had obvious decrease trends. During the period from 2004 to 2013, the mean annual temperature of the shallow permafrost decreased 0.27°C under the left shoulder and 0.44°C under the right shoulder, respectively. Generally, in order to prevent potential thaw settlement of embankment caused by melting of the ground ice, the permafrost table under the embankment should be maintained or upraised after construction. From this point, the basic thermal stabilities of the three type's crushed rock embankments could be guaranteed due to the obvious uprising of permafrost tables in the 10 years' monitoring period. However, their long-term stabilities cannot be ensured considering future climate warming, due to the permafrost warming under the CRBE and CRSE, as discussed above. Among the 3 structures, the UCRE showed significant cooling effects and symmetrical temperature distribution, it can be thus inferred that the UCRE has the capability of defending against the impacts of climate warming and can ensure its long-term stability.

B. *Freeze-Thaw Process Of The Monitored Embankments*

The temperature distribution within and beneath an embankment is the performance at a fixed time during the freeze-thaw process. Thus, an analysis of the freeze-thaw process was necessary to investigate the cooling characteristics of different embankment structures. Fig. (7) shows variations of soil temperatures with time and depth in the left shoulder boreholes of the monitored embankments.

Firstly, for the CRBE, the thaw depth (0°C isotherm) under the left shoulder showed an increasing trend before 2007 and then decreased gradually near to the original ground surface up to 2013 and the largest thawing depth CRBE were 7.8 m, which was 2.4 m below the original ground surface. However, for the CRSE and UCRE, there was no increasing trend in the thaw depths since the embankments were constructed. The thaw depths under the left shoulders, especially for the UCRE, decreased quickly in the initial years and kept stable above the original ground surface since 2009, indicating that after 5 freeze-thaw processes, the thawing process in the warm seasons only occurred in the interior of the embankments but not permeated into the natural ground.

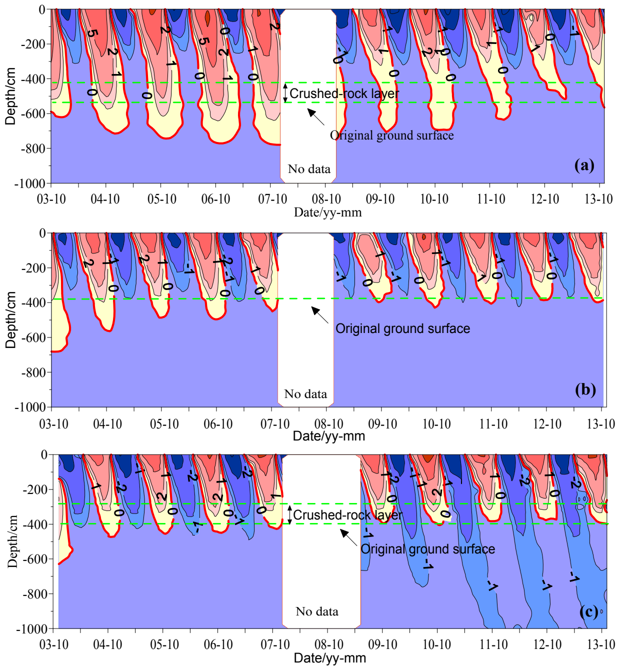

Figure 7. Freeze-thaw processes at the left shoulder boreholes of different structures. (a) CRBE; (b) CRSE; (c) UCRE.

Secondly, differences in seasonal freezing depths (with an example of −1.0°C isotherm) were observed in different embankment structures. For the UCRE, the depths of−1.0°C isotherms from the freezing process under the left shoulder was below the original ground surface, and showed significant downtrends, which means that seasonal freezing depths had reached into the shallow permafrost and deepened gradually, indicating that the shallow ground near the original permafrost table beneath the UCRE had obvious cooling process. However, for the CRBE and CRSE, there was no obvious deepening of seasonal freezing depths occurred in the left shoulders, and depths of the −1.0°C isotherms were all above the original ground surface, meaning that the strong freezing process from cold seasons did not permeate into the original ground. In the comparisons, freeze-thaw processes under the sunny shoulders differed significantly with embankment structures. The UCRE showed the best effects in controlling the seasonal thawing and freezing depths and all these characteristics were very beneficial to its long-term thermal stability.

IV. Conclusions

Our analyses on cooling effects and characteristics of crushed rock embankments with three different structures led to the following conclusions:

1. All the three types of crushed rock embankments have the active cooling effects on the underlying permafrost but cooling characteristics vary significantly with different structures. Obvious asymmetries existed in the ground temperature field within the CRBE, indicating thermal regime of this structure was disadvantageous for its thermal stability.

2. The ground temperature fields of both the CRSE and UCRE were well symmetrical. However, the UCRE gave better thermal stability than the CRSE because slow warming of deep permafrost was observed under the CRSE, indicating the cooling effect of CRSE was relatively limited. The UCRE, as a combination of the CRBE and the CRSE, had the best effects in both reducing the ground temperature and maintaining the symmetry of the embankment temperature distribution.

3. In general, we confirmed that the roadbeds constructed under a principle of cooling-roadbed are long-term effective thereby minimizing the effects of thaw subsidence. It is helpful in providing references for future's improved engineering design and maintenance of roadbeds in permafrost regions.

This paper is a one-hour lecture on the topic of fault current limiter presented to engineering students. The lecture has started with the causes and effects of fault on power systems. The traditional ways of fixing fault current have been described. The detailed analysis of two types of fault current limiters: based on magnetic materials and high temperature superconductor materials have been presented. With some modification (elimination of mathematical part) the lecture can be presented to general public.

Conflict Of Interest

The authors confirm that this article content has no conflicts of interest.

Acknowledgment

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