Cold Regions Science and Technology 145 (2018) 14–20

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Field experimental study on long-term cooling performance of sun-shaded embankments at the Qinghai-Tibet Railway, China

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ARTICLE INFO

Keywords:
Permafrost
Qinghai-Tibet Railway
Sun-shaded embankment
Cooling performance

ABSTRACT

Sun sheds were once used as an effective roadbed cooling technique in permafrost regions. Numerical and indoor-experiment results have confirmed the cooling effects of the sun-shaded embankments, but field-monitored data are still necessary to evaluate their long-term performance. This paper discusses the cooling effects of a sun shed over a section of the Qinghai-Tibet Railway embankment, by examining near-surface air and ground temperatures and the permafrost table depth at the shaded section, at an unshaded embankment section, and in surrounding natural ground. Monitoring results from 2006 to 2010 indicate that the sun shed has lowered near-surface air temperatures and underlying permafrost temperatures beneath the embankment, and promoted permafrost aggradation. The estimated annual heat budget of the permafrost beneath the sun-shaded embankment section has been negative over the past nine years, indicating the sustained cooling performance of the sun shed. This study confirms the utility of sun sheds as an effective design and maintenance concept for infrastructure embankments in warm permafrost regions, provided that the structure can resist harsh environmental conditions.

1. Introduction

The construction of roadbeds in permafrost regions significantly disturbs the ground surface energy balance, which may cause permafrost degradation under the embankment. Qinghai-Tibet Railway (QTR) crosses about 550 km of continuous permafrost. About half of the route overlies permafrost with a mean annual ground temperature (MAGT) above -1 °C, and permafrost is ice-rich along approximately 40% of this distance (Cheng, 2005). Climate warming is causing permafrost to degrade on Qinghai-Tibet Plateau (QTP) (Jin et al., 2008; Wu et al., 2004), and resulting changes to the mechanical strength and load-bearing capacity of underlying permafrost will affect the stability and long-term safe operation of the railway (Batenipour et al., 2013; Doré et al., 2016; Ma et al., 2011). Crushed rock (air convection) embankments, duct-ventilated embankments, sun sheds, and thermosyphons have been used to promote ground cooling and ensure roadbed stability (Cheng et al., 2008; Niu et al., 2006; Wu et al., 2008; Yu et al., 2017). Except for sun sheds, the performance of these structures has been widely validated by field experimentation in operational projects (Ma et al., 2008; Niu et al., 2015; Zhang et al., 2008, 2011).

Sun sheds were first tested along the Siberian Railway, and were found to effectively protect permafrost and increase embankment stability (Kontratjev, 1996). A shading board formerly installed on the embankment slope of QTR at the Beiluhe test section also successfully cooled the underlying permafrost (Yu et al., 2008). However, the strong winds and ultraviolet radiation on the QTP degraded and destroyed the shading board after several years. Laboratory test results indicate that sun sheds may significantly reduce frost heave and thaw settlement of the roadbed, thereby improving safety conditions (Feng et al., 2006). Numerical simulations have also suggested that a sun shad can protect permafrost from thawing (Feng et al., 2006). The largest difference in thaw depth observed on an embankment under a sun shed and in an adjacent unprotected section was approximately 0.9 m (Ling, 1999). Niu et al. (2010) performed field experiments on QTR to evaluate the cooling effects of an operational sun shed. Short-time results indicate that shading can effectively protect the underlying permafrost from thaw (Niu et al., 2010). However, long-term field monitoring data on sun shed performance are limited. An assessment of the long-term embankment thermal regime is essential for evaluating the engineering efficiency and applicability of shading structures.

The sun shed in this study had an imbricated steel structure, which can withstand the harsh environment on the QTP. This study analyzes

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http://dx.doi.org/10.1016/j.coldregions.2017.09.010
Received 15 May 2017; Received in revised form 7 September 2017; Accepted 20 September 2017

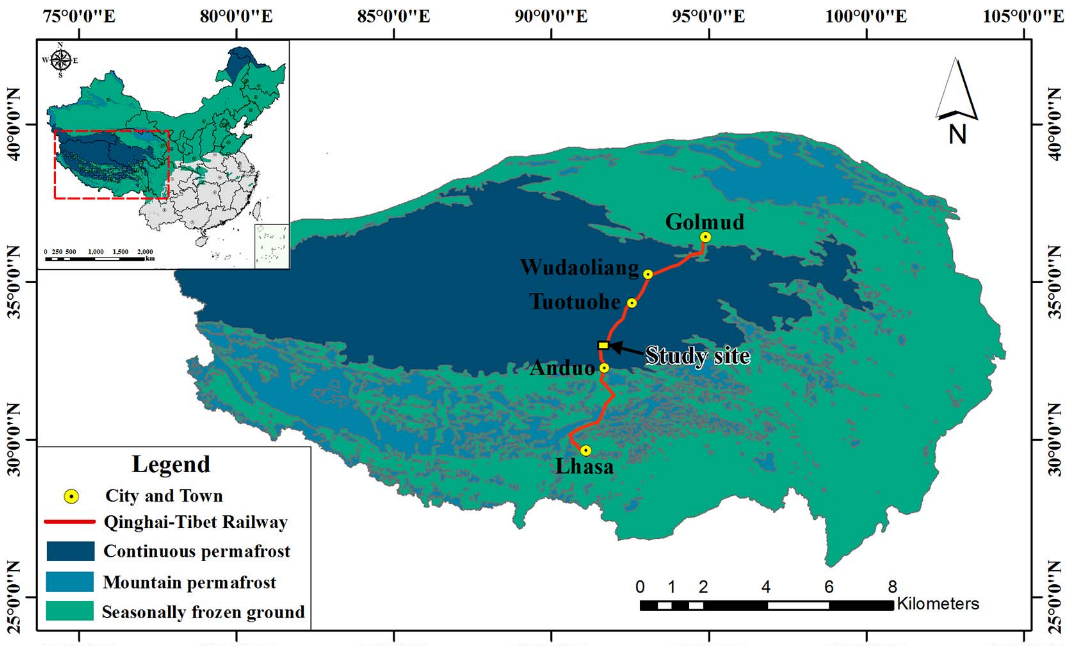

Fig. 1. Location of the study site in the continuous permafrost zone of the QTP.

the long-term thermal regime of the embankment under the sun shed and evaluates its sustained cooling performance using nine years of ground temperature measurements.

2. Study area and monitoring program

The monitored sun-shaded embankment is located in the uninhabited land of the Tangula Mountain at 4934 m above sea level, in the hinterland of the QTP (Fig. 1). Permafrost under the embankment is warm, with a MAGT of − 0.4 °C. The active-layer thickness is 4.4 m in the surrounding undisturbed ground and 3.0 to 5.5 m under the railway embankment. The surficial sediments consist of 8–14 m of Quaternary Holocene powder and gravel soil underlain by Jurassic limestone. The location of the 100-m long monitoring section along the railway is at K1384 + 010 to K1384 + 110.

Two monitoring sections were established in October 2006. The first was near the middle of the sun shed, and the second was 50 m from the end of the structure on an unshaded embankment section (Fig. 2a). Three 20-m deep boreholes were drilled along section No.1, and two 20-m deep boreholes were drilled along section No.2 (Fig. 2b and c). Thermistor cables were installed in each borehole. The thermistor spacing on the cables was at 0.5 m intervals from the surface to 10 m depth, and at 1 m intervals from 10 to 20 m depth. The thermistors were manufactured and assembled by the State Key Laboratory of Frozen Soil Engineering and had a precision of ± 0.02 °C. Temperatures were recorded twice a month by a CR3000 data logger (Campbell Scientific Inc., USA). Ground temperature measurements commenced in December 2006.

Three air-temperature measurement stations (A1 to A3) were arranged along section No.1. A1 was in natural ground far away from the sun shed; A2 and A3 were located outside and inside of the sun shed, respectively (Fig. 2a). Each air temperature station included nine sensors at heights between 0.1 and 1.5 m from the ground surface. Air temperatures were recorded every 30 min, beginning in December 2006, on a DT500 data-logger powered by a solar panel attached to a 12 V rechargeable battery.

3. Results and analysis

3.1. Air temperatures inside and outside the sun shed

3.1.1. Mean annual air temperature

The mean annual air temperatures (MAAT) from 2006 to 2016 at different heights in natural ground (A1), near the sun shed (A2), and inside the sun shed (A3) are shown in Fig.3. The air temperature in natural ground was significantly higher than inside the sun shed due to the greater incident solar radiation outside the structure. The difference in air temperature between the inside of the sun shed and the natural ground decreased with height, so that the maximum difference was near the ground surface at heights of 0.1–0.3 m. The MAAT in natural ground decreased with height, while the air temperature inside and near the sun shed varied little with height (Fig. 3). The MAAT near the natural ground surface was approximately 1 °C higher than at heights > 1.0 m, while the difference inside and near the sun shed was < 0.5 °C.

The sun shed reduced the amount of incident solar radiation, naturally resulting in lower air temperatures within the structure. In addition, the effect of shading was most pronounced near the ground surface due to increased convection and mixing at greater heights in the sun shed. These results highlight the cooling effect of the sun shade, particularly near the roadbed surface.

3.1.2. Daily air temperature

Mean daily air temperatures at 0.1 m height were calculated in both the warm season (August) and the cold season (January) to investigate daily air temperature variation inside and outside the sun shed. The greatest difference in air temperature between the natural ground and the sun shed occurs from 7:00 to 16:00 in the warm season (A in Fig.4a). The maximum air temperature difference recorded in this period was 5.4 °C and occurred at 12:00. Daily air temperature variations in the cold season exhibited nearly the same trends as in the warm season (Fig.4b). The greatest temperature differences between inside and outside of the sun shed occurred from 7:00 to 14:30, with the maximum value of 4.5 °C at 11:00, slightly lower than in the warm season (B in Fig.4b). Therefore, in both summer and winter, temperature differences between the sun shed and outside occurred during the