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Analysis of asymmetric temperature fields for the duct-ventilated embankment of highway in permafrost regions

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ABSTRACT

The heat capacity and polythermal effect of highway roadbeds with wide asphalt pavements have become increasingly significant, which causes their influences on engineering and permafrost issues to become prominent. A duct-ventilated embankment is a potential mean to proactively cool ground temperatures. This method is applied experimentally in a highway for the first time. According to a field testing in the Tibetan Plateau Highway Pilot Project, a duct-ventilated embankment has excellent cooling effect. The mean annual ground temperature reduction at the embankment/natural ground surface interface is 1.62 °C. The mean annual temperature difference between the south- and north-facing slopes reaches 2.39 °C. This difference results in the asymmetry of the underlying temperature field and longitudinal roadbed cracking. The asymmetric distribution of the duct-ventilated embankment temperature field is caused by differential sun exposure and the heat transfer process and intensity within the duct. Differential sun exposure is a major factor between the south- and north-facing sides, accounting for 84%, whereas the remaining 16% is ascribed to the different heat transfer processes within the duct. The amount of asymmetry is increased to 20% by the duct and slightly accentuated by the ventilation duct. To avoid this effect, future projects should focus on solving problems related to roadbed direction and the effect of slope temperature difference on ground temperature. Measures are recommended to be taken to regulate both slope temperature adjustment and ventilation ducts, and thus, effectively combine the advantages of both measures in embankment design.

1. Introduction

Heat transfer between the land and the atmosphere in permafrost regions is a major factor that influences the geothermal field through surface thermal boundary condition. A considerable temperature difference may form between the south- and north-facing slopes after embankment construction (Zhang et al., 2011). The mean annual temperature of shallow strata in the south-facing slope can be over 3 °C higher than that in the north-facing slope. Such difference forms an asymmetrical distribution of the temperature field in the underlying soil layer of the embankment, which results in certain potential hazards, such as the non-uniform lateral deformation of the embankment (Sheng et al., 2005). A survey conducted on the roadbed cracking defects of the Qinghai–Tibet Highway (Dai et al., 2006) presents the following results.

1) Longitudinal cracking of the roadbed in permafrost regions is closely related to solar radiation.
2) The number of longitudinal cracks on the south-facing side of the roadbed accounts for 78% of the total number of cracks, whereas the total length of longitudinal cracks on this side of the roadbed accounts for over 75% of the total crack length.
3) Longitudinal cracking is the most severe damage on road sections along the north–south direction.
4) Longitudinal cracking of the roadbed is the second most prevalent type of roadbed defects, ranking below roadbed subsidence.

The major influencing factors of longitudinal cracking are roadbed direction and embankment height, solar radiation, and wind velocity and direction (Dou et al., 2002; Li, 2001). To minimize or eliminate the influences of these factors, a geotextile has been laid on highways in permafrost regions in Alaska, USA to enhance the mechanical stability of the roadbed (Savage, 1991). Meanwhile, related measures, such as the application of duct-ventilated embankment, crushed-rock revetment, sunshields, and heat pipes, have been used to maintain roadbed stability by adjusting the temperature fields of embankment slopes, embankments, or roadbeds (Niu et al., 2003; Sun et al., 2006; Yu et al., 2005, 2007a; Hayley et al., 1983; Lepage et al., 2010).

A duct-ventilated embankment is an engineering technique that uses ventilation ducts buried horizontally at a certain depth within an

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embankment to connect with the atmosphere. Ventilation ducts are typically perpendicular to the subgrade direction. Thus, permafrost temperature below the embankment can be adjusted via convective heat transfer between ducts and soil. Some studies on this approach via indoor physical model tests, in situ engineering tests, and numerical simulations have been conducted in the Qinghai–Tibet Railway. The results of these studies indicate the following findings: 1) Enhancing the thermal stability of a roadbed by using a duct-ventilated embankment is technically feasible (Niu et al., 2002; Yu et al., 2002; Lai et al., 2004). 2) Various factors, such as the diameter of the ventilation duct, buried depth, and duct spacing, considerably influence the cooling effect of duct-ventilated embankment (Niu et al., 2006a, 2006b; Li et al., 2005). Effective cooling can be achieved under certain circumstances, such as a large duct diameter and shallow buried depth of ventilation ducts. In addition, the lateral asymmetry of the temperature field of the lower soil layer can be improved. 3) Small ventilation duct spacing improves cooling effect. Given that the main source of heat absorption for an embankment with a gravel road surface originates from the slope, temperatures at the two sides of the embankment remains distributed in an asymmetrical manner (Niu et al., 2008). With the planning and development of highway construction in western China, the increased width of high-grade asphalt highways will inevitably increase the risk of severe hazards because of stronger permafrost degradation compared with that in current highways. Previous research was mostly conducted using the Qinghai–Tibet Railway as the basis. However, essential differences exist in boundary conditions, heat transfer processes, and heat transfer strengths between roads and railways (Yu et al., 2006). An investigation of heat transfer processes in a duct-ventilated embankment (Yu et al., 2007b) showed that the mean annual heat release per meter of roadbeds at 0.5 m below the ventilation duct was 469 J/(m·h) for gravel pavements, whereas the heat release for asphalt pavements was only 96 J/(m·h). Considering climate warming and inappropriate design, current engineering measures are likely to be ineffective for asphalt pavements. For a wide, high-grade asphalt highway, the convective heat transfer efficiency of a ventilation duct will be reduced to a certain degree because of the increase in heat absorption at the roadbed center. In addition, the increased length of a ventilation duct further aggravates the problems in the use of such structures in wide, high-grade asphalt pavements. Based on practical engineering applications, this study describes the analyses of the following issues: (1) the cooling effect of a duct-ventilated embankment under strong endothermic conditions; (2) the influence of increased subgrade width on embankment thermal boundary conditions, ventilation duct temperature change, airflow characteristics, and ground temperature distribution features; and (3) the engineering problems arising from such influences. Researching and analyzing these issues are of critical for effective decision making and for prioritizing research related to highway construction in permafrost regions in China.

2. Test field and observations

The duct-ventilated embankment for the test road of the Chinese Academy of Sciences (CAS) was completed in August 2009. This road is located at the Beilu River Experiment Base of the State Key Laboratory of Frozen Soils Engineering (SKLFSE)–Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), CAS (34°49′N, 92°54′E), in the open area between the Qinghai–Tibet Highway (K3056 + 500) and the Qinghai–Tibet Railway. The mean annual air temperature is −3.8 °C. The freezing and thawing indices are 2131 °C. d and 903 °C. d, respectively. The mean annual wind velocity is 4.1 m/s. The prevalent wind direction is northwest. Geographical features include the south Beilu River Basin and piedmont alluvial highland plains. The highland meadow area is relatively flat with a slight topographic relief and a vegetation coverage of 70%–90%. Soil sampling shows that the moisture content of the test subgrade seasonal active layer is approximately 18%. The permafrost table is approximately 2.0 m. A 1.0–5.0 m soil-bearing ice layer is present near the permafrost table. The ice volume is over 80%. The surface is covered by a 20–30 cm layer of thick highland vegetation, with mostly silty sand and silty clay at a depth of 10 m below the surface. The layer below this layer mainly consists of intensely weathered reddish brown mudstone. The mean annual ground temperature ranges from −1.0 °C to −0.5 °C. The test result is highly representative because the area is located in a typical permafrost region with a high ice volume and warm ground temperature on the Qinghai–Tibet Plateau.

The test roadbed is directed 20° north of east, with clearly defined south- and north-facing sides as shown in Fig. 1 (The south-facing side is located on the left of the embankment when facing the direction of Lhasa, whereas the north-facing side is located on the right). The distance from the center of the ventilation ducts to the natural ground in the embankment is 120 cm. The ventilation ducts are open-ended, and their diameter is 40 cm. Temperature probes were arranged at the center and on the wall of the ventilation ducts, the roadbed center, the left and right shoulders, and the left and right slope bases. The spacing

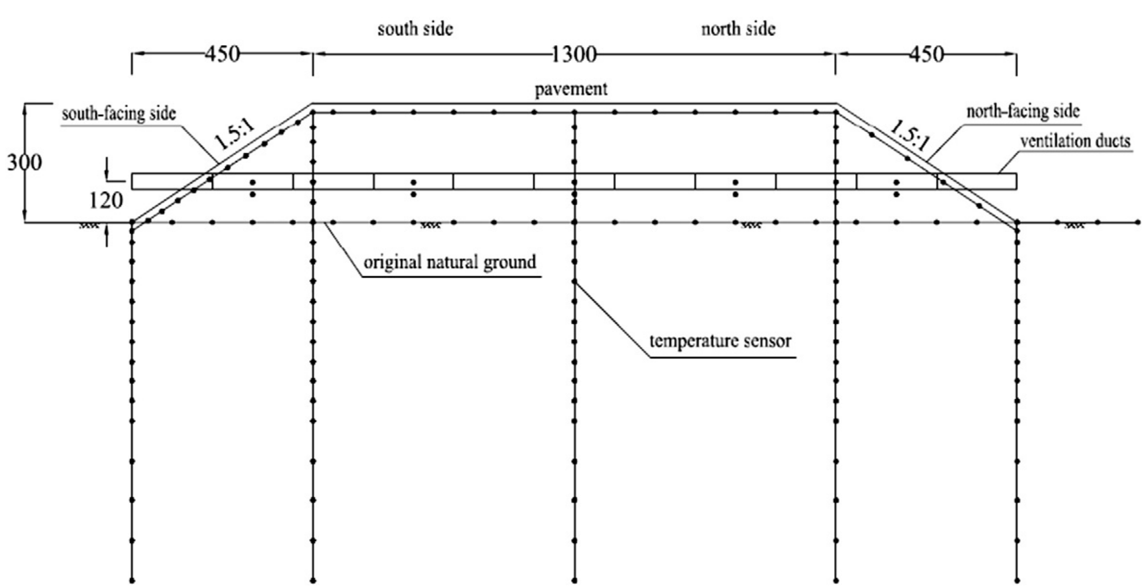

Fig. 1. Diagram of the test roadbed design and the roadbed temperature observation system (unit: cm).