1 INTRODUCTION

The Qinghai-Tibet railway is the longest railway at high altitude in the world. It runs from Xi’ning, the capital of Qinghai province, to Lasha, the capital of the Tibet autonomous district, China. The total length of the line is 1,959 km, of which 841 km has been completed (between Xi’ning and Golmud) and the remaining section (from Golmud and Lasha) is 1,118 km long and crosses the hinterland of the Qinghai-Tibet high plateau. Of this section, 630 km’s of railway line will cross permafrost with mean annual air temperature of $-7$ to $-2^\circ$C. The high altitude of the plateau means that there is a large-area of permafrost, which causes many engineering difficulties to railway construction. These problems include subsidence, frost heave, underground ice and debris flow caused by melting ice. Under the influence of both global warming trends and engineering construction, thaw settlement might occur, leading to destabilization of the railway roadbed and failure of the structure. The most hazardous damage is due to degradation of the permafrost and thawing settlement of the roadbed. In fact, most failures of railway roadbeds in permafrost regions are due to the degradation of permafrost caused by engineering influences. For example, about 70% of roadbed deformations along the Baikal-Amur railway are due to the degradation of permafrost (Belozeroz 1993).

Presently, two engineering principles are applied in preventing the deformations caused by the degradation. The first one is to protect the frozen soil, and the other one is to pre-thaw the frozen soil (Cheng 2001). Currently, the Qinghai-Tibet railway is mainly required to be constructed under the first principle. Proposed methods include the following: using a crushed stone roadbed, constructing a railway-bed on insulating layers, making a reserve by increasing the roadbed width and height, and ventilating the roadbed. Among these methods, the first three are passive to prevent the degradation, needing too much cost for construction and maintenance. These methods are also aimed at overcoming the consequences of existing permafrost degradation (Kondratjev 1996). Ventilating the roadbed is an active method to remove heat from the ambient soil, so that the primary permafrost table can be kept stable or even raised.

Though roads and tunnels have been constructed on the high plateau and relative temperature calculations have been done (Li & Wu 1998, Lai et al. 1999), there is no experience of constructing railways on such high altitude land, especially when the railway crosses ice-rich or high-temperature permafrost regions. To obtain basic knowledge and initial data of ventilation of the roadbed and due to the tight time schedule of field-testing projects, laboratory studies have been pursued in advance of fieldwork. The main object of the experiments is to compare the temperature distribution in the roadbed with and without ventilation ducts, and to analyze the ventilation effect.

The ventilation method is widely used in the construction of garages, warehouses and storage tanks in permafrost. In the past, two methods of construction have been adopted. One is to install open-ended ducts in the pad or roadbed, oriented in the direction of the prevailing winds (Nixon 1978). Another one is based on the chimney effect, to induce air movement in stacks connected to the ventilation ducts (Tobiasson 1973). As it is very windy on the Qinghai-Tibet high plateau, the roadbed with an open-ended ventilation duct is studied in this paper.
VENTILATION ROADBED MODEL

The experiment consisted of five parts. They are the model box, the cooling system, the wind system, the model soil body and the monitoring system. Each of them is introduced below.

The inner dimension of the model box is 8.0 m long, 1.84 m wide and 2.7 m high, and it is constructed from a 10 cm thick insulation plate. The box was reinforced with a steel frame on the outside, so that the wall can resist the vertical and lateral soil pressure during soil compaction.

The cooling system consists of a refrigerating machine and cooling pipes. Cooling media is compressed and delivered to fans in the model box. The air temperature in the box can be controlled automatically between −30 and 40°C.

The wind system consists of cooling fans, heaters, a wind-speed-controlling sheet, a wind-direction-adjusting shutter and an air-returning tunnel. The air-returning tunnel is used to recycle air in these experiments. Wind speed in the box can be set freely in the required speed range during the experiments, and the prevailing wind direction is set parallel to the long side of the box and is vertical to the extending direction of the model roadbed. In the experiments, the air temperature is about 7 to 5°C and the wind speed is 2 m/s during the freezing period and 18–20°C during the thawing period.

As the purpose of the experiments is to determine temperature distributions of the roadbeds with and without ventilation ducts, and extracting massive insitu soil samples is difficult, the soil mass used in the experiments is loess from Lanzhou. Physical parameters of the soil are tested for use in further calculations, and these are listed in Table 1. Two types of sample bodies are constructed in the experiments, one is a normal railway roadbed and the other is a ventilation roadbed. Each of the models is 2.0 m thick, 5.8 m wide at the bottom, 2.2 m wide at the top and 1.84 m long, which is nearly 1/4 scale of the real roadbed of the Qinghai-Tibet railway.

Table 1. Physical parameters of the experimental soil.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ranges of values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry density</td>
<td>1.46–1.50</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Water content</td>
<td>12.9–13.6</td>
<td>%</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.833(23°C)–0.947(−6°C)</td>
<td>W/m°C</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>1.47(23°C)–2.0(−6°C)</td>
<td>×10⁻¹⁸m²/h</td>
</tr>
<tr>
<td>Specific heat</td>
<td>1.27(23°C)–0.99(−6°C)</td>
<td>kJ/kg°C</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>2187(23°C)–1705(−6°C)</td>
<td>kJ/m³°C</td>
</tr>
</tbody>
</table>

Air temperature, soil temperature, soil deformation and wind speed were monitored in the experiments, with thermal sensors, displacement sensors and anemometer respectively. Data were collected every 20 minutes by a DATATAKER 500, and then transferred to a computer for subsequent analysis.

RESULT OF MODEL EXPERIMENTS

3.1 Experiment No. 1

In experiment No. 1, compacted loess and crushed stone were used. The soil model is 1.5 m thick, 5.8 m wide at the bottom, 2.8 m wide at the top and 1.84 m long, and a 0.5 m thick crushed stone covers it. The model is frozen under −7 to −5°C for 480 hours, and then thawed for 240 hours. Two temperature monitoring transects, named A and B, are put in the model. Section A is located along the central section of the body and section B is 0.50 m away from the center.

3.2 Experiment No. 2

The model soil body in experiment No. 2 is the same size as in No. 1, while a 4.8 m long duct, with an inner-diameter of 0.28 m was put in the soil body at a height of 0.5 m above ground level. The two monitoring sections are the same as in experiment No. 1. The soil is also frozen for 480 hours and then thawed for 240 hours.

Five deformation monitoring sensors are placed on the surface of the soil models. According to the monitored data, the maximum frost heave is only 3 mm.

3.3 Experiment results

3.3.1 Temperature changing process

A total of 60 thermal sensors are used in the experiment to monitor temperature, four of them are located at critical positions in the soil body (Fig. 1). The sensors at positions P1 and P2 are used to represent the effect at the initial ground surface (the bottom of the soil body is insulated in the experiments); the sensor

![Figure 1. Four typical temperature-monitoring positions.](image-url)
at P3 indicates the temperature at the center of the soil body; and P4 measures the temperature at the surface of the soil body below the crushed stone layer. The soil temperatures are shown in Figure 2 at the four sensor positions for a total 740 hours.

Figure 2a clearly indicates that temperatures dropped from 12.4°C and 12.1°C to 12.4°C and 12.3°C, respectively at positions P1 and P2 after 120 hours of freezing in experiment No. 1. While in experiment No. 2 (Fig. 2b), the changes are from 15.5°C to 10.6°C and 15.6°C to 11.3°C, respectively.

The values show the differences between the changing ranges in the two experiments. In addition, although the initial temperature values of the soil in experiment No. 2 are about 3.0°C higher than those of experiment No. 1, they are more than 1.0°C lower than these in No. 1 only after 120 hours of freezing. Another phenomenon is that the differential temperature value between the two experiments at the same position of P1 and P2 increases with time during the first 240 hours (3.1°C at P1 and 2.5°C at P2) and then decreases. After another 240 hours, the difference between the two experiments at P1 and P2 is 2.4°C and 2.1°C, respectively.

The difference between the two experiments reaches 3.9°C after 120 hours of freezing at position P3, and even extends to 4.0°C after the next 120 hours. This means that the temperature difference is more distinct, and the temperature changes at P1, P2 and P3 indicated that ventilation duct can cool the roadbed soil body down more quickly than the normal roadbed structure does. At the beginning of the freezing time, the cooling velocity is high and then it decreases slowly.

The surface temperature of the model soil in the two experiments is nearly 2°C different at P4 at the beginning of the experiments, but soon they tend towards the same value. After 20 days of freezing, the differential value between temperatures at P4 in the two experiments is only 0.11°C. This shows that the surface temperature is mainly controlled by the air temperature and is not related to the presence of a ventilation duct.

In general, the different freezing processes of the soils in the two experiments show that it is much easier to lower soil temperatures in a ventilated roadbed than a normal roadbed, especially during the earliest periods of freezing time. Therefore a ventilated roadbed could be efficient in protecting the thermal state of the original frozen ground and even consume heat from the ground.

The temperatures at the four positions in the two experiments are also different during the thawing period. Although the temperatures of the soil bodies are different at the beginning of thawing, after 240 hours of thawing, the temperatures in the two experiments are nearly the same. This indicates that if ventilated roadbeds were to be adopted for construction of the Qinghai-Tibet railway, the ducts should be closed in warm seasons, or some other measures should be used to prevent thawing from occurring quicker than for an unventilated roadbed.

3.3.2 Temperature field distribution

As temperature distribution of the two sections of experiment No. 1 is nearly similar, only one of them has been compared with the two sections of experiment No. 2. Figure 3 shows the initial temperature distributions in the soil body of the two experiments. Although temperatures in the soil bodies are uneven (12–17°C), the general temperature conditions of the two can be considered to be more or less the same. This means that the experiments are started under similar conditions, except that the temperature difference at the bottom of the two soil bodies. The temperature at the bottom of the soil body in experiment No. 1 is 12.1–12.4°C, while that of experiment No. 2 is 15.4–15.6°C.

Figure 4 shows temperature distributions of the three sections after 240 hours of freezing. Figure 4a indicates that the freezing front (0°C line) in the model body of experiment No. 1 extends to the depth of 63 cm, while that of experiment No. 2 reaches 76 cm below the top surface (Fig. 4b). In section A of experiment No. 2, the whole part above the ventilation duct and about 2/3 of the whole soil body would have been frozen (Fig. 4c). The temperature at the bottom of the soil body of No. 1 decreases to 9.6–9.7°C while
that of No. 2 decreases to 6.5–7.2°C: the difference is clearly apparent. On the other hand, Figure 4 also indicates that the uneven phenomena of temperature distributions in experiment No. 2 is more distinct than those in experiment No. 1, which means that the most possible influential factors are the introduction of the duct, as well as the wind direction.

Figure 5 shows the temperature distributions at the end of the freezing period (after freezing for 480 hours). The three figures indicate that in experiment No. 1, the freezing front reached 76 cm below the top surface (Fig. 5a), and 92 cm in section B of experiment No. 2 (Fig. 5b). After 480 hours of freezing, the temperature at the bottom of the soil body of No. 1 decreases to 6.1–6.3°C and that of No. 2 decreases to 3.7–4.2°C. Meanwhile, nearly the whole area of section A of the model body in experiment No. 2 has been frozen (Fig. 5c). This figure provides important information that the ventilated roadbed is much more efficient than the normal roadbed in keeping the soil frozen.

Figure 6 shows the temperature distributions of the model soil bodies after 240 hours of thawing. In section B (Figs 6a, b), the temperatures in the soil of experiment No. 2 are generally lower than in No. 1. The reason for this is that the thawing starts at a different temperature in the two experiments. In section A of experiment No. 2 (Fig. 6c), the general temperature is higher than that in section B of both experiments No. 1 and No. 2. This means that the open-ended ventilation ducts should be closed in warm seasons, otherwise, additional thawing settlement might occur, leading to failure.

The model tests of a single ventilation duct indicate that a ventilated roadbed is efficient in protecting frozen ground from thawing. Based on these results, a 400-meter-long field project has been designed for the Beiluhe region of the Qinghai-Tibet plateau. The climatic character of this region shows that the freezing time is 8 months (from September to April). During this period, the dominant wind direction is NW, and the annual-mean wind speed is 4.1 m/s. These conditions are similar to those of the laboratory experiment. Therefore, the results obtained from the experiments are valuable to the field-testing project, which is currently under construction.

The results of the experiments revealed the temperature distributions throughout the model roadbed. However, the experiments were carried out with only a single wind direction with stable temperature, whereas in a real project, the circumstances would be
much more complex. In future experiments, a variable temperature should be considered so that the real conditions could be modeled more closely.

4 CONCLUSIONS

(1) The temperature distributions in the experiments with and without a ventilation duct indicate that the soil body in a ventilated roadbed is easier to freeze than soil in an unventilated roadbed. After 480 hours of freezing, the temperature at the bottom of the soil body in the ventilated roadbed is reduced by 11.3–11.8°C, while in the unventilated roadbed, it is reduced only by 5.9–6.3°C. Therefore, the ventilated roadbed is efficient in protecting permafrost under a railway roadbed and can even extend it. Such a result is also expected during construction of Qinghai-Tibet railway if ventilated roadbeds are adopted.

(2) The temperature distribution in a ventilated roadbed along a section parallel to the ventilation duct is uneven under cooling wind blowing in a single-direction. Moreover, sections at a different distance from the duct also show a very different temperature distribution. Therefore, uneven frost heave and thawing deformation must be considered in real projects if the soil is frost-susceptible. 

(3) During periods of high temperatures (or in warm seasons), the open-ended ventilation ducts should be closed, otherwise the roadbed will tend to thaw and additional thawing settlement might occur.

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