

Defects and Countermeasures of Highway Subgrade in Plateau Permafrost Regions

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Abstract: This study collects the maintenance history, reconstruction material, and disease data of the Qinghai–Tibet Highway (QTH) over the past 60 years. The QTH is then divided into a stable region, a basically stable region, an unstable region, and an extremely unstable region based on road deterioration rate. Subsequently, 134 km of typical deteriorated sections are selected, and the relations between the road deterioration and the mean annual ground temperature (MAGT), permafrost degradation rate, and ice content are studied based on the survey data. The average road service life is determined in addition. Newly developed diseases and their temporal effects are analyzed using treatment measures. Furthermore, new stabilizing technologies adapted to large-scale permafrost subgrade (e.g., distributed ventilation subgrade, unidirectional heat conduction board subgrade, and integrated pavement-subgrade heat drainage structure) are introduced. The results show that the MAGT, degradation rate of permafrost tables, and ice content are negatively correlated with road service life. Among treatment measures, thermosyphon, rubble and block stone, insulation board, and ventilation duct (in addition to flagstone and block stone) have higher effective rates of heat prevention compared to other measures.

Keywords: permafrost; temporal effect; subgrade defect; field investigation; large-scale subgrade; stabilizing technology

1 Introduction

The Qinghai–Tibet Highway (QTH) is an important material transportation channel in western China; it passes through permafrost regions where the climate is cold, the environment is harsh, and the geological condition is complex. According to data from the Ministry of Transport of the PRC, the QTH crosses 528.5 km of permafrost regions with an altitude ranging from 4000 m to 5231 m. The mean annual air temperature ranges from $-7\text{ }^{\circ}\text{C}$ to $-2\text{ }^{\circ}\text{C}$. The mean annual total solar radiation exceeds $8000\text{ MJ}\cdot\text{m}^{-2}$, which is approximately five times the amount of radiation than average for China. The freezing period is approximately 7–8 months per year. After the construction of asphalt pavement in this area, the permafrost beneath the subgrade continuously degrades into seasonal frozen soil with high

water content because of the heat absorption of the black asphalt pavement. In addition, the repeated freeze-thaw effect weakens the subgrade. In a certain period of time, defects, such as frost heave, tumbling, and thawing settlement, develop and influence the safety and comfort of driving on the highway.

For the problem of road defects in permafrost regions, the existing research results mainly focused on the mechanism of defect occurrence, influencing factors, and constitutive models of permafrost [1–6]. Among these studies, the corresponding treatment measures were proposed based on adjusting the height of the subgrade, active cooling of permafrost, and passive thermal resistance [7–13]. The main factors influencing road defects in permafrost regions and corresponding treatment methods were identified by some research projects [14–17]. Most of the results were adopted by the QTH project. However, several problems,

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such as the time of defects occurrence and the average service life of the subgrade (depending on multiple factors), were only superficially studied. The road defects in permafrost regions had a significant temporal effect, namely, the occurrence and worsening of road defects had a certain periodicity under different conditions with different mean annual ground temperature (MAGT), ice content, and degradation rate of the permafrost table. The road service life was closely related to the above-mentioned factors. Based on both the temporal effect of roadbed defects in permafrost regions and long-term monitoring data along the QTH, the author determined the influence of MAGT, degradation rate of the permafrost table, and ice content on road service life. On-the-spot investigation of the defect status of various special subgrades was conducted, and the applicable conditions and treatment effects were evaluated based on the investigation result.

2 Basic data

Taking MAGT, degradation rate of the permafrost table, and ice content as references, the survey road sections were divided. Among these sections, the MAGT determined whether the permafrost was thawed or not and its sensitivity to changes in air temperature. The degradation rate of the permafrost table was an important index for the stability of the subgrade and the asphalt pavement secondary defects. The amount of ice content in the permafrost beneath the roadbed often determined the severity of road defects after the permafrost table degraded. The relationships between MAGT, degradation rate of the permafrost table, and stability zoning are shown in Table 1. The shares of ice content and different service life sections for different partitions are shown in Table 2.

The time from completion of road construction to the next road maintenance in Table 2 was defined as the defect time period (the service life). The defect time period was divided into five categories, which are <10 years, 15 years, 20 years, 30 years, >40 years. According to the road maintenance and repair time

data, the incidence rate of road defects in each time period was calculated.

3 Analysis of factors in the development of subgrade defects in permafrost regions

3.1 Mean annual ground temperature

To study the influence of the MAGT on the development of subgrade defects, sections of the QTH with MAGT values of $-3\text{ }^{\circ}\text{C}$ to $-0.5\text{ }^{\circ}\text{C}$ with a length of 20 km were selected. According to the annual defect development, the road was divided into stable regions, basically stable regions, unstable regions, and extremely unstable regions, as shown in Fig. 1 and Fig. 2. Among these regions, the service life of maximum probability is referred to as the defect time period of most road sections in the statistical sample, whereas the average service life period is the average time of defect occurrence.

From Fig. 1, Table 1, and Table 2, we see that the subgrade service life of maximum probability continuously decreased with increasing MAGT. In the stable region, where the MAGT was lower than $-3.0\text{ }^{\circ}\text{C}$, the service life of 80% of the road sections exceeded 40 years. When the MAGT was between $-3.0\text{ }^{\circ}\text{C}$ and $-1.5\text{ }^{\circ}\text{C}$, the ratio of road sections with the same service life declined to 35%; the service life of most surveyed road sections was shortened by more than 10 years. When the MAGT was from $-1.5\text{ }^{\circ}\text{C}$ to $-0.5\text{ }^{\circ}\text{C}$, 65% of the subgrade was damaged within 15 years, and the remaining 35% subgrade was not in service for more than 10 years. When the MAGT was from $-0.5\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$, the 80% subgrade service life was less than 10 years. The average service life proposed in Fig. 2 can be calculated from following equation:

$$T = \sum_{i=1}^n \rho \cdot T_i \quad (1)$$

where, T is the average service life, n is the number of time periods (the time period is divided into five parts, i.e., <10 years,

Table 1. Relationships between MAGT, degradation rate of the permafrost table, and stability zoning.

Stability zoning	MAGT ($^{\circ}\text{C}$)	Degradation rate ($\text{cm}\cdot\text{a}^{-1}$)
Stable region	<-3.0	<10
Basically stable region	$-3.0 - -1.5$	10–15
Unstable region	$-1.5 - -0.5$	15–20
Extremely unstable region	$-0.5 - 0$	20–30

Table 2. Proportion of road sections with different ice content and service life in different partitions.

Stability zoning	Ice content				Service life					%
	0–20%	20%–60%	Ice content > 60%	Service life <10 years	Service life 15 years	Service life 20 years	Service life 30 years	Service life >40 years		
Stable region	49	42	9	0	20	0	0	80		
Basically stable region	34	50	16	15	0	10	40	35		
Unstable region	25	32	43	35	65	0	0	0		
Extremely unstable region	16	38	46	80	20	0	0	0		

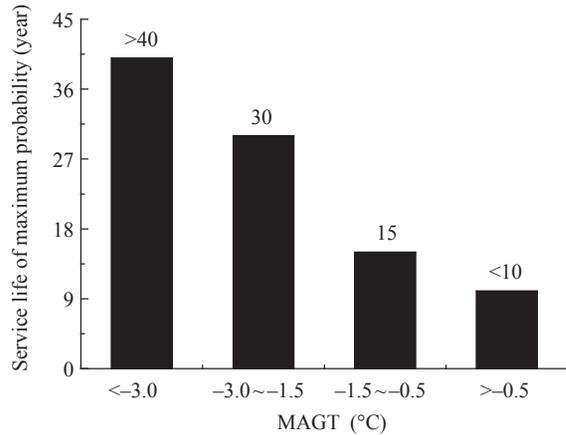


Fig. 1. Relationship between MAGT and service life of maximum probability.

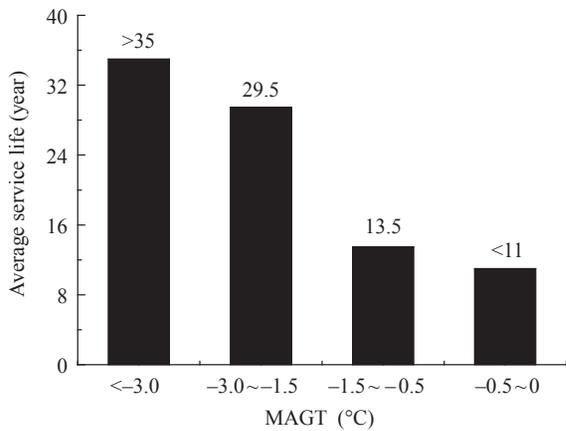


Fig. 2. Relationship between MAGT and average service life.

15 years, 20 years, 30 years, and >40 years), T_i is the time limit of each road segment, and ρ is the ratio of the subgrade length to the total survey length for each time period. According to the calculation, the road average service life was reduced by more than 4 years with a 0.5 °C increase in MAGT. From the analysis of reduced service life, the subgrade temporal effect was the most significant when MAGT changes near -1.5 °C.

3.2 Degradation rate of permafrost table

To analyze the effect of asphalt pavement on the degradation rate of permafrost and determine the impact of degradation rate on the development of roadbed defects, a 69-km-long typical road section was selected along the QTH for investigation. First, the relationship between MAGT and degradation rate of the permafrost table was determined, as shown in Fig. 3. Then, the permafrost table degradation on the probability of subgrade defects was analyzed.

Fig. 3 shows that MAGT was positively correlated with permafrost table degeneration rate. The permafrost table degradation rate was less than 10 $\text{cm}\cdot\text{a}^{-1}$ when MAGT was below

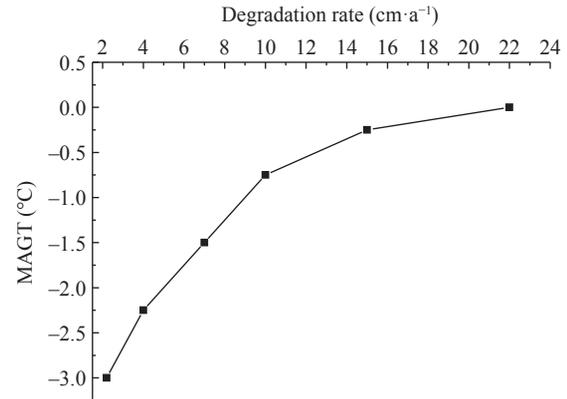


Fig. 3. Relationship between MAGT and degradation rate.

-3 °C (Table 1). The permafrost table degradation rate gradually increased with increasing MAGT; however, the degradation accelerated. The degradation rate only increased by approximately 1.67 $\text{cm}\cdot\text{a}^{-1}$ for a 0.5-°C increase in MAGT within the range of -3 °C to -1.5 °C. Within the range of -1.5 °C to 0 °C, the degradation rate rapidly increased, rising to 5 $\text{cm}\cdot\text{a}^{-1}$ when the ground temperature rose by 0.5 °C. The relationship between MAGT and permafrost table degradation rate showed that a -1.5 °C MAGT was a turning point for the conversion of warm and cold permafrost. When the MAGT of the permafrost was higher than this value, the permafrost table degradation rate accelerated.

3.3 Ice content

In stable regions, the proportion of road sections with an ice layer containing soil was only 9%. However, this proportion rose to 46% in extremely unstable regions, as shown in Fig. 4. The average road service life got shorter with an increased ratio of high-ice-content sections. Specifically, in warm and rapidly-degrading permafrost regions, the ice layer subgrade containing

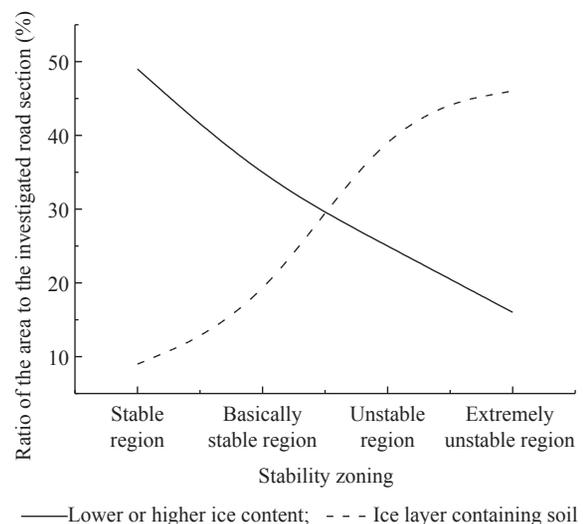


Fig. 4. Relationship between ice content and stability class.

soil typically caused defects within 2 to 3 years after paving the asphalt. Additionally, these regions needed urgent remediation due to serious defects after 5 to 10 years of operation.

3.4 Special treatment measures

To mitigate permafrost subgrade defects and improve subgrade stability, special structural measures (including adding thermosyphon, extruded polystyrene foam (XPS) board, rubble and block stone, and ventilation duct into the subgrades) were used on several damaged road sections during the QTH reconstruction project of 2003. Several new structures that were combinations of two single measures were adopted in certain road sections where geological conditions were poor. This special structure construction was completed in 2003 and ground temperature, deformation, and defects data were monitored for 13 years. To analyze the impact of the special structures on subgrade defects in permafrost regions, ground temperature, deformation, and defect monitoring data for several road sections were collected and analyzed, as shown in Table 3, Table 4, and Fig. 5.

Fig. 5 shows that if no special measure was taken on a road section with poor geological conditions, approximately 80% of road sections would have serious subgrade damage within 2 to 4 years, and that the subgrade would remain unstable after reconstruction. In treatments using thermosyphon, XPS board, rubble and block stone, and ventilation duct subgrades, the effective prevention rate of road defects was between 60% and 80%. Most of the defect cases would be identified within 2 to 5 years after subgrade construction, and defect incidence would gradually stabilize. Our results show that special treatment measures

must be remedied twice, and that the working status of the subgrade gradually stabilized after reconstruction.

3.4.1 Defect development process in thermosyphon subgrade

In the 10 surveyed thermosyphon subgrade samples along the QTH, the monitoring geotemperature data at only one sample location showed that the thermosyphon subgrade did not provide a good cooling effect. The cooling effect of the thermosyphon subgrade along the QTH was 90%. In normal working sections of the thermosyphon subgrade, 70% road sections were effectively protected. Specifically, in high subgrade conditions, the effect of thermosyphon subgrades was more obvious, and the service time was up to 13 years. In 30% of road sections, serious longitudinal cracks, settlement, and other kinds of defects appeared within 2 to 4 years, which seriously affected the traffic capacity. The biggest problem after using the thermosyphon subgrade was that serious longitudinal cracks appeared in several road sections. These longitudinal cracks often ran through the entire treatment section and were located 2 to 3 m away from the thermosyphon.

3.4.2 Defect development process in rubble and block stone subgrade

From the surveyed data, only 55% rubble and block stone subgrade samples had a significant cooling effect. Compared with the thermosyphon subgrade, the rubble and block stone subgrade had an insufficient cooling effect. However, in the analysis with the contrasting section of conventional subgrade, 80% of the rubble and block stone subgrade mitigated defects. Of the remaining 20% of rubble and block stone subgrade, 10% of the rubble and block stone subgrade began to exhibit pavement defects from the fourth year onward, and the other 10%

Table 3. Temporal effect of defects in special treatment sections along the QTH.

Special treatment	Observation time (years)	Cooling or thermal insulation (%)	Defect prevention (%)
Thermosyphon	13	95	70
Rubble and block stone	13	55	80
Extruded polystyrene foam (XPS) board	13	90	60
Ventilation duct	13	90	70
Ventilation duct + rubble and block stone	13	75	80

The effectiveness rate of cooling or thermal insulation refers to the ratio of sections with a significant cooling effect after the construction of special treatment measures to the total sample section; the effectiveness rate of defect prevention refers to the ratio of sections whose operation was not impacted after the construction of special treatment measures to the total sample section.

Table 4. Relationship between defect rate and construction time of subgrade in special treatment sections along the QTH.

Special treatment	Defect rate of subgrade at different construction times (%)			
	2 years	4 years	6 years	8 years
Thermosyphon	5	30	–	–
Rubble and block stone	5	10	13	20
Extruded polystyrene foam (XPS) board	3	15	25	40
Ventilation duct	3	16	25	30
Ventilation duct + rubble and block stone	3	8	12	20

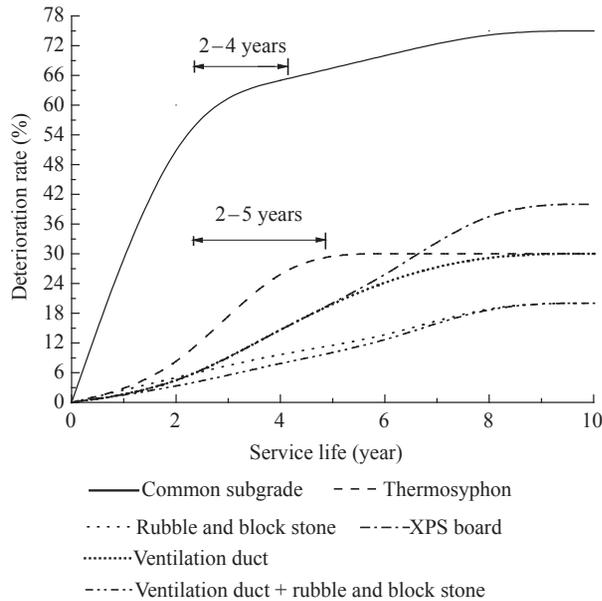


Fig. 5. Service life of different special treatments.

of the subgrade did not show pavement defects until the eighth year.

3.4.3 Defect development process in XPS insulation board subgrade

In the surveyed XPS insulation board subgrade sample, 90% of the insulation board subgrade prevented heat absorption from the asphalt pavement. However, only 60% of all treatment measures played a role in preventing defects from occurring. At the beginning of construction of the thermal insulation subgrade, the road defect incidence was relatively small, at only 3% to 15%. The road defect incidence rapidly increased after the fourth year. The road defect incidence reached 40% in the eighth year; the main forms of defects were settlement and pothole formation. As a passive heat-resistance measure, the insulation board delays the defect occurrence where the subgrade defects is caused by permafrost thawing. However, defects could not be completely eliminated (Fig. 6).

3.4.4 Defect development process in ventilation-duct subgrade

In the surveyed ventilation-duct subgrade sample, 90% of the ventilation-duct subgrade could reduce the subgrade temperature by introducing ambient “cold energy”. Specifically, for several test sections, a temperature-controlled switch was used. The ventilation duct damper could be closed in warm seasons and opened in cold seasons, which greatly improved the cooling efficiency. 70% of the ventilation-duct subgrade effectively prevented road defects. Additionally, when ventilation ducts and rubble and block stone were used in combination, the defect treatment efficiency could be increased to 80%. Note that some of the ventilation ducts might be blocked, which affects the cooling effect of the structure due to pavement settlement and the accumulation of wind sand. The ventilation-duct subgrade is shown in Fig. 7.



Fig. 6. Potholes above thermal insulation board subgrade.



Fig. 7. Used case of ventilation-duct subgrade.

4 Development of new stable technologies

4.1 Forced distributed ventilation subgrade

The forced distributed ventilation subgrade was controlled by an intelligent control module. In cold seasons, the fan is started by the intelligent control module and cold air flows along the distributed ventilation based on forced wind. In warm seasons, the fan is closed and the thermal resistance of the subgrade increases, which avoids downward heat transfer and is favorable to protecting the underlying permafrost. A schematic diagram of the forced distributed ventilation subgrade is shown in Fig. 8.

4.2 Unidirectional heat conduction board subgrade

The unidirectional heat conduction board subgrade was composed of a thermal insulation board and a small thermosyphon. On the one hand, in warm seasons, the heat absorbed by the black asphalt pavement was resisted by the thermal insulation board based on its higher thermal insulation performance. On the other hand, in cold seasons, cold air was introduced into the subgrade, the temperature of the subgrade decreased, and the permafrost table did not degrade. The design scheme and prin-

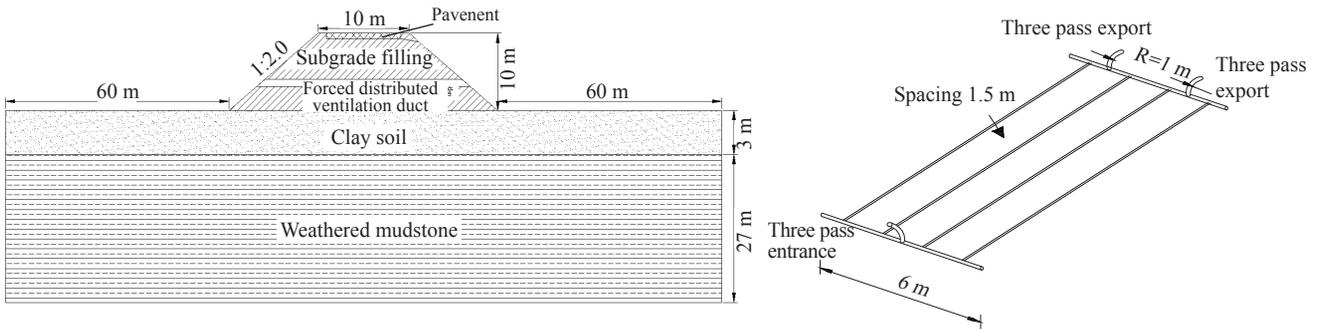


Fig. 8. Schematic diagram of forced distributed ventilation-duct subgrade.

principle of the unidirectional heat conduction board are shown in Fig. 9 and Fig. 10, respectively.

4.3 Integrated pavement-subgrade heat drainage structure

Heat transfer in the pavement was regulated by establishing a gradient heat conduction structure. The design principle is shown in Fig. 10. First, the thermal conductivity of the upper layer was changed to reduce heat being absorbed from solar radiation as much as possible. Second, the structure had high thermal conductivity in the middle layer and low thermal conductivity in the lower layer, which was detrimental for heat transfer from the middle layer to the lower layer. Therefore, the integrated pavement-subgrade heat drainage structure could reduce heat accumulation in structure layers.

5 Conclusions

(1) Road defects in permafrost regions were closely related to MAGT, degradation rate of permafrost table, and ice content. Traditional research methods only formulated defect treatment measures from the perspective of defect occurrence mechanisms and their influencing factors. However, these studies lacked a comprehensive evaluation of the subgrade over long time scales.

(2) When MAGT increased from $-3\text{ }^{\circ}\text{C}$ to $-0.5\text{ }^{\circ}\text{C}$, the time from when the road defects occurred to when the traffic capacity was severely affected was shortened from 40 years to less than 10 years. The subgrade with permafrost table degradation rate of more than $20\text{ cm}\cdot\text{a}^{-1}$ needed to be repaired within 10 years. In the section where MAGT was high and the permafrost table degraded rapidly, the high-ice-content subgrade often had significant defects within 2–3 years of project construction, requiring urgent reinforcement within 5–10 years.

(3) The control measures' cooling efficiency, i.e., thermosyphon, rubble and block stone, XPS insulation board, and ventilation-duct subgrades, were 95%, 55%, 90%, and 90%, respectively. Among them, the thermosyphon subgrade cooling effect was the best, followed by XPS insulation board subgrade, and ventilation-duct subgrade; rubble and block stone subgrade was the worst. However, the rubble and block stone subgrade had high

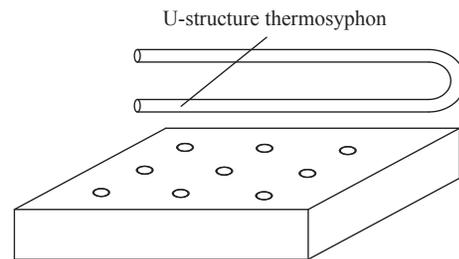


Fig. 9. Design scheme of unidirectional heat conduction board.

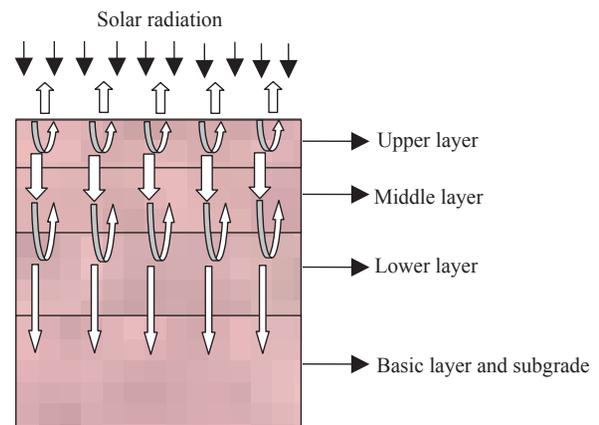


Fig. 10. Principle of operation of unidirectional heat conduction board.

strength and good water permeability; its ventilation and convective ability controlled the geotemperature. Rubble and block stone could greatly enhance the stability of the subgrade. When ventilation-duct subgrade and rubble and block stone subgrade were used in combination, the defect treatment efficiency could be increased to 80%.

References

- [1] Jin L, Wang S J, Chen J B, et al. Study on the height effect of highway embankments in permafrost regions [J]. *Cold Regions Science and Technology*, 2012, 83–84(7): 122–130.
- [2] Wang S J, Huo M, Zhou W J, et al. Subgrade failure of Qinghai-Tibet highway in permafrost area [J]. *Highway*, 2004(5): 22–26. Chinese.
- [3] Peng H, Ma W, Mu Y H, et al. Degradation characteristics of per-

- mafrost under the effect of climate warming and engineering disturbance along the Qinghai-Tibet highway [J]. *Natural Hazards*, 2015,75(3): 2589–2605.
- [4] Cheng G. A roadbed cooling approach for the construction of Qinghai-Tibet railway [J]. *Cold Regions Science and Technology*, 2005(42): 169–176.
- [5] Cheng G, Wu T. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau [J]. *Journal of Geophysical Research Atmospheres*, 2007,112(F2): 93–104.
- [6] Bray M T. Secondary creep approximations of ice-rich soils and ice using transient relaxation tests [J]. *Cold Regions Science and Technology*, 2013, 88(2): 17–36.
- [7] Collis P M, Morgenstern N R. Influence of ground ice variability on settlement in thawing permafrost [J]. *Arquivos Brasileiros De Cardiologia*, 2010, 81(4): 349–354.
- [8] Luetschg M, Lehning M, Haerberli W. A sensitivity study of factors influencing warm/thin permafrost in the Swiss Alps [J]. *Journal of Glaciology*, 2008, 54(187): 696–704.
- [9] Wen Z, Sheng Y, Ma W, et al. Evaluation of EPS application to embankment of Qinghai-Tibetan railway [J]. *Cold Regions Science & Technology*, 2005, 41(3): 235–247.
- [10] Wen Z, Sheng Y, Ma W, et al. Analysis on effect of permafrost protection by two-phase closed thermosyphon and insulation jointly in permafrost regions [J]. *Cold Regions Science and Technology*, 2005, 43(3): 150–163.
- [11] Wu D, Jin L, Peng J, et al. The thermal budget evaluation of the two-phase closed thermosyphon embankment of the Qinghai-Tibet highway in permafrost regions [J]. *Cold Regions Science and Technology*, 2014, 10(3): 115–122.
- [12] Wang S J, Chen J B, Huang X M. Numerical simulation of cooling effect for heat pipe subgrade [J]. *Journal of Traffic and Transportation Engineering*, 2005(3): 41–46. Chinese.
- [13] Dong Y H, Lai Y M, Zhang M Y, et al. Laboratory test on the combined cooling effect of L-shaped thermosyphons and thermal insulation on high-grade roadway construction in permafrost regions [J]. *Sciences in Cold and Arid Regions*, 2009, 1(4): 307–315.
- [14] Dong Y, Lai Y, Li J, et al. Laboratory investigation on the cooling effect of crushed-rock interlayer embankment with ventilated ducts in permafrost regions [J]. *Cold Regions Science and Technology*, 2010, 61(2): 136–142.
- [15] Lai Y, Ma W, Zhang M, et al. Experimental investigation on influence of boundary conditions on cooling effect and mechanism of crushed-rock layers [J]. *Cold Regions Science and Technology*, 2006, 45(2): 114–121.
- [16] Wang S J, Sun B X, Xu X Z, et al. Research on laboratory experiment of natural convection mechanism of embankment ballast [J]. *China Journal of Highway and Transport*, 2004, 17(2): 19–24. Chinese.
- [17] Wang S J, Liu G, Ye L, et al. Research on control countermeasures of thermal effect of wide embankment in permafrost regions [J]. *China Journal of Highway and Transport*, 2015, 28(12): 26–32. Chinese.