Heat transfer process of roadway embankments with different type and width of road surface in permafrost regions*

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Abstract The stability of roadbed in permafrost areas has become a big concern with rapid development and construction of throughways, highways and railways in these areas under the current climate change since it is governed by the thermal condition, or in other words, the heat transfer process in the embankment. We carried out a finite element analysis to analyze the effects of different types of road surface and the effect of breadth of embankment on the embankment heat transfer process. The results indicated that the mean annual heat transfer rate at the bottom of the roadway embankment with asphalt surfaces is 3 times that with sandy gravel surfaces. This means annual heat transfer rate increased by 60% when the breadth of asphalt surface was doubled. The increased heat transfer rate was mainly located at the bottom of the embankment and resulted in the effect of thermal concentration,. leading to degradation of the permafrost by as much as 1.6 times. It was also found that increasing embankment height would not reduce these increases of the heat transfer rate. Therefore both asphalt road surface and increased embankment breadth can lead to an intensified heat transfer rate in roadway embankment, consequently degradating the underlying permafrost and embankment instability.

Keywords: wide road surface, roadway embankment, permafrost regions, process of heat transfer, heat flux, ground temperature field.

Massive ground ice, which can reach a few to tens of meters, can be formed via long-term evolution, grows and changes in permafrost regions[1]. With the rapid development of Chinese economy, highway construction with asphalt surface and wide embankment breadth in permafrost region is brought up on the agenda, and the engineering problems coming along are great challenges. The previous researches have been mainly focused on the change of environment, frost-damage mechanism, embankment settlement and deformation for common road construction. The heat transfer process in the embankment, especially with wide road surface, has been hardly specifically considered[2—7]. The heat transfer process in different embankment structures was analyzed in this study to benefit to the design, construction and maintenance of highway embankments, as well as to understanding the permafrost table variation, permafrost thermal condition under highway embankments.

1 Analysis of the ground heat transfer process

The permafrost temperature field is the result of heat exchange between the atmosphere, the underlying soil layers and the heat reservoir of the earth crust. The heat conduction is described by the following unsteady-state partial differential equation[8]:

$$\rho c \frac{\partial t}{\partial \tau} = -\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right),$$

where ρ is density, c is specific heat capacity and τ is time. From the equation it can be found that temperature gradient is the impelling force of heat flux in the roadway embankment. Heat transfer leads to the change of soil temperature. In this process temperature gradient is the necessary and sufficient condition, the heat transfer is a process and the change of soil temperature is the result. The distribution and amount of the heat flux control the development trends of the temperature field. Through studying the heat flux distribution, we would be able to know more about the temperature field variation of the embankment and the underlying permafrost layers. In this paper, we focus on the numerical analyzing of heat flux distribution in and under embankments.

A thermal modeling software MARC was used in the analyses. The modeling was based on a testing section at Beiluhe, Qing-Tibet railway and the physi-

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cal property parameters were obtained from test results on borehole samples as shown in Fig. 1. The stratum and physical parameters are listed in Table 1. The boundary conditions for the natural ground surfaces, the slopes of the road embankment and road surface were set with sine curve temperature fitted to the measured annual temperatures. The temperature was measured at a depth of 0.5 m below the ground surface in order to avoid instantaneously ambient influences such as radiation, precipitation, wind and so on. Half of the embankment section was set up in the model since the embankment was approximately considered symmetric. The fitted temperature variation of the upper boundary is as follows:

$$T = T_0 + \alpha \cdot t + A\sin\left(\frac{2\pi \cdot t}{8760} + \frac{\pi}{2}\right),$$

where T_0 is the mean annual temperature, it is −0.5℃ for the natural ground (B3), 1.0℃ for the slope (B2) and the sand surface (B1), 3.5℃ for the asphalt surface (B1); α is the mean annual climate warming rate which is approximately 0.02℃ $\cdot$ yr^{-1}; t is time; A is the amplitude of temperature, it is 11.5℃ for the natural ground, and 14.5℃ for the embankment surface.

Table 1. Soil/strata physical properties

Soil/Strata	Symbols in Fig. 1	Depth (m)	Dry density ($kg \cdot m^{-3}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)		Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	
				Frozen	Non-frozen	Frozen	Non-frozen
Land pebble	S1	Embankment height	2060	1.40	1.15	706.6	861.7
Sandy loam with gravel	S2	0—0.5	1800	1.98	1.60	977.2	1266
Pebbly sand	S3	0.5—2.0	1900	2.61	1.92	810	1044
Clayey loam	S4	2.0—8.0	1600	2.12	1.42	1222	1608
Rotten mudstone	S5	8.0—30	1800	1.82	1.47	981.8	1272

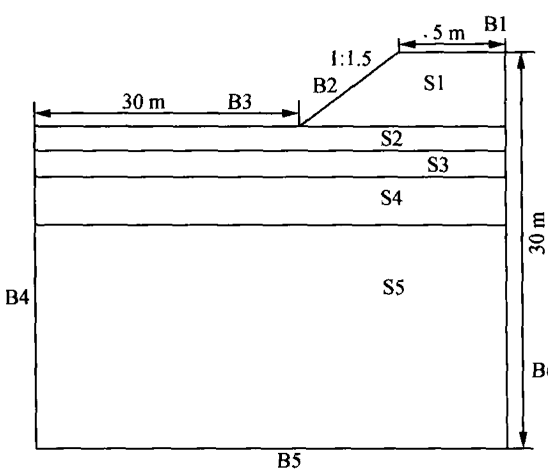

Fig. 1. The profile of half embankment for calculation.

The model was set to start at the time when the peak boundary temperature in a year was reached. The lower boundary condition was set with a constant heat flux of 196.56 $J \cdot m^{-2} \cdot h^{-1}$ at a depth of 30 m below the natural ground surface (B5), which was calculated based on the borehole measurement of a constant heat flux of 0.03℃ $\cdot$ m^{-1}. The vertical boundaries, both sides of the model, were assumed adiabatic (B4, B6). The initial condition of the natural ground was set as the resulting temperature field after 100 yr simulation and at the same time the embankment temperature was set with the maximum in a year.

The observed temperature variation with depth at the third year after construction of Beiluhe railway embankment testing section and the modeled results are both plotted in Fig. 2. The numerical results are very consistent with the observed data, which attest to the accuracy of the model.

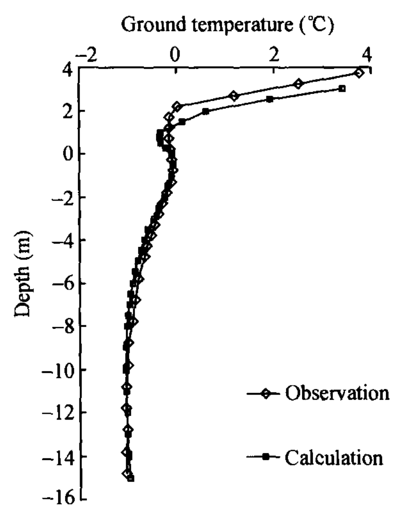

Fig. 2. Comparison between numerical result and observed result at the 3rd year after embankment construction.

The height of roadway embankment of Qing-Tibet road after several times of reconstruction is 2.5—

3 m, and the observed data indicated that when the mean annual temperature of environment is -3.5℃, the mean annual temperature in the permafrost is -1.0℃[9,10], and then it is the boundary of the mechanical property and engineering property of frozen ground that show different characteristics[11—14]. So in the numerical test, a 3 m height of embankment and -3.5℃ environment temperature were considered. Through numerical analysis it was found that the mean annual heat fluxes at the bottom of embankment and surface ground reached a stabilized condition in the second year after the roadway embankment construction, however the temperature varied all the time. Therefore it is of significance to investigate and compare the heat flux instead of temperature. In our analysis the mean annual heat flux was chosen from the August of the fourth year to the August of the fifth year. The upward vertical component of heat flux was considered positive and it means heat yield, conversely, it means heat absorption.

2 Effect of different types of road surface on the heat flux at the bottom of the roadway embankment

The vertical mean annual heat fluxes at the bottom of the roadway embankment with a sand and asphalt surface were modeled and the results are shown in Fig.3. The lateral coordinate is the horizontal bottom of the roadway embankment, the origin of the coordinate is set at the toe of the embankment slope, and the end point is the centre of roadway embankment bottom. As indicated, the mean annual heat fluxes at the roadway embankment bottom with two different kinds of road surfaces show entirely different characteristics.

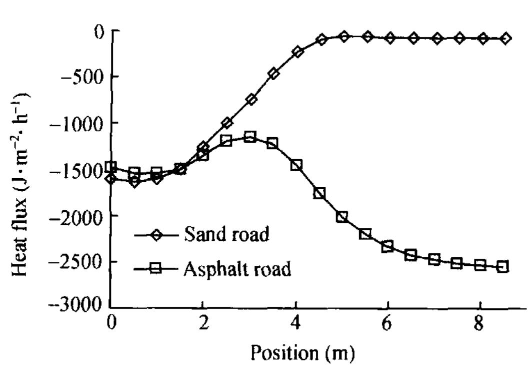

Fig. 3. Comparison of the bottom heat flux with two kinds of road surface.

The heat flux distribution at the bottom of asphalt surface embankment generally increases from the toe of slope and reaches the maximum value at the center of the embankment bottom, but with a second peak value at the toe of the slope. For the sand surface road, the maximum value of heat flux is at the toe of the slope while it is nearly zero at the center part.

All the calculated heat fluxes are negative, which indicates that both the sand and asphalt surface embankments transfer heat to the underlying ground and result in temperature rising. In addition, the value of heat flux under the asphalt surface road is much larger than sand surface road. Further calculation indicates that the average heat transfer rate at the bottom is $-5648\ J \cdot h^{-1}$ for sand surface embankment, while heat flux for asphalt surface embankment is $-17559\ J \cdot h^{-1}$, 3.1 times greater. In other words, with the same height and ambient temperature, the heat transfer rate to the underlying permafrost of asphalt surface road is much larger than sand surface embankment, and the heat reservoir mainly concentrates at the center of the embankment bottom. These heat fluxes cannot diffuse effectively and as a result heat can be accumulated under the road embankment.

3 Effects of road surface breadth on heat flux distribution

Each direction of a highway is generally composed of three lanes with a total breadth of about 20 m, whereas common road breadth is usually about 10 m. In the modeling, the surface width of a half highway embankment section is 9 m, while it is 5 m for a half of common road embankment. Both of the embankment slopes are 1∶1.5. The distributions of mean annual heat flux from August of the fourth year to August of following year after embankment construction are plotted in Fig. 4. Same as above, the lateral coordinate is along the roadway embankment bottom, the origin of coordinate is set at the toe of embankment slope, and the end point is at the center of roadway embankment. For the curves in the figure, 5 m and 9 m indicate the road with different widths, and the horizontal and vertical is the direction of heat flux component.

With asphalt surface road, it is found from Fig. 4 that with the same embankment height, both the annual mean lateral and vertical heat fluxes do not vary much with breadth change. The calculated average of the annual mean heat flux is $-1857\ J\cdot m^{-2}\cdot h^{-1}$ for the 5 m wide model section and $-2052\ J\cdot m^{-2}\cdot h^{-1}$ for the 9 m wide model section, which are very close to each other. However, the calculated heat transfer rates are quite different, $-17645\ J\cdot h^{-1}$ and $-27698\ J\cdot h^{-1}$, which means that heat transfer rate increases by 60% when the breadth of the embankment increases by 100%.

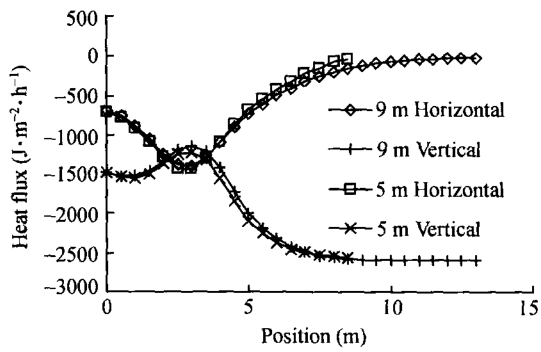

Fig. 4. The mean annual lateral and vertical heat flux at the bottom of asphalt surface embankment.

The drastic changes of the mean annual heat flux at the embankment bottom edge mean that there is thermal diffusion to the surrounding soil and it weakens the vertical heat flux transferring to the underlying soil. From the distribution of mean annual heat flux in the horizontal direction in Fig. 4, it is found that the direction of the heat flux is outward and the net annual heat flux increases. In that sense, a narrow road surface is more favorable because it has better thermal diffusion. When the surface breadth increases, the breadth of embankment bottom and horizontal thermal resistance will also increase, as a result the heat flux at the center area is more difficult to diffuse to the surroundings. In Fig. 4 the lateral heat flux at the center of the 9 m model is nearly zero, which means nearly zero heat diffusion. In other words, wider embankment has stranger effect of thermal concentration compared to common embankment, and it can result in heat accumulation at the embankment bottom.

4 Analysis of heat flux characteristics of asphalt embankment with different breadths and heights

The calculated heat fluxes of three different heights of asphalt road sections in 2 m, 3 m and 4 m are shown in Fig. 5, where the "normal" indicates the half width of road surface in 5 m and "broad" in 9 m. The influences of embankment height and breadth on the heat flux are discussed as follows.

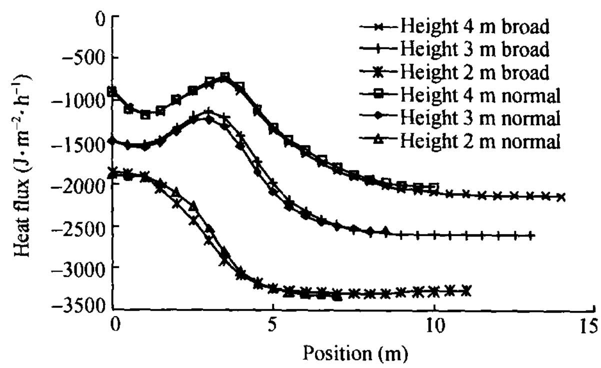

Fig. 5. Bottom mean annual heat flux with different heights and breadths.

The influences of the embankment height on heat flux are mainly reflected in the distribution of the heat flux and heat flux intensity. The road surface mainly affects the distribution of heat flux, and at the same time with the embankment height increasing the slope starts to affect the heat flux distribution. There is a secondary peak value, which is getting larger continually at the bottom edge. The distribution of bottom heat flux is also translated from concentrative heat transfer in the center to primarily in the road surface and secondarily in the slope. Regarding heat flux intensity, with the increasing embankment, the mean annual heat flux and heat transfer rate of the embankment bottom decrease dramatically, but this decrease cannot change the increasing trend of the frozen soil temperature. The mean annual heat flux intensities of the road embankments with heights of 2 m, 3 m and 4 m are calculated to be $-19700\ J\cdot h^{-1}$, $-16717\ J\cdot h^{-1}$ and $-13800\ J\cdot h^{-1}$, respectively. When the embankment height is below 2 m, the heat flux intensity is strong and is mainly caused by the road surface, and the heat flux is two times the value of the 4 m high embankment. Considering the stability of the roadbed, increasing the height of embankment can decrease the asymmetry of the heat flux distribution and consequently heat flux intensity, and can also decrease the influence of heat disturbance to the underlying permafrost. Especially for embankment with height less than 2 m, the heat flux intensity is concentrative and strong, which makes more thermal disturb to the permafrost, and leads to permafrost thawing and lowering of permafrost table. So in designing of a wider surface road in permafrost regions, the embankment height should be taken as a major concern. For a high road embankment design, on the other hand, protection may be required to avoid differential deformation at the slope toe and shoulder of the embankment due to thaw settlement caused by the secondary peak heat flux.

For road embankments with different heights, the road surface breadth has the same effect, i.e., the increased heat flux concentrates at the center part at the base of embankments.

The statistical results of the bottom mean annual heat flux for different heights and breadths are summarized in Table 2. The statistical results reflect the influence of the heights and breadths of embankments on the heat transfer rate at the base of embankment. For the influence of embankment height, when with a sandy gravel road surface, there is a minimum value of heat transfer rate at the embankment bottom for the two kinds of breadths when the embankment height is 3 m. It implies that for different breadths, there is an optimal height of the sand surface embankment. However, with an asphalt road surface, the heat transfer rate always decreases regardless embankment height. When the embankment height changes from 2 m to 4 m, the bottom heat transfer rates decrease by 33% for both breadths. There is no optimal height for asphalt surface road embankment. Concerning about the influence of road breadth, for the sandy gravel surface road embankment, the bottom heat transfer rate increases slowly with the increasing breadth of different height embankments, which means that the influence of the breadth on heat transfer rate at the bottom is small. For the asphalt surface, however, the bottom heat transfer rate increases drastically with increasing breadth. The bottom heat transfer rate increases about 60% when the breadth increases by about 100%. It indicates that the mean annual heat transfer rate of the asphalt surface is closely related to the breadth of embankment. The heating effect of the wider road surface as stated above does not vary with embankment height.

Table 2. The mean annual heat flux at embankment bottom with different heights and breadths

Embankment height (m)	Mean annual heat flux for different widths ($J \cdot h^{-1}$)				The ratio of heat transfer rate (9 m/5 m)	
	5 m sand surface	5 m asphalt surface	9 m sand surface	9 m asphalt surface	Sand surface	Asphalt surface
2	−8547.3	−21018.0	−8441.5	−34370.8	0.99	1.64
3	−6386.8	−17474.4	−6726.6	−28768.7	1.05	1.65
4	−6661.6	−14547.7	−7461.5	−23286.2	1.12	1.60

5 Effects of road breadth on ground temperature field

For the asphalt road surface, the black surface can absorb more radiation and lead to temperature rising in the embankment. The observed data showed that the mean annual temperature at 0.5 m below the black road surface was approximately 4.5℃ higher than that of the same depth of natural ground, and 5℃ higher than that of permafrost[5]. Under the temperature gradient, heat is more easily transferred to the underlying permafrost, and leads to the permafrost warming and thawing and lowering of permafrost table, i.e., permafrost degradation. The above analyses indicate that for the increasing surface width the bottom heat flux increases largely and this will lead to permafrost degradation and serious engineering problems. Since massive ground ice generally presents at approximately 3 m below the ground surface, close to the upper limit of permafrost, it is the most sensitive and acute to the environment changes, and a representative of temperature change of frozen soil. So the analysis of temperature variation at the depth of 3 m should be emphasized.

For a 3 m high asphalt surface embankment, the calculated temperature change, artificial upper limit at 3 m depth below the ground surface and at the embankment center are presented in Figs.6 and 7. The results indicate that, for both the 5 m and 9 m modeled embankments, ground temperature increases rapidly until the fourth year after construction and then turn to a moderate increasing trend. From the fourth year to the thirtieth year the temperature increment of the modeled 5 m embankment is 0.6℃ and it is 1.0℃ for the modeled 9 m embankment, 66% more than the 5 m embankment. Based on Fig. 6, it is estimated that for a half width of 5 m surface the temperature takes 20 years to reach 0℃ at 3 m beneath ground, while that of the 9 m surface needs about 12 years, i.e., 60% shorter. In Fig.7 the upper limit of permafrost of the 5 m surface has dropped about 2 m after 30 years and that of the 9 m surface has dropped 50% more, about 3 m.

In summary, when the half width of road surface increases from 5 m to 9 m, the temperature at 3 m below ground surface increases by 66%, and the time needed for the permafrost table drops to 3 m is shortened by 60%, the upper limit drops more than and 50%. This means when the surface width is doubled, and the progress of the permafrost degradation can be 1.6 times faster.

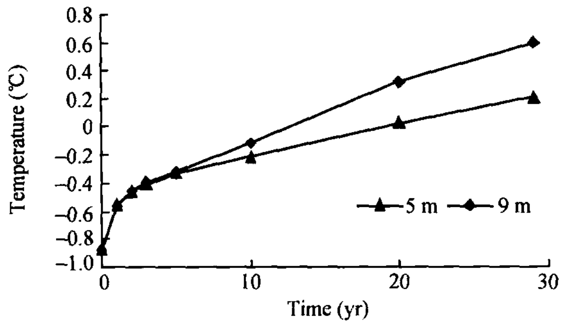

Fig. 6. The change of soil temperature at depth − 3 m within 30 years.

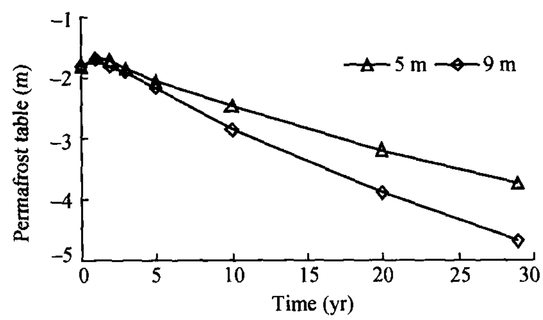

Fig. 7. The change of permafrost table within 30 years.

6 Conclusions

(1) The mean annual heat flux at the base of asphalt road surface embankment is 3.1 times as the sandy gravel road surface embankment. The heat flux distribution is mainly concentrated at the center area of the base for asphalt road surface embankment, while the heat flux is mainly at the edge of the base for sandy gravel road surface embankment.

(2) For asphalt road surface embankment, the mean annual heat transfer rate can increase by 1.6 times when the breadth of road surface increases to twice of the original. The heat transfer rate maximizes at the center of the embankment base and results in thermal concentration and consequently heat accumulation at this location. The change of the breadth of sand gravel surface embankment rate has minimal influence on the bottom heat transfer rate.

(3) The mean annual heat transfer rate at the base of asphalt surface embankment decreases greatly with the increase of embankment height, but it still acts as heating effect to the underlying permafrost. The distribution of bottom heat flux is also transferred from concentrative heat transfer at the center to primarily at the road surface and secondarily at the slopes. For sandy gravel road surface embankment, on the other hand, an optimum embankment height exists for different embankment breadth.

(4) For asphalt road surface embankment, the heat flux at the embankment base can increase by 60% when embankment breadth increases by 100%, consequently the underlying permafrost degradation rate increases by 60%.

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