Influence of Slope Angle on Thermal Stability of Embankment in Permafrost Regions

D.Q. Li[a], X. HUANG[a], F. MING[a], J.K. LIU[b]

Abstract—**Based on the principle of energy balance, established the governing equations which reflected the changing characteristics of frozen soil temperature field. Through comparing the measured data and the numerical simulation data, the model was proved to be reliable. Based on this model, the influence of different slope angles on temperature field was analyzed. The results show that the permafrost table rises as the slope angle slackens. But with the slope angle continued to slacken, the permafrost table would descends. Lower ground temperature of the embankment slope, the slope foot would reduces, with the gradient of slope slackens. The slope gradient has little influence on the temperature field of roadbed where the annual mean temperature is very low. The nearer approaches the embankment centerline the more influence of embankment slope would suffer.**

Index Terms—**permafrost, thermal stability, natural permafrost table, slope angle**

I. Introduction

AFTER the road was built in permafrost regions, the heat exchange conditions between atmosphere and surface were changed by the disturbance of climate change and engineering effect. It also destroyed the initial thermal equilibrium state and accelerated the degeneration of the frozen soil under the embankment. This phenomenon has attracted wide attention from researchers [1-2]. So, keep the heat stability of embankment is becoming the key issue of solving embankment and pavement diseases in permafrost regions [3-4].

At present, the asphalt concrete pavement is usually used as common pavement structure. Because the temperature sensitivity of black asphalt pavement is strong, the pavement absorbs a huge amount of radiation to increase the pavement temperature. It has a significant impact on temperature field under pavement and has disadvantage to the stability of permafrost embankment. In permafrost regions, the temperature is main element that influences the deformation of embankment. In order to keep the heat stability of embankment and protect the frozen soil under embankment many measures were taken during the construction of Qinghai-Tibet Railway and Highway. There were some measures, such as block-stone embankment [5], crushed rock revetment [6] and duct-ventilation embankment [7]. Li J.P. et al [8] surveyed embankment diseases of National highway 214 by taking spot investigation and analyzed the mechanism of asphalt and concrete pavement diseases. Li D.Q. et al [9] discussed the applicability of different types of pavement built in high temperature permafrost districts of eastern Tibetan Plateau. Zhang J.W. et al [10]through analyzing the pavement material found that the maximum thawing depth under asphalt pavement was deeper than that was under concrete pavement, the difference of thawing depth was more significantly especially at the situation that the height was very low. Yu Q.H. et al [11] through calculation found that under asphalt pavement heat flow increment would reach 60 % when doubled the width of road. The incremental heat flow was centered in the centre of embankment and had a heat accumulation, which would cause the permafrost degradation accelerated 0.6 times. Wang T.H.[12] et al through combining the survey results of the Qinghai-Tibet Highway and computation results obtained the numerical methods for the gravel and asphalt roadbed ‘s critical heights in permafrost regions, found that the increment of the embankment height didn’t raise the permafrost table. The embankment stability studies were mainly about pavement material, structure, width and critical heights, rarely took into consideration of slope gradient of embankment.

Therefore, the governing equations were established which reflected the changing characteristic of frozen soil temperature. Then proved the model was reliable through comparison the measured data and the numerical calculated data. Consideration of global warming effect, the heat stability of different slope gradient in permafrost regions was analyzed by the numerical methods.

II. Mathematical Model

Heat transfer and temperature variation in the frozen-thaw process of soil is very complex. It is only use the definitive means according to the certain situation of the problem that can obtain results which are of value in practical application. On the basis of the theories of heat conduction and mass transfer, omit the convection and moisture transfer in soil, only take into account of the problem of heat conduction and phase change, so equations for transient heat conduction can be expressed as follows[9].

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D. Q. Li is with the State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, CO 730000, China(Corresponding author(D. Li): phone: +86 931 4967278; fax: +86 931 8271054. e-mail: dqli@lzb.ac.cn).

X. Huang is with the State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, CO 730000, China(e-mail: 250037213 @qq.com).

F. Ming is with the State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, CO 730000, China(e-mail: mf0329@163.com).

J. K. Liu is with the School of Civil Engineering, Beijing Jiao tong University, Beijing, CO 100044, China(e-mail: jkliu@bjtu.edu.cn).

The temperature field in unfrozen soil area Ω_u is:

$$C_u \frac{\partial T_u}{\partial t} = \frac{\partial}{\partial x}(\lambda_u \frac{\partial T_u}{\partial x}) + \frac{\partial}{\partial y}(\lambda_u \frac{\partial T_u}{\partial y}) \quad (1)$$

The temperature field in permafrost region Ω_f is:

$$C_f \frac{\partial T_f}{\partial t} = \frac{\partial}{\partial x}(\lambda_f \frac{\partial T_f}{\partial x}) + \frac{\partial}{\partial y}(\lambda_f \frac{\partial T_f}{\partial y}) \quad (2)$$

On the moving phase change interface $s(t)$ must meet the temperature continuous conditions and energy conservations:

$$T_u = T_f = T_m \quad (3)$$

$$\lambda_f \frac{\partial T_f}{\partial n} - \lambda_u \frac{\partial T_u}{\partial n} = L\frac{ds}{dt} \quad (4)$$

Here, λ is thermal conductivity of soil; C is heat capacity of the soil; the subscripts *f*, *u* denote physical quantity of the frozen state and thaw state, respectively; T_m is the freezing temperature; *L* is the converted latent heat for unit mass of soil, $L = L_w \rho_d (w - w_u)$, and L_w is the latent heat of water (334.56KJ/kg), w is the frozen soil water content, w_u is the unfrozen water content.

Equations（1）-（4）satisfy conditions in their respective regions but dissatisfy conditions in other regions. In order to form uniform expressions in region Ω , ratio of the mass heat capacity c and thermal conductivity λ will adopt following expressions:

$$C = \begin{cases} C_u \\ C_f + \dfrac{C_u - C_f}{T_a - T_b}(T - T_b) + \dfrac{L_w}{1+w}\dfrac{\partial w_i}{\partial T} \\ C_f \end{cases}$$

$$\lambda = \begin{cases} \lambda_u & T > T_a \\ \lambda_f + \dfrac{\lambda_u - \lambda_f}{T_a - T_b}(T - T_b) & T_b < T < T_a \\ \lambda_f & T < T_b \end{cases} \quad (5)$$

Here, T_a 、T_b denote upper and lower limit temperature of phase change region; the unified temperature field equation in permafrost region Ω is:

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial T}{\partial y}) \quad (6)$$

III. FEM MODEL

A. Finite Element Model

The Hua-shi-xia test section of national highway 214 in Qinghai province is used as calculation models. Fig.1 is the computational domain of embankment. The height of embankment is 3 m and the width of road surface is 10m. The computational domain is extended for 30 m outward from the toe of the side slope and the bottom boundary is located at 30 meters depth. In order to study the characteristic of temperature field, the numerical calculation is set in the condition that air temperature of Tibetan Plateau will rise 2.6 ℃ in the future 50 years.

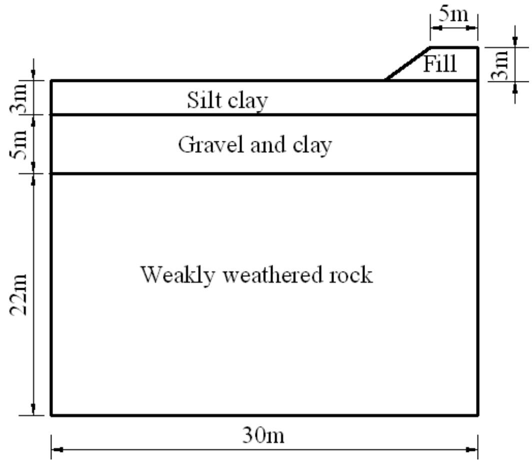

Fig.1 Profile of embankment computational model

B. The Calculation Parameters

Based on the geological investigation and related data[1], in Fig.1, region I is the subgrade fill, region Ⅱ is the silt clay , region Ⅲ is the gravel-clay and region IV is the weakly weathered rock. In the process of numerical calculation, heat capacity of soil is only adopting the volume heat capacity which is in frozen state or molten state. Moreover, the value of thermal conductivity is only dependent on the frozen state and molten state. The thermodynamic parameters for each layer of soil are referred to table.1.

Table1 Thermal parameters of various materials

Parameter Names	Thermal conductivity of frozen soil λ_f (W/(m·℃))	Heat capacity of frozen soil C_f (J/(m^3·℃))	Thermal conductivity of unfrozen soil λ_u (W/(m·℃))	Heat capacity of unfrozen soil C_u (J/(m^3·℃))	Latent heat L (J/m^3)
Subgrade fill	1.928	1.613×10^6	1.424	2.183×10^6	2.54×10^7
Silt clay	1.301	1.781×10^6	0.945	2.258×10^6	7.258×10^7
Gravel-clay	1.215	1.932×10^6	0.867	2.446×10^6	6.013×10^7
Weakly Weathered rock	1.942	1.846×10^6	1.578	2.099×10^6	3.772×10^7

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C. Boundary Conditions

In the process of temperature calculation, it is assumed that the phase change section is (0,-0.2). Take into consideration the influence of climate warming and use experimental sections as calculation model. The computational domain is shown in Fig.1. Take into account the influence of global warming and suppose the air temperature of Tibetan Plateau will raise 2.6 ℃ in the future 50 years, it is assumed that the annual temperature is -4.0 ℃. According to the principles on the adhere layer, the incremental temperature of asphalt pavement is 6.5 ℃.

Referred to related information boundary conditions are as following:

The temperature of natural ground surface changes as flowing formula:

$$Tt=-1.5+12\sin(2\pi t/8760+\pi/2)+a*t \tag{7}$$

The temperature of embankment slope changes as flowing formula:

$$Tp=0.7+13\sin(2\pi t/8760+\pi/2)+a*t \tag{8}$$

The temperature of asphalt pavement changes as flowing formula:

$$Tl=2.5+15\sin(2\pi t/8760+\pi/2)+a*t \tag{9}$$

Here, T is temperature (℃); t is time (h); a is temperature rising rate, a=2.6/438000, ℃/h.

The heat flow density across the bottom boundary is q = 0.03W/m2, the left and right boundary are regarded as thermal insulation.

The upper boundary conditions of computational domain for years repeated computation are not included the equation （7） which is the rising natural ground surface temperature. Take the temperature on July 15th after stabilized as the initial temperature field of computational domain. The temperature of embankment is adopting the surface soil temperature 11 ℃ at that time as the initial temperature.

IV. Results Analysis

The boundary conditions, initial conditions and thermal parameters above are put into the model, and obtain the numerical calculation for the maximum thawing depth of the centre embankment in the second year after construction; moreover the results are compared with the measured value. The measured temperature curves are consistent with the numerical calculation, and the fitting degree of the two curves is very well. It is demonstrated that the calculation model has high precision and the model is proved to be reliable. The calculation of temperature field is consistent with the measured datum as a whole. But, the error is big near the ground surface that is because the precision of boundary conditions are the determinants.

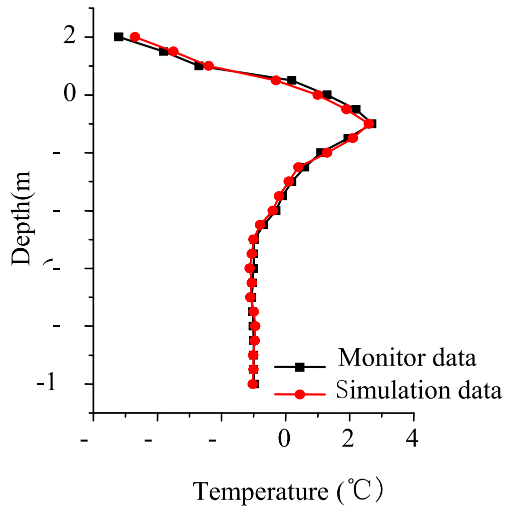
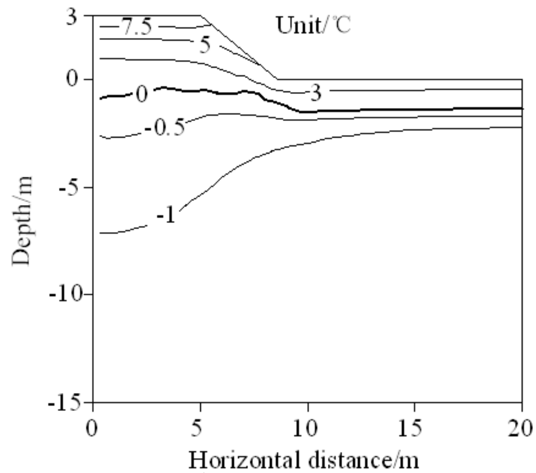


Fig.2 Measured and calculated temperature values at the maximum thawed depth of embankment centre

Through calculation obtain the temperature distribution of asphalt pavement at the slope gradient is 1:1.5 in different operating life. It can be seen from the Figure.3 on September 15th in the second year, the 25th year and the 50th year after the construction of embankment, the permafrost table under embankment is -1.28 m、-3.85 m and-6.49 m, and the corresponding natural permafrost table is -1.87m、-2.69 m and -3.55 m respectively. As the operating time goes on the temperature becomes rise and the thaw depth of frozen soil under embankment becomes deeper, but the natural permafrost table has relative small changes. Moreover, not only the permafrost table is descending and the temperature of frozen soil is rising, but also some negative isothermal curves are disappeared after many years. It is exist -1℃ isothermal curve in the second year, but that temperature curve degenerate into -0.5 ℃ in the 25th year and change into -0.2 ℃ in the 50th year. As can be seen, the ground temperature is rising gradually and will form unstable high-temperature frozen soil which has disadvantage to the stability of embankment in frozen soil.



(a) The 2nd year after construction

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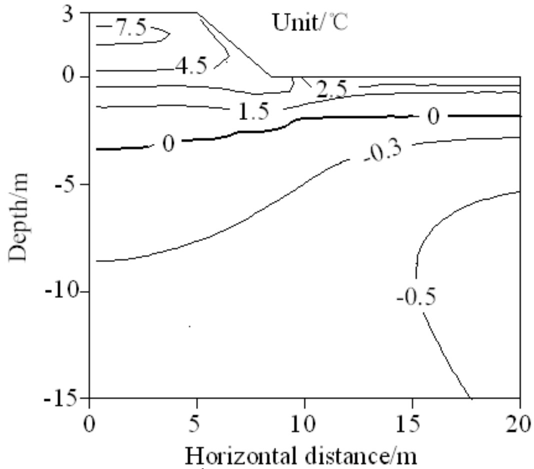
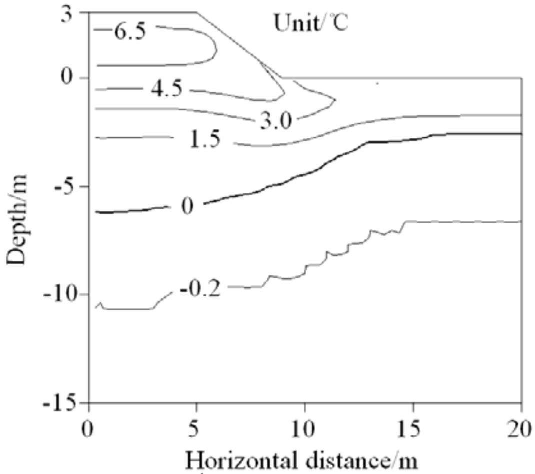


(b) The 25th year after construction



(c) The 50th year after construction

Fig.3 Temperature field on October 15 in 2nd, 25th, 50th

Figure.4 is the change trend of permafrost table with time under the condition of different slope gradient, the mean temperature is -4 ℃ and the asphalt pavement with operation period 50 years. It can be seen from the figure the permafrost table under embankment under several conditions descends with the time increase. It can be found out that the permafrost table under embankment raised after the construction of embankment. The permafrost table rise to the highest position in the fifth year of construction, after that is begin to decline. The permafrost table is the same as natural permafrost table in tenth year. The thaw depth of slope gradient 1:2 is 0.4~0.6 meters deeper than slope gradient 1:1.75. The thaw depth of slope gradient 1:1.25 and 1:5 of embankment has no significant difference. Comparing the change trend of different slope gradient, the permafrost table is rise with the slope gradient slackens. While the slop angle continues to slacken, the permafrost table will descend.

When the permafrost table is the same as natural permafrost table it will form thaw bulb under embankment. As time goes on the permafrost table will continue to decline and the scope of thaw bulb will increase. At this moment the embankment is like a heat source. So the permafrost table under embankment will decline faster on the condition that the slope gradient is gentle.

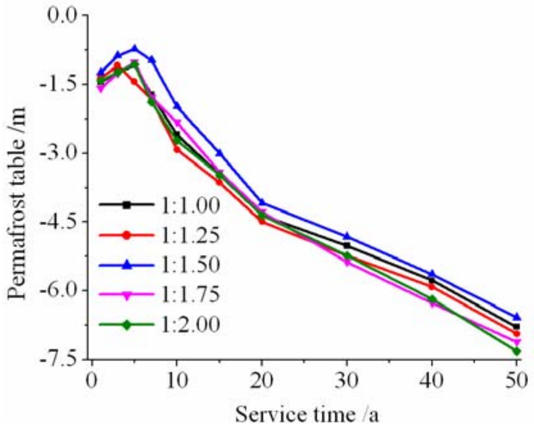
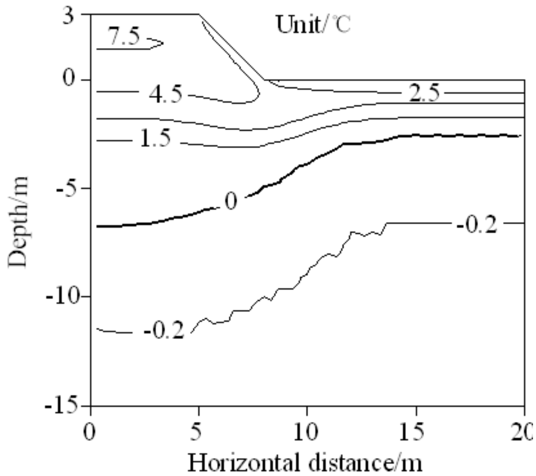


Fig.4 The permafrost table changes with time under different slope gradient

Figure.5 is the temperature field distribution of asphalt pavement for the slope gradient 1:1, 1:1.50 and 1:2 on September 15th the fiftieth year after construction, under the condition that the annual mean temperature is -4 ℃. It is intuitive to compare the influence of different slope gradient on the temperature which is under embankment, toe of a slope and natural ground surface by using the figure. It can be found out that the deepest thaw depth under embankment and natural ground surface is at the slope of 1 in 2, the second one in depth is at the slope of 1 in 1.1, and the last is at the slope of 1 in 1.50. But because the impacts of thermal resistance of slope soil, the maximum thaw depth under the slope toe of embankment at the slope of 1 in 2 is smaller than that at the slope of 1 in 1. It can be seen from the figure under the condition that at the slope of 1 in 1, the permafrost table is closer to the natural permafrost table at the 13 meters' distance to the embankment center; under the slope of 1 in 1.50 the distance is 15 meters and the distance is 17 meters at the condition of slope 1 in 2. That is to say the scope of the influence of embankment is increase with the slope gradient slackens.



(a) Slope of 1 in 1

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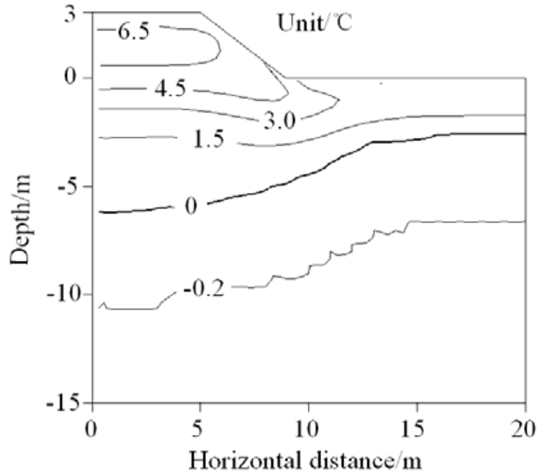
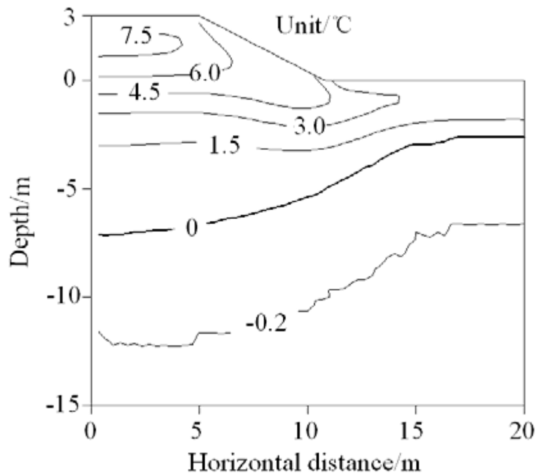


(b) Slope of 1 in 1.50



(c) Slope of 1 in 2

Fig.5 The temperature distribution on September 15th of the fiftieth year for different slope

In order to analyze the influence of soil temperature at certain depth of slope and slope toe under the condition of different slope gradient, figure.6 gives the horizontal distribution of ground temperature at the depth of 3 meters under embankment when the road is operated 5 years. It can be seen from the figure, because the permafrost table is higher than the natural permafrost table, so the temperature at the depth of 3 meters under embankment is negative value. As the increment of distance to the embankment centerline the temperature will decline, that is because the initial thermal equilibrium state was been destroyed after the construction of embankment. The nearer approaches the embankment centerline the more influence will suffer. The farther approaches the embankment centerline, the more closely the temperature to the initial ground temperature.

Fig.7 gives the temperature distribution under condition of different annual mean temperature and which the road operation life is 50 years. It can be seen from the figure the thaw bulb of the annual mean temperature at -4℃ is bigger than the annual mean temperature at -6℃, and the permafrost table is decline more obviously. The influence radius of lateral is larger. That is to say the lower the annual mean temperature, the smaller the influence scope of slope to the temperature field. So during the construction of road in permafrost regions, local temperature conditions are needed to be combined to choose proper slope gradient.

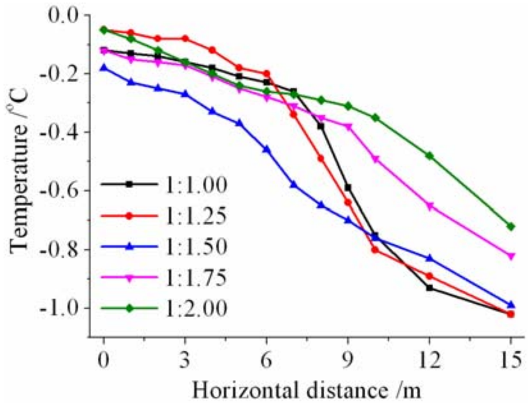
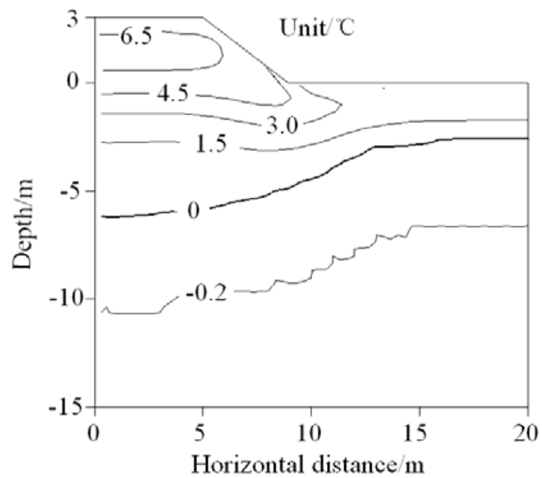
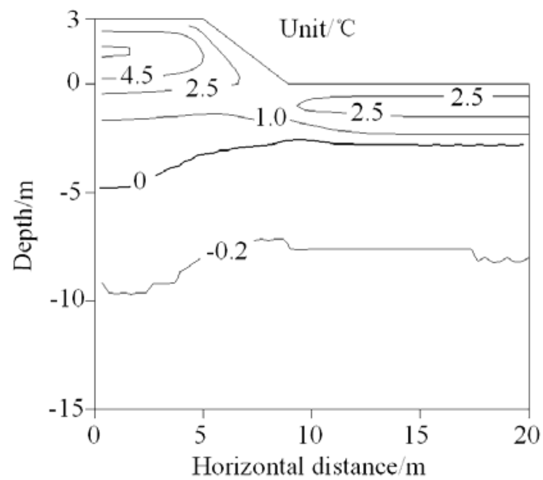


Fig.6 The horizontal distribution of ground temperature at the depth of 3 meters on September 15th of the fiftieth year



(a) Annual mean temperature at -4 ℃



(b) Annual mean temperature at -6 ℃

Fig. 7 The temperature distribution of embankment under different annual mean temperature

V. CONCLUSION

1) Under the condition that the annual mean temperature at -4 ℃, the thaw depth under embankment will increase with the slope gradient change. Moreover, when the slope is gentler, the time for embankment refrozen will be longer.
2) The lower ground temperature of the embankment slope and the slope foot will reduce with the gradient of slope slackens, but the decline is very small.
3) The influence of slope gradient on thermal state of permafrost embankment is relate to local mean temperature, as the annual mean temperature is very low the influence of slope gradient on temperature field will become small.

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