Experimental Study on Application Effects of Thermal Pipes along Chai-Mu Railway

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ABSTRACT

Thermal pipe is a kind of two-phase closed thermosyphon in use of civil engineering, widely applied not only in large-scale linear engineering, such as highway, railway, but also airport and buildings in permafrost regions. Average annual air temperature, frozen soil type, engineering geological condition, permafrost environments as well as other local factors including sunny-shady slope effect are principal causes which have to be taken into account in order to accurately evaluate the cooling effect of thermal pipe. Through field data of observed cross-sections, the cooling effect of thermal pipe in permafrost regions was analyzed. The result indicates that thermal pipe revetment embankment has perfect effect on cooling the roadbed in permafrost regions. (1)There is a negative exponential function between ground temperature and the distance between thermal pipe and thermometer hole, and the regression equations were shown. Based on the different temperature standards, including the average annual temperature, the highest annual temperature and the lowest annual temperature, the cooling radii of thermal pipe are 2.4m, 0.5m and 4.5m, respectively. (2) In extremely high-temperature unstable permafrost regions and high-temperature unstable permafrost regions, although the typical sections are built on sloping wetlands, the engineering measure that the thermal pipes have stood in two ranks on sunny side and there is a row of pipes on shady side can uplift the artificial permafrost table of the whole embankment, and can reduce the permafrost temperature and the high-temperature permafrost layer. Meanwhile, this engineering measure has removed sunny-shady slope effect and enhanced thermal stability of the embankment.

KEYWORDS: thermal pipe; cooling radius; sunny-shady effect; temperature field; freezing–thawing process

INTRODUCTION

Thermal pipe is an element with very good properties of heat transfer, first suggested by R.S. Gaugler (1942). In 1964, G.M. Grover et al. of the Los Alamos National Lab independently produced a device which is similar to the element suggested by R.S. Gaugler, called "Thermal pipe"or "Hot pile". Based on these researches, thermal pipes have become thermosiphon without any additional power and have been widely used in civil engineering projects due to their outstanding properties. Also, thermosyphon can be widely applied not only in large-scale linear engineering, such as highway, railway, but also airport and buildings in cold regions. Researchers and skilled technicians at home and abroad have done much of their work in the relevant field, and have basically solved the craftsmanship, design calculation of thermal pipe and its key technologies (Sergei, 2004; Li et al.., 2003; Guly, 2004). Guo et al. (2009) reviewed research and application of thermosyphon, including influential factors of heat conduction and engineering design parameters in cold regions based on field data and theoretical analyses. And the application future of thermosyphon in cold regions is discussed. Sun et al. (2009) built a 3-D numerical value calculation model of thermal field of permafrost roadbed and adopted finite element method to predict and compare thermal field of ordinary roadbed and two-phase closed thermosyphon roadbed by rising 2.6°C in the coming 50 years. Wu et al. (2010) evaluated cooling effect of two-phase closed thermosyphon by estimating heat budget based on the geological bore data and ground temperature data of the Qinghgai-Tibet Railway. Li (2011) researched on the relationship among diameter of thermal probes, producing cold quantity and cooling effect on ground temperature. Based on the principle of thermosyphon and combined with filling subgrade in Tanggula permafrost regions in China, Guo et al. (2014) analyzed the cooling effect of thermosyphon on filling subgrade with FEM considering thermal conductivity of thermosyphon, southern and northern slopes and phase change.

There are 20391 thermal pipes along the Chaidaer Muli Railway, which is simply called the CMR. It is the first local railway with the total length of 142 km in northeastern Qinghai Province, China, starting in Chaidaer County (100º25′55″E, 37º35′40″N) and ending in Muli Country (99º11′00″E, 38º08′38″N) on the Qinghai-Tibet Plateau. It has run across many sloping wetlands, and most subgrade sections are asymmetric, and sunny-shady slope phenomenon is commonly serious. The sunny-shady slope phenomenon means there was an obvious thermal difference between the southern slope and the northern slope, and in Chinese which is named as "sunny-shady slope effect". The elevation of this region ranges from 3600m to 4100m and the average annual air temperature varies from about -2.4°C to -5.8°C. According to the meteorological data, the minimum air temperature is -39.37°C and the maximum air temperature is 17.06°C, respectively. The maximum wind speed is 14.97m/s. The average annual wind speed is 2.29m/s. There is rich rain and snow, and swamps as well as marshes are both developed. The annual precipitation along the CMR is approximately 500 $mm.a^{-1}$. The vegetation coverage is more than 60% in most of this permafrost region, and the wetlands are widely distributed. About 77 km of all the CMR runs across wetlands. The permafrost is discontinuous and unstable with average annual ground temperature ranged from -1°C to 0°C. The ice contents in most permafrost regions are also very higher. So the permafrost environment and the engineering geological conditions along the CMR both are typical of complexity and inconstancy.

The thermal pipes adopted along CMR are two-phase closed thermosyphons, whose thermal power is much higher. The working medium is NH_3. According to research fruits, the diameter of thermal pipe is 83mm, and the wall thickness is 5mm. Fig.1 is a schematic drawing that illustrates the processing of two-phase closed thermosiphon. In order to eliminate the sunny-shady slope problem, the thermal pipes have stood in two ranks on sunny side but there is a row of pipes on shady side. The longitudinal spacing of thermal pipe is 3m. On the sunny side, one row of thermal pipes is situated at the embankment foot, and another row of thermal pipes lies beside the revetment foot. There is 3m between the two rows of thermal pipes. On the shady side, there is one row of thermal pipes beside the revetment shoulder(Fig.2). Section DK74+500, section DK99+100 and section 99+200 are thermal pipe revetment embankments, whose embankment strikes are 70°, 35°, 35°, respectively. The mean annual ground temperatures of the three sections are -0.32℃, -0.89℃ and -0.99℃, respectively. The construction of embankments began from October, 2007. And until July, 2008, the main monitoring equipment and apparatus have completely finished. By the early in 2010, the whole observation time has been not enough up to 2 annual cycles.

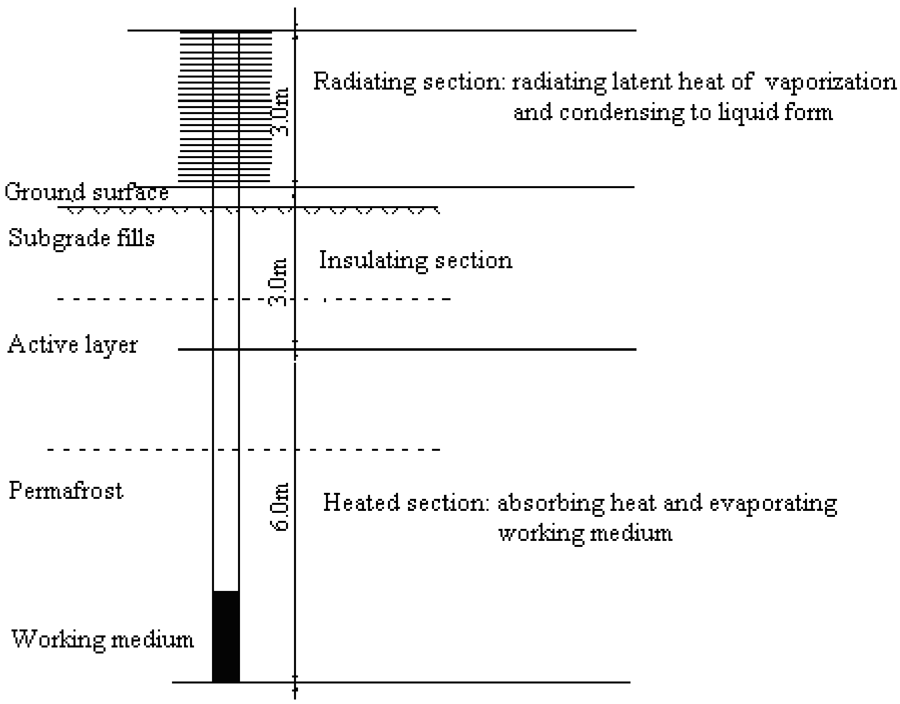

Figure 1: Schematic drawing of the two-phase closed thermosiphon

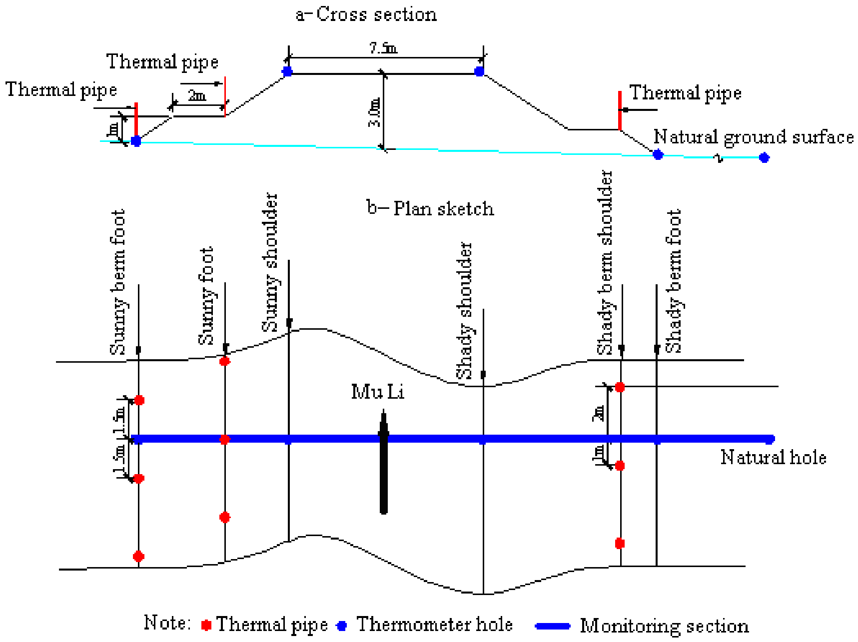

Figure 2: Schematic layout of the thermal pipe in section DK99+100

COOLING RADIUS OF THERMAL PIPE

Cooling radius of thermal pipe has important influence on its engineering effect. In order to grasp whether the design parameters are rational or not, the cooling radius of thermal pipe in section DK99+100 has been observed from October, 2008. Fig.3 shows the construction site of observing cooling radius of thermal pipe. Taking one thermal pipe as the base, along the vertical direction of the embankment there are laid out thermometer hole 1, thermometer hole 2, thermometer hole 3 and thermometer hole 4 (natural hole) in sequence, respectively. And the distances from these four thermometer holes to embankment are 0.5m, 1.0m, 1.5m and 15.0m, respectively. The depths of thermometer holes are all 8.0m. The data acquisition apparatus is composed of thermal-susceptible resistance sensors and Fluke IV multimeters with a 0.1Ω precision. The space between two probes is 0.5m. The frequency of observation is once every 30 days and the data are hand-picked. Fig.4 gives the ground tempera-ture curves of all holes on 11 December in 2009. From 1.5m to 5.5m under ground surface, there are great differences in ground temperature among the 4 thermometer holes. The closer the thermometer hole lives to thermal pipe, the lower the temperature is. That is to say, the cooling effect of thermal pipe becomes weaker and weaker with the increasing distance. As the circumstances and air temperature change, so does the engineering effect of thermal pipe. In different months, the cooling effect of thermal pipe on soil is different. In order to accurately describe how the air temperature influences on the working radius of thermal pipe, the article analyses it from 3 respects, including average annual temperature, the highest annual temperature and the lowest annual temperature. Table 1 gives temperature indices of various different depths. Taking the average annual temperature as evaluation criterion, we can understand working radius of thermal pipe throughout all the year. Taking the highest annual temperature as evaluation criterion, we can understand working radius of thermal pipe in the most unfavorable season. And taking the lowest annual temperature as evaluation criterion, we can understand working radius of thermal pipe in the most favorable season.

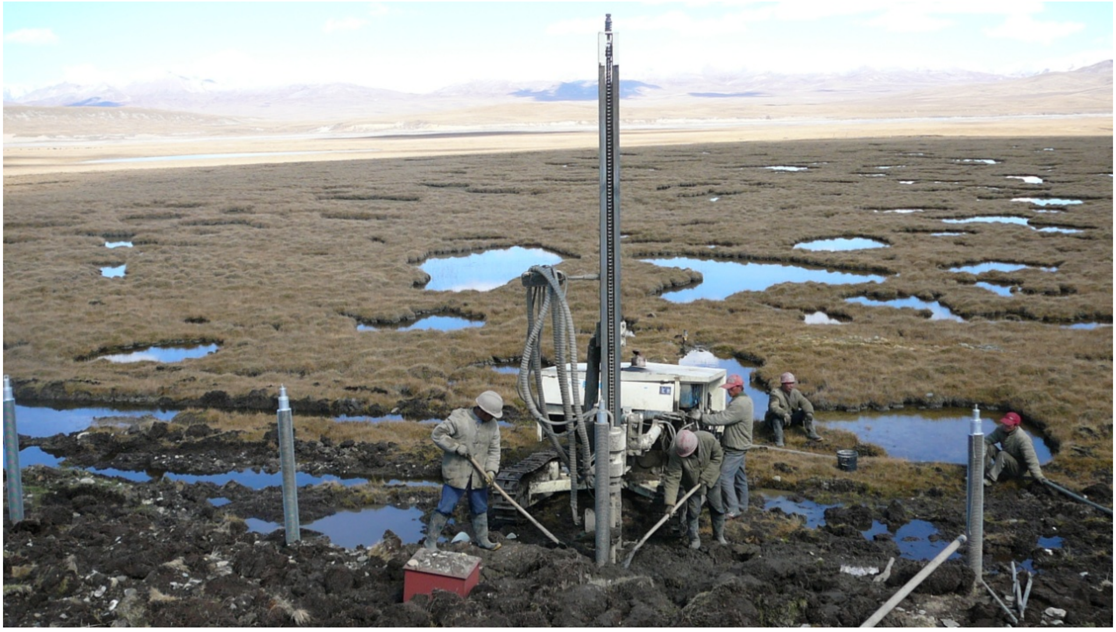

Figure 3: The construction site of observing cooling radius of thermal pipe

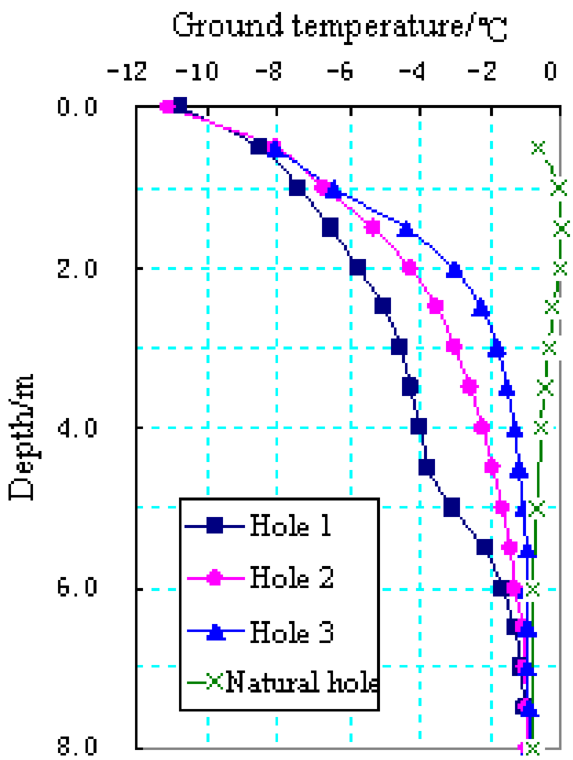

Figure 4: Ground temperature curves of all holes on 11 December in 2009

Table 1: Temperatures of monitoring holes in thermal pipe embankment at various depths (°C)

Radius /m	*0.5m*			*1.0m*			*1.5m*			*15.0m*		
Depth /m	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.
0.5	-2.15	8.54	-11.42	-3.43	2.48	-12.24	-1.51	9.54	-8.47	-0.76	4.09	-7.28
1.0	-2.95	2.19	-8.96	-2.76	1.25	-7.83	-2.06	3.25	-7.58	-0.53	2.42	-3.60
1.5	-2.66	0.41	-7.78	-2.44	0.32	-6.51	-1.77	1.36	-6.13	-0.39	1.15	-2.27
2.0	-2.42	-0.01	-6.73	-2.23	-0.08	-5.36	-1.85	0.22	-4.83	-0.50	0.22	-1.97
3.0	-2.22	-0.88	-5.33	-1.89	-0.40	-3.81	-1.58	-0.30	-3.42	-0.54	-0.07	-1.29
4.0	-2.06	-0.88	-4.51	-1.70	-0.62	-3.17	-1.42	-0.55	-2.71	-0.62	-0.37	-0.92
5.0	-1.95	-0.66	-3.89	-1.46	-0.67	-3.22	-1.24	-0.66	-2.35	-0.69	-0.55	-0.82
6.0	-1.38	-0.70	-2.34	-1.11	-0.73	-1.53	-1.01	-0.72	-1.35	-0.71	0.03	-0.95
8.8	-0.91	-0.74	-1.09	-0.85	-0.74	-0.96	-0.86	-0.74	-1.03	-0.81	-0.66	-0.90

Taking the middle section of thermal pipe evaporator as a baseline for measuring cooling radius. Fig.5 shows how the average annual temperature, the highest annual temperature and the lowest annual temperature have varied according to horizontal distance, respectively. The result indicates there is a negative exponential function between ground temperature and the distance between thermal pipe and thermometer hole. And the fitting curves are as follows.

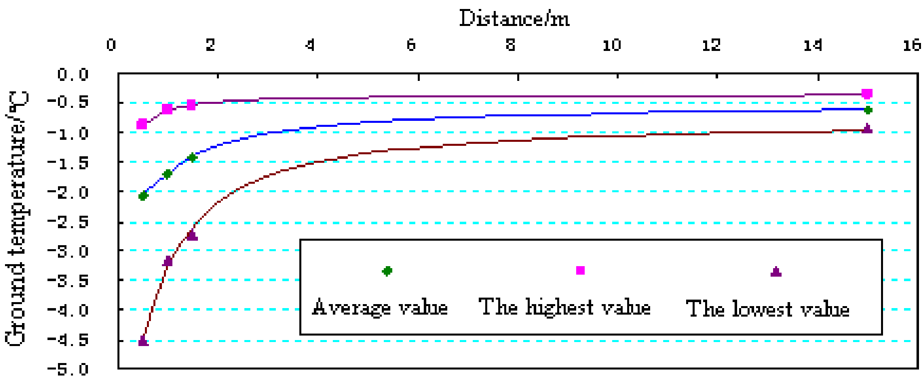

Figure 5: Horizontal temperature distribution around thermal pipe

The fitting curves between the average annual temperature and cooling radius,

$$T = \frac{0.4286}{r^2} - \frac{1.6294}{r} - 0.5149$$ Correlation coefficient: $R^2 = 0.9997$

The fitting curves between the highest annual temperature and cooling radius,

$$T = \frac{0.0137}{r^2} - \frac{0.2905}{r} - 0.3524$$ Correlation coefficient: $R^2 = 0.9983$

The fitting curves between the lowest annual temperature and cooling radius,

$$T = \frac{0.661}{r^2} - \frac{3.1956}{r} - 0.7448$$ Correlation coefficient: $R^2 = 0.9951$

T—Ground temperature; *r*—the distance between thermal pipe and thermometer hole, named cooling radius.

Taking decreasing in temperature at -0.5℃ as the reference standard of cooling radius of thermal pipe, then the corresponding temperatures of the average annual temperature, the highest annual temperature and the lowest annual temperature are -1.12℃, -0.87℃ and -1.42℃, respectively. Through above-mentioned fitting method, based on different temperature standards, the cooling radii of thermal pipe are 2.4m, 0.5m and 4.5m, respectively. In the most unfavorable season, such as in summer, ground temperature at 3.0m depth is influnced not only by energy accumulated in winter but also by strong heating from ground surface. And thermal pipe could hardly perform its cooling functions. Also, cooling reference standard and cooling radius are interrelated and interacted with each other. Under the condition that the cooling reference standard is -0.5℃, the cooling radius is 0.5m. If the cooling reference standard is taken as -0.2℃, the cooling radius has risen to 1.3m. In the most favorable season, such as in winter, the cooling effect of thermal pipe comes from the energy release of ground surface. These active factors have extended cooling radius of thermal pipe, so the cooling radius is up to 4.5m. Taking the average annual temperature, a more objective method of evaluating description, as evaluation criterion, the cooling radius is up to 2.4m. And this result is consistent with data report previously（Li et al., 2006）. The spacing of thermal pipe along CMR is 3m, which means the cooling radius in practice is no larger than 1.5m. This value is much smaller than 2.4m which is got according to the average annual temperature. So the layout of thermal pipe along CMR is tailored to meet the needs of embankment stability. In order to conveniently describe, in the following the left side means sunny side and the right side means shady side in all sections.

COOLING EFFECT IN EXTREMELY HIGH-TEMPERATURE UNSTABLE PERMAFROST REGIONS

The cooling effect of thermal pipe varies with the average annual ground temperature. Section DK74+500 is located on wet slope of the nothern Datong River, and its strike is 70°, nearly from east to west. The average annual ground temperature is -0.3℃, belonging to high-temperature extremely unstable permafrost regions. Section DK74+500 was finished in late 2007, and thermal pipe was set up in mid-2008. Fig.6 gives sectional shape and temperature field of section DK74+500 on 10 September in 2008. The temperature field inside embankment has many features.（1）Relative to the natural permafrost table, the maximum thaw depth of the whole embankment has been clearly elevated, and the artificial permafrost table of sunny shoulder, shady shoulder and embankment itself is shallower 1.0m than that of sunny foot. （2）In contrast to natural ground surface, the maximum thaw depth of sunny shoulder is almost equal to that of shady shoulder, and this embodies that the thermal pipes have stood in two ranks on sunny side has reached better cooling effect. But the maximum thaw depth of sunny foot is deeper 0.5m than that of shady foot. （3）There is a layer of high temperature permafrost (-0.2~0.0℃) about 3m thickness throughout the embankment.

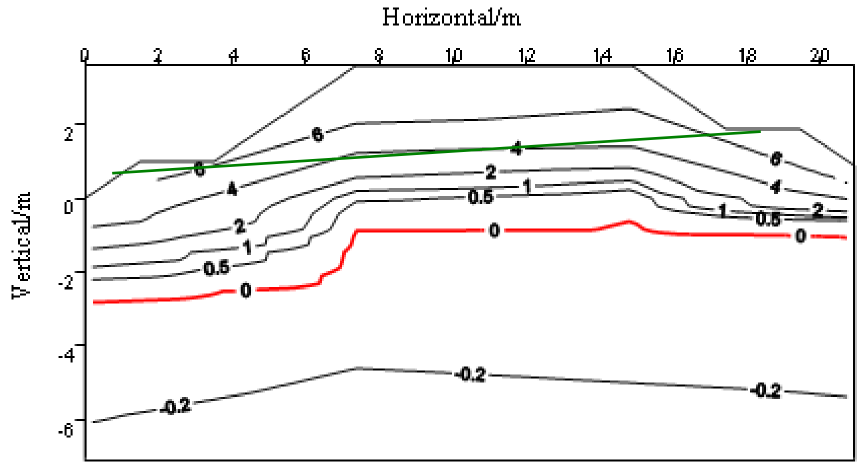

Figure 6: Sectional shape and temperature field of section DK74+500 on 10 September in 2008（unit：℃）

Fig.7 gives temperature field of section DK74+500 on 26 September in 2009. According to the distribution of temperature fields in Fig.6 and Fig.7, section DK74+500 is developing towards cooling direction. First, the “0°C” isotherm has been clearly elevated—especially the “0°C” isotherm under sunny foot has elevated by 2.0m. Secondly, the isotherms in Fig.7 are even straighter than those in Fig.6, which means thermal pipe has mainly eliminated the sunny-shady slope problem. Finally, the layer of high temperature permafrost (-0.2~0.0°C) has been reduced.

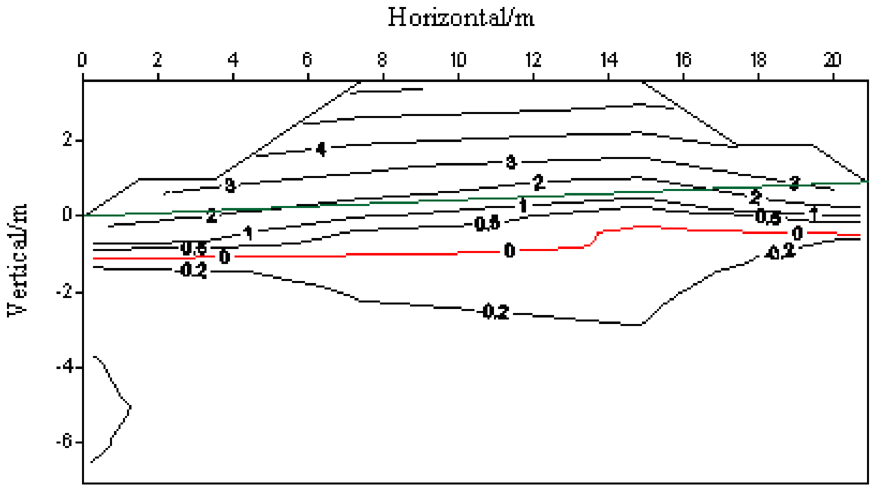

Figure 7: Temperature field of section DK74+500 on 26 September in 2009（unit：℃）

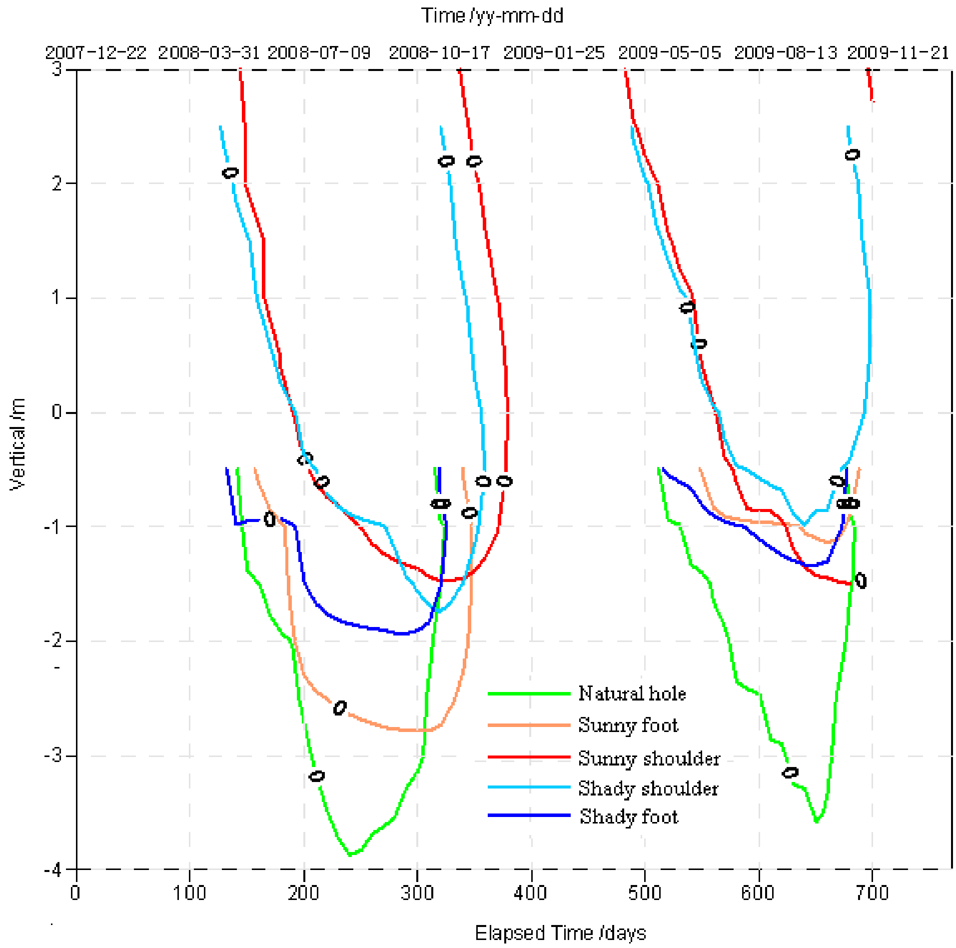

Figure 8: Developing process of "0°C" isotherm of section DK74+500

The maximum depth of "0°C" isotherm has reflected the artificial permafrost table. That is to say, the artificial permafrost table has been quickly finalised through the developing process of "0°C" isotherm. Therefore, the developing process of "0°C" isotherm can fully reflect engineering effect of thermal pipe. Fig.8 gives the developing process of "0°C"isotherm of section DK74+500. From 2007 to 2009, the permafrost table of natural hole has uplifted from 3.88m to 3.58m. The artificial permafrost table of sunny foot hole has uplifted from 2.79m to 1.14m. The artificial permafrost table of sunny shoulder hole has been little changed at 1.50m. The artificial permafrost table of shady shoulder hole has uplifted from 1.73m to 0.98m. The artificial permafrost table of shady foot hole has increased from 1.93m to 1.33m. Most of the permafrost tables under different holes have uplifted, and all the artificial permafrost tables under embankment are shallower than that under natural hole. Based on the field data, the engineering measure that the thermal pipes have stood in two ranks on sunny side and there is a row of pipes on shady side can uplift the artificial permafrost table of the whole embankment, and can reduce the permafrost temperature and the high-temperature permafrost layer. Meanwhile, this engineering measure has removed sunny-shady slope effect and enhanced the thermal stability of the embankment.

COOLING EFFECT IN HIGH-TEMPERATURE UNSTABLE PERMAFROST REGIONS

Sections DK99＋100 and DK99＋200 are test sections of thermal pipe, located on Sainuo and Rang Terrace, belonging to high-temperature unstable permafrost regions. Section DK99＋355 is the contrast section, without any measures. The average altitude of this region is about 3780m. And the landscape is wider, flatter and very scenic. In summer, there is filled with water on groud surface, belonging to typical wetlands. As the weather gets warmer, this region could become wetlands.Therefore, permafrost in this region is degenerative. According to field survey, there is humus layer of 20～80cm thickness, and under which there is gravel soil. The ground bottom are weathering mudstones. The ice content of permafrost is about 20%, and in some local areas ice content is more than 80%. The frozen types are ice-saturated frozen and soil-laid ice layer. The embankment height is strongly dependent on the topography. The embankment heights of section DK99+100 and DK99+200 are both 3.0m, and embankment height of section DK99+355 is 4.5m. Average annual ground temperatures of section DK99+100 and DK99+200 have ranged from -0.89 to -0.99℃. Average annual ground temperature of section DK99+355 has been about -1.3℃, belonging to low-temperature stability permafrost. Fig.9 shows ground temperature of natural holes on 16 April in 2009. Average annual ground temperature of permafrost varies with moisture characteristics of ground surface. So, section DK99+100, section DK99+200 and section DK99+355 are located near each other, but the difference of thermal state has varied. According to the basic operating principle of thermal pipe, the low average annual air temperature will benefit the cooling effect of thermal pipe.

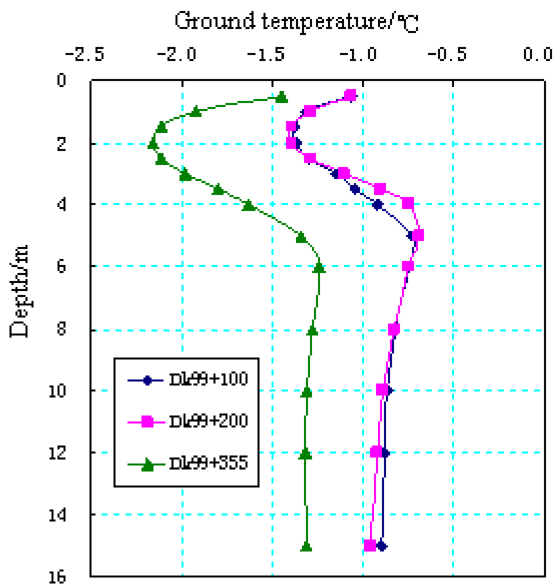

Figure 9: Ground temperature of natural hole on 16 April in 2009

Fig.10 gives the developing process of “0℃” isotherm of section DK99+100. The sunny foot hole and sunny shoulder hole are damaged during construction. Here we expatiate the cooling effect of thermal pipe by comparying shady foot hole, shady shoulder hole and natural hole. Because the thermal pipes of section DK99+100 were finished at the beginning of October, 2007, the thawing process did not depend on the thermal pipe in 2007. In 2008, the artificial permafrost table of shady shoulder hole is 1.8m, which is almost equal to the natural permafrost table（1.9m）. The artificial permafrost table of shady foot hole is 1.42m. In 2009, after a year the average annual temperature has rised and the permafrost table of natural hole reached 2.3m. The artificial permafrost table of shady foot hole has uplifted from 1.42m to 0.84m, and the artificial permafrost table of shady shoulder hole has uplifted from 1.8m to 1.62m. So, the cooling effect of thermal pipe is very considerable.

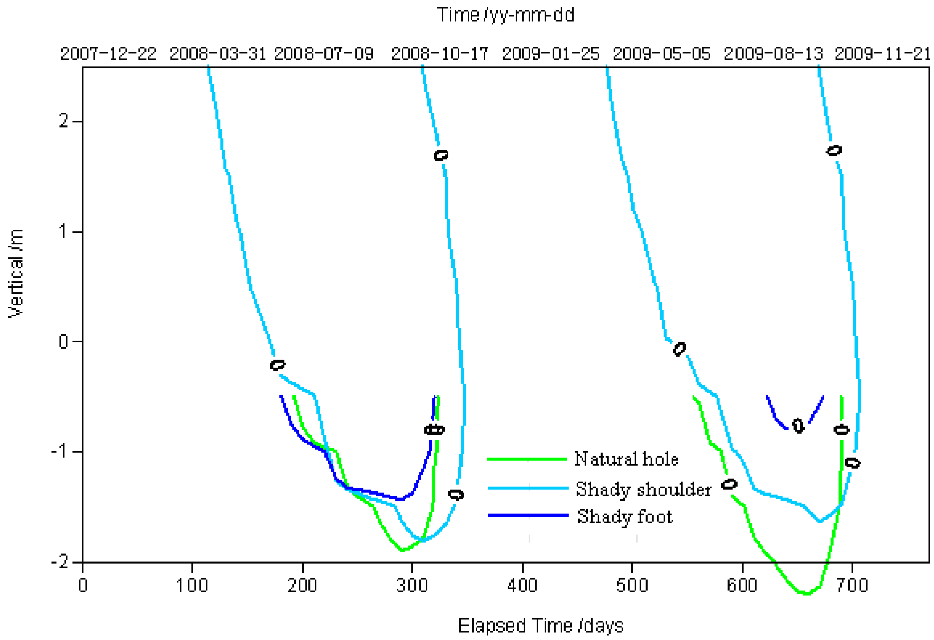

Figure 10: Developing process of “0°C” isotherm of section DK99+100

Section DK99+200 has been working from June, 2008 when automatic data acquisition instrument was fitted. Fig.11 gives temperature fields of section DK 99+200 on 1 October in 2008 and on 1 October in 2009, respectively. There are some characteristics：（1）The shapes of isotherm are almost horizontal, which means there is no obvious sunny-shady effect.（2）In comparison with 2008, the “0°C” isotherm of two feet on 1 October in 2009 remains substantially unchanged, but the “0°C” isotherm of sunny shoulder has been a slight increase. The artificial permafrost table of all holes is shallower than that of natural hole. (3) On 1 October in 2009, the “-1.0°C” isotherm and the “-0.5°C” isotherm are both elevated, which means the permafrost is moving toward thermal stability.

Table 2 gives statistical results of annual temperature of 4 sections. We could just see even in the high-temperature unsteady permafrost regions, if the thermal pipe has been particularly intense in the embankment sunny side, which has completely healed differential settlement as well as the sunny-shady phenomenon. In this case, the artificial permafrost table of the whole embankment cross section has been significantly elevated.

Table 2: Statistical results of annual temperature of 4 sections （℃）

Field location	*DK74+500*	*DK99+100*	*DK99+200*	*DK99+355*
Shady slope	9.24	7.10	7.20	-0.32
Sunny slope	-0.18	0.28	1.39	1.31

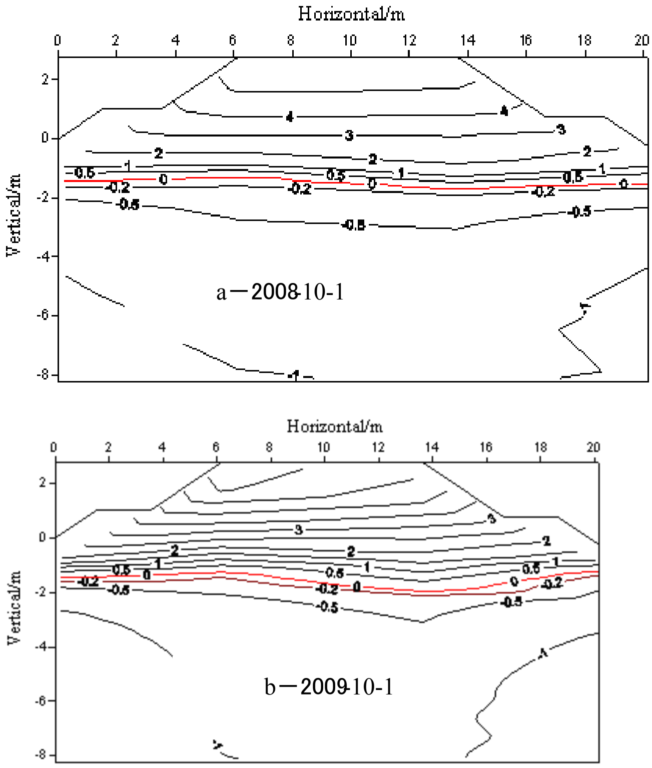

Figure 11: Temperature field of section DK99+200 on 1 October in 2008 and 2009 (unit: ^{o}C)

CONCLUSION

Through the field data of observed cross-sections, the cooling effect of thermal pipe in permafrost regions was analyzed. The influence of average annual air temperature, sunny-shady slope effect and related indexes of temperature were analyzed. And how thermal pipe has effect on the thermal stability of permafrost was studied. Under these experimental conditions and analysis, conclusions are as follows..

(1) There is a negative exponential function between ground temperature and the distance between thermal pipe and thermometer hole, and the regression equations were shown. Based on the different temperature standards, including the average annual temperature, the highest annual temperature and the lowest annual temperature, the cooling radii of thermal pipe are 2.4m, 0.5m and 4.5m, respectively.

(2) In extremely high-temperature unstable permafrost regions and high-temperature unstable permafrost regions, although the typical sections are built on sloping wetlands, the engineering measure that the thermal pipes have stood in two ranks on sunny side and there is a row of pipes on

shady side can uplift the artificial permafrost table of the whole embankment, and can reduce the permafrost temperature and the high-temperature permafrost layer. Meanwhile, this engineering measure has removed sunny-shady slope effect and enhanced thermal stability of the embankment.

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