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Study on permafrost thermal stability due to geohazards of China-Russia Crude Oil Pipeline

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ABSTRACT

The Mohe–Daqing oil pipeline (MDOP) of China–Russia crude oil pipeline (CRCOP) goes through a 441 km permafrost in high-latitude regions. Construction technology, oil temperature, and global warming effect cause the increase of ground temperature and accelerate the degradation of permafrost. The influence of geohazards on the existing CRCOP and its accompanying road was investigated in this study, which showed that the current engineering had been affected by freezing-thawing. In view of this problem, the permafrost thermal stability of the oil pipe and accompanying road was simulated based on the MDOP, considering different oil temperatures, global warming, thermal insulation, and different distances between the two. The numerical results indicate that the oil temperature had considerable influence on the thawing rate of permafrost. Placing the thermal insulation material around the oil pipe can effectively mitigate or even control the degradation of permafrost. With this measurement, the thaw depth has remained stable after 5 years of construction and had been controlled within 3.0 m when the thermal insulation thickness reached 8.0 cm. The larger the distance between the oil pipe and accompanying road, the lesser the thermal disturbance. Therefore, the thermal stability of MDOP can positively adopt a suitable oil temperature for thermal insulation thickness, along with an optimized distance away from the accompanying road as well. This study would also provide an essential theoretical and technological support for the design of oil pipeline in other permafrost regions.

INTRODUCTION

Frozen soil consists of solid mineral particles, ice inclusion, liquid water (unfrozen water and tightly bound water), and gaseous inclusion (water vapor and air) (Tsytovich, 1985). It is a special type of soil that is highly sensitive to temperature changes. Permafrost is widely distributed around the world, occupying 25% of the land on earth (French, 1996). It is mainly distributed in parts of northern Canada, Alaska in the United States, Siberia in Russia, Northern Europe, and the Qinghai–Tibet Plateau and Xing'an Mountains in China.

Permafrost regions are rich in oil and gas resources. In these areas, long-distance pipes have become the most economical way of oil transportation. In North America, several oil pipelines have been built in Canada and Alaska since World War II and it even has a formed network. Canada built an oil pipeline from Norman Wells Oil field to Alaska during this period. Furthermore, in 1956, an oil pipeline was built in Fairbanks, Alaska, with a diameter of 203 mm. Moreover, other countries rich in permafrost have carried out many oil pipes as well. In Siberia, Russia built the Nadym–Pur–Taz Gas pipe network where the buried pipe was used in permafrost regions. In addition, China built the Golmud–Lhasa oil pipeline across the Qinghai–Tibet Plateau from 1973 to 1977. This engineering project covers a distance of 1,076 km, 550 km of which is within permafrost (Li *et al*., 2015). In 2010, the China–Russia crude oil pipeline (CRCOP) was built in northeast China; the pipeline passes through areas with complex geological conditions, including a 441 km long permafrost section and a 512 km long seasonally frozen section in Xing'an Mountains and Nenjiang Valley (Jin *et al*., 2008; Li *et al*., 2008).

Constructing an oil pipe in permafrost regions has its own peculiarity and difficulty due to its adverse impact on frozen soil foundation. The change of freezing and thawing conditions could directly affect the physical and mechanical properties of permafrost, which has a high probability of inducing frost hazards (*Yu et al.*,2016; *Jin et al*., 2010). Thus, this condition will threaten the stability of oil pipes. Regarding the differences in geological conditions, frozen soil types, and topographic features of construction site, the freezing and thawing process is of remarkable inhomogeneity, which may result in an inhomogeneous deformation around oil pipe. Specifically, oil with negative temperature may form a freezing circle around the pipe and cause a large frost heave. Furthermore, warm oil could cause thawing of ice-rich soil adjacent to the pipeline when it crosses through permafrost, thereby resulting in thaw settlement of the pipeline and variation of soil properties. The two aspects influence the permafrost foundation that would induce damage on the pipeline in the future, especially in the freezing thaw transitional zone. Thus, the oil temperature distribution along the pipeline during the long-term operation period is a key factor in pipeline foundation design, especially in the context climate warming (Li *et al*., 2010).

At present, numerous studies on thermal exchange between oil pipe and surrounding soil have been accomplished, such as on thermal regimes, thaw depth, oil temperature, thaw settlement, frost heave, and pipe deformation (Wen, et al., 2010; Doblanko, *et al*., 2002; Chen, *et al.*, 1994; Cui and Zhang, 2004; Hastaoglu and Hakin, 1996; Yu *et al*., 2011). Researchers have discovered that the frost heave and thaw settlement are the key problems in oil pipes during the design and working periods (Wen *et al*., 2010). The peak oil temperature of crude oil pipeline in Alaska reached 60 °C, which brought a serious thaw hazard in permafrost regions. To improve the stability of pipelines, the overhead type pile and thermosiphon foundation were used in these regions (Lachenbruch, 1970; Johnson and Hegdal, 2008). In addition, similar problems occurred in the Norman Oil pipeline in Canada (Nixon and Kaye, 1996). Thus, the ambient temperature oil transportation was adopted in CRCOP, so that large areas of thawing would not appear along the pipeline. However, we have to note that a large diameter (813 mm) and the buried pipe type were used in this engineering structure because of concerns about frequent forest fires in the region (Jin and Brewer, 2005; Yu *et al*., 2014). Furthermore, the oil temperature was positive during the working period according to the monitoring data. As shown in Fig.1, the oil temperatures at the Mohe, Tahe, and Jagdaqi inlet sites are all above 0 °C even in winter (Li *et al*., 2015). The large heat input of permafrost foundation is negligible from the oil pipe. In addition, several accompanying roads are along the oil pipeline in this region to provide services for pipeline during the construction and operation periods. The coupled heat effect may further induce thaw hazard of permafrost. Thus, the operational safety of the oil pipeline may face a greater challenge especially under global warming.

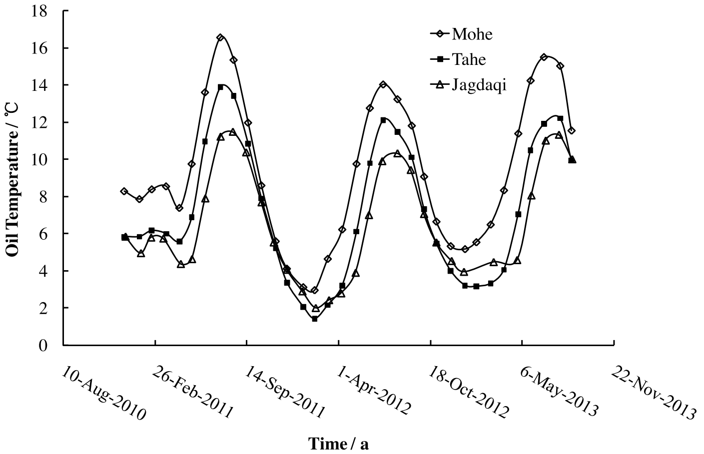


Fig. 1. Monitoring results of oil temperatures in three pumping stations (Mohe, Tahe, and Jagdaqi).

This paper investigates the influence of geohazards on the existing CRCOP and its accompanying road. The current engineering has been affected by freezing–thawing. The thermal interference between each other could lead to more serious geohazards. In view of this problem, this study chooses CRCOP and accompanying road as the object to study their thermal budget. An oil-road coupled heat transfer model was proposed, which represented the thermal influence between the two engineering structures. The research results would provide essential theoretical and technological support for the oil pipeline engineering in permafrost regions.

PERMAFROST GEOLOGICAL CONDITIONS AND FREEZING-THAWING HAZARDS ALONG MDOP AND JDH

Overview of permafrost geological conditions in Mohe–Daqing oil pipeline

CRCOP starts from Skovorodino in Russia, reaches Mohe in China, and ends in Daqing across northern Heilongjiang and eastern Inner Mongolia. In the China region, the pipeline is called Mohe–Daqing pipeline (MDOP). The ambient temperature sealing transportation technology is adopted in this engineering project with a diameter of 813 mm and design pressure of 8.0 MPa (Jin *et al*., 2010; PetroChina Petroleum Planning Institute, 2005). The design oil temperature at Skovorodino and Mohe inlets was –6 °C in winter and 10 °C in summer.

The MDOP goes through 441 km of permafrost (from Mohe to Dayangshu) and 512 km of seasonally frozen soil region (from Dayangshu to Daqing), most of which are located in Xing'an mountain and Nenjiang valley, as shown in Fig. 2 (Jin *et al*., 2010). The terrain is generally hilly, with industrialized rivers, forest, and marsh along the oil pipeline. The geological condition of permafrost is very complicated, and a series of harmful frozen soil phenomena occur, as thermokarst lake, flooding icing, and others. The geological characters of permafrost are as follows: (1) The developed features of permafrost are mainly controlled by latitude. As the latitude decreases, the permafrost distribution decays continuously to an island with an expanding thaw zone. (2) The freezing–thawing transition problem is relatively serious, thereby causing poor sustainability. (3) The permafrost is mainly warm with a ground temperature higher than –1.0 °C.

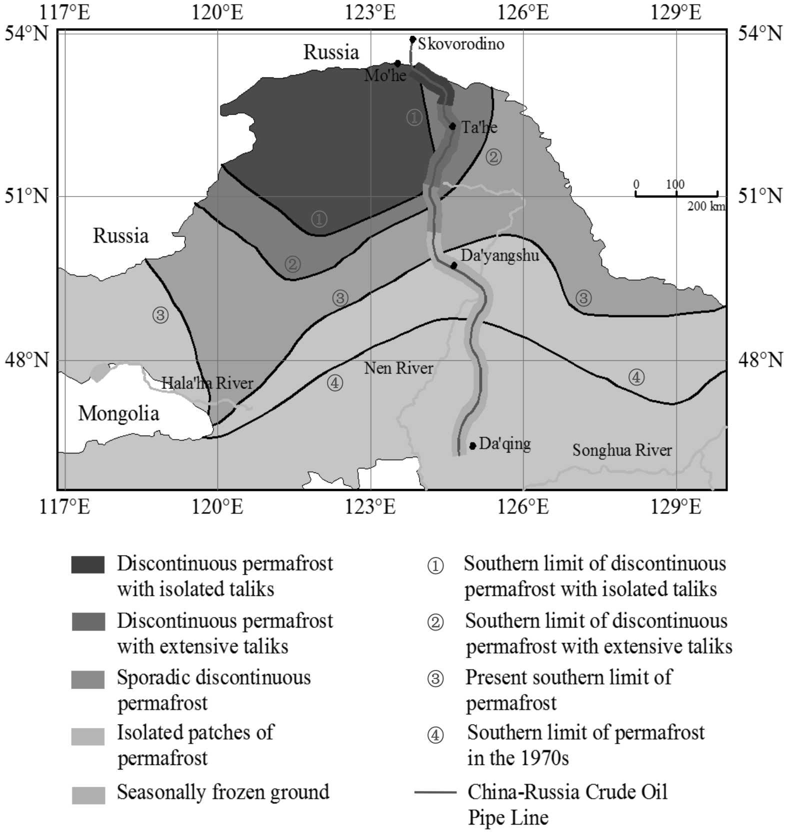


Fig. 2. Permafrost distribution along Mohe–Daqing line of China–Russia oil pipeline.

The thawing and freezing indexes are important parameters for evaluating the distribution of permafrost (King *et al*., 2006). A region is covered by permafrost if the thawing index is lower than the freezing index. Furthermore, an area is likely to develop continuous permafrost with a lower thawing index and a higher freezing index (Frauenfeld *et al*., 2007). The mathematical expression is as equation (1):

$$MAFI = \int_{L_0}^{L_1} |T| dt_1 \qquad T < 0°C; \qquad MATI = \int_{L_0}^{L_1} |T| dt_1 \qquad T > 0°C \tag{1}$$

where *MAFI* and *MATI* denote the freezing index and the thawing index, respectively, and L_0 and L_1 and *T* denote the air temperature.

In the Mohe region, the starting point of MDOP, the freezing period is from October to the next April. Annually, the average freezing index changes from 3000 to 3300 °C·d, while the thawing index changes from 2700 to 3100 °C·d (Fig. 3), which indicates that island permafrost developed in this region. The freezing depth is from 1.5 m to 2.0 m, which can be up to 2.26 m according to monitoring data.

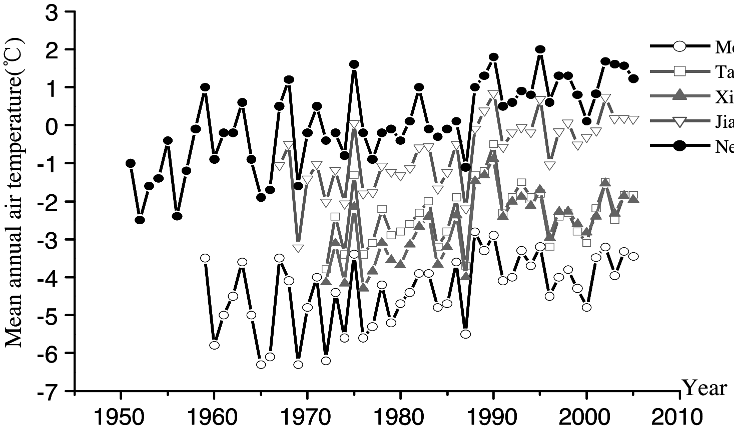


Fig. 3. Mean annual air temperature from 1950 to 2010.

To ensure the construction and maintenance of MDOP, the Jagdaqi–Daqing Highway (JDH) was built as an accompanying road for MDOP. The JDH was built in May 2009 and was opened to operation in September 2012. The climate and permafrost conditions are similar to those along MDOP.

Freezing–thawing hazards along MDOP and JDH

Freezing–thawing hazards along MDOP

The main factors that affect the stability of the MDOP are degradation of permafrost, freezing–thawing cycles, and disturbance of engineering activities. The pipeline has been running for nearly six years. Based on the field investigation, the exposed piping diseases were mainly caused by frost heave around the pipe and thaw settlement under the pipe. Moreover, this pipeline is emplaced JDH due to the thermal influence between the two engineering structures, and the defects of the pipeline become serious to a certain extent.

According to the investigation, the permafrost swamps and wetland regions are widely distributed along the MDOP. Change in the oil temperature would result in water migration and then frost heave, which would be harmful to the operation of the pipeline in these regions. Fig. 4 shows a case of frost heaving mounds around the pipeline located in Dayangqi town. The pipeline crosses the frost heaving mounds at K033 of JDH. The field investigation indicated that a larger frost heaving mound was formed above the pipeline, whose height could reach about 1.5 m after winter. Several cracks appeared at the top of the mound with a width of 5.0–20.0 cm. This section is located in a permafrost swamp, where suprapermafrost water has developed. In cold seasons, the aquifer is frozen; then, an ice layer gradually thickens under the influence of ground water pressure and frozen effect. Furthermore, in this section, the ground deformation is relatively higher due to lack of a thermal insulation layer around the pipeline. To improve the stability of the oil pipeline, several necessary measures should be adopted. Groundwater interception engineering is a basic principle for controlling the frozen damage. In addition, replacing it with coarse-grained soil and installing a thermal insulation layer around pipe are effective as well.

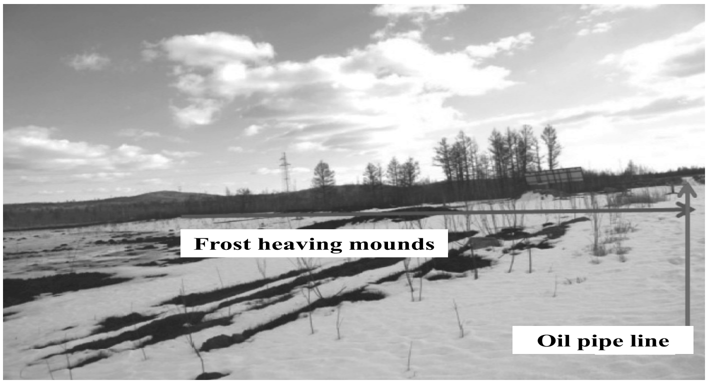


Fig. 4. Frost heaving mounds around the oil pipeline.

Thaw settlement is another main piping disease type along the MDOP. As shown in Fig. 1, the oil temperature at pumping stations is above 0 °C, which means that the pipeline is under a high temperature state. A field investigation for thawing depth was carried out with georadar in October 2012 and June 2013 (Li *et al.*, 2015), which indicated that a larger thaw bowl formed under the pipe in October 2012 with a maximum thawing depth of 1.0 m. However, the profile in June 2013 showed a gradual increase of thawing depth. Thus, to solve these problems and improve the thermal stability of the pipeline, several special measures should be installed, such as thermal insulation layer and thermosiphon.

Thermal stability of JDH

According to the survey data of the JDH, a series of diseases has appeared along the road with various degrees. For continuous freezing–thawing effect, the embankment fill presents a relatively higher water content. In warm seasons, the water in the embankment fill could not discharge in a timely manner, which significantly weakens the embankment strength. With the effect of vehicle loads, the embankment deformation occurs and forms cracks and ruts at the pavement. Furthermore, the rainwater in summer immerses into the embankment through pavement cracks, which further weakens the embankment strength in particular. For the aforementioned reasons, the main road disease types were longitudinal cracks, ruts, uneven frost, and pumping (Fig. 5–6).

Fig. 5. Longitudinal cracks of JDH.

Fig. 6. Frost pumping of JDH.

To monitor embankment stability in a timely manner, several deformation monitoring sections along JDH were established in 2010. A typical monitoring section is shown in Fig. 7. In this section, five deformation monitoring boreholes were embedded, including left-toe bore, left-shoulder bore, central bore, right-lane bore, and right-shoulder bore. Fig. 8 shows a deformation process of different points at K8+200 of the JDH from 2010 to 2013. The monitoring results at different depths under natural surface are listed in this figure. The data on September 1, 2010, were set as the initial point. In this figure, the deformation process presented a whole deformation state. Specifically, the deformation was mainly oriented from the zone at the depth of 4.0–6.0 m. The deformation below 9.0 m changed slightly during the operation period. On the other hand, the deformation at the cross section presented an obviously uneven deformation. The maximum deformations at the right shoulder lane were 75.6 and 69.3 mm. The specific deformations at different positions are summarized in Table 1.

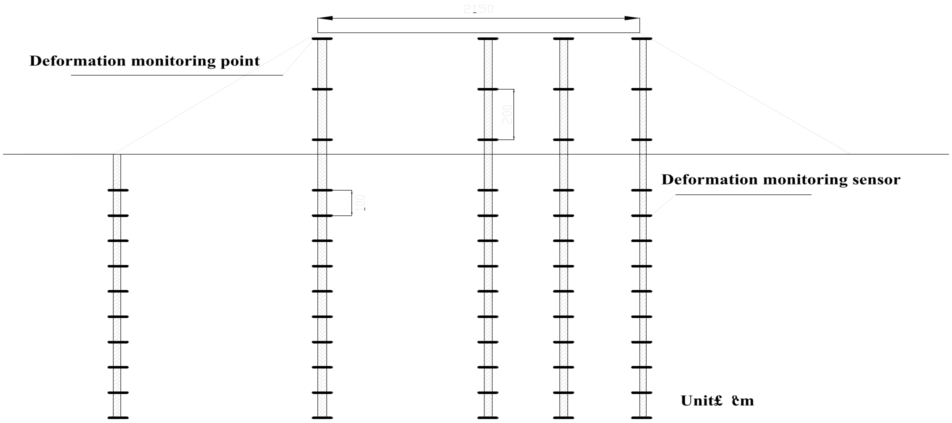
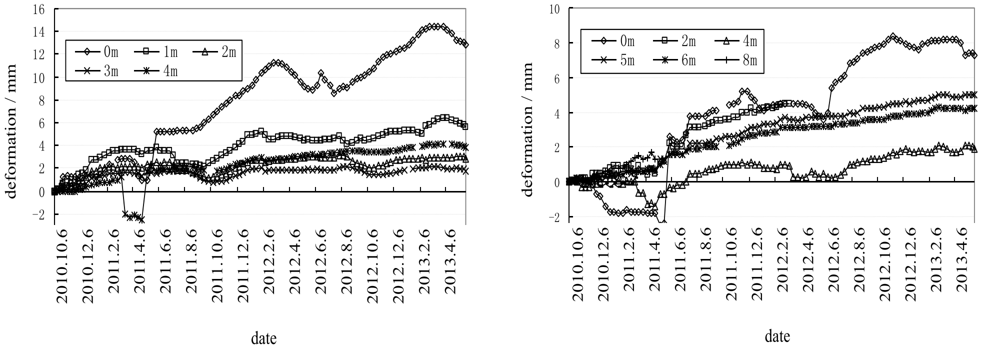


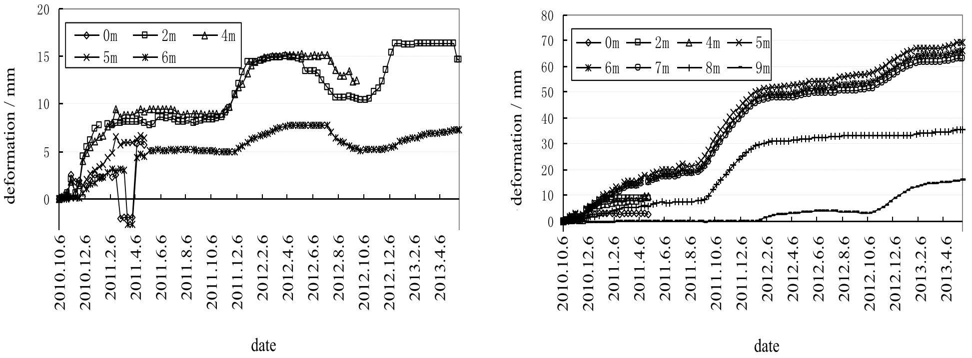
Fig. 7. Distribution of deformation boreholes in cross section.

Table 1. Deformation results at different positions (up to 2013.10).

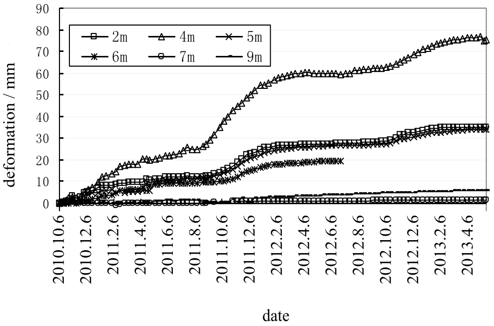
depths	deformation/mm							
	0m	2m	4m	5m	6m	7m	8m	9m
left-shoulder	8	7	-2~2	5	4.2			
central	6	16.4	15.1		8			
right lane	3	10	10	69.3	66	63.2	35.4	15.3
right-shoulder		35.1	75.6	25	19.4			
depths	deformation/mm							
	0m	1m	2m	3m	4m			
left-toe	14.4	6.4	3.0	1.9	4.0			



(a) left-toe bore (b) left-shoulder bore



(c) central bore (d) right lane bore



(e) right-shoulder bore

Fig. 8. Deformation curves at different depths.

Thermal disturbance between MDOP and JDH

To ensure operational safety and ordinary maintenance, some newly constructed highway and existing highways were inevitably used as accompanying highway during the construction of the MDOP. These highways are the key channel for material transportation such as personnel, material, machinery, and so on. The maximum distance between the JDH and MDOP is over 100 m and the nearest distance is only 10 m. In permafrost regions, the mutual and cooperative influence of oil temperature and strong heat-absorbing effect of asphalt pavement would further increase engineering catastrophe risk. These risks are embodied in two aspects. First, the engineering construction of the MDOP and JDH would heavily damage the regional ecological environment between them. It is extremely unfavorable for permafrost protection as vegetation is damaged by human activities and construction disturbance.

Secondly, surface runoff condition would also be broken and would result in an accumulation of surface water in construction areas. Based on field investigation, ponding depth in some regions reached up to tens of centimeters, which caused some bodies of water such as swamps, plash, and others. Under freezing-thawing circumstance, ice piton, frost mound, and other permafrost disasters would occur in these regions and cause potential trouble for engineering stability. The heat effect caused by pipeline construction cannot be ignored, as permafrost under the highway near the pipeline would accelerate the thawing process. The permafrost degradation would result in an uneven embankment settlement. Meanwhile, the heat effect caused by asphalt pavement and pipeline temperature would overlay each other, which means that the frozen soil foundation around the pipeline would thaw to a great extent, posing a threat to pipeline safety.

ESTABLISHMENT OF NUMERICAL MODEL FOR THERMAL STABILITY ANALYSIS

To evaluate the influence of thermal disturbance between the oil pipeline and its accompanying road on permafrost and engineering stability, the numerical method was used.

Mathematical model and equations

The heat exchange between the permafrost and oil pipe occurs during the service process, which results in a ground temperature rise of the permafrost foundation. For the strong heat absorption of asphalt pavement, the accompanying road has a similar problem. Since the oil pipe and accompanying road are long linear projects, two-dimensional plane solutions were employed. The oil pipe could be assumed as a linear heat source. During the process of heat transfer in soil, the heat convection is very small and could be neglected compared with heat conduction. Thus, the unsteady government equation for the heat transfer could be expressed as equation (2):

$$C_e \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_e \nabla T) \tag{2}$$

where T is temperature, and λ_e and C_e are soil equivalent thermal conductivity and soil equivalent volumetric heat capacity of soil, respectively.

The ice-water phase change occurs in a range of temperature ($T_m \pm \Delta T$). A stepwise function can be used to compute the soil equivalent thermal conductivity and the soil equivalent volumetric heat capacity based on the theory of sensible heat capacity. λ_e and C_e can be expressed as equation (3) and equation (4):

$$\lambda_e = \begin{cases} \lambda_f & T < (T_m - \Delta T) \\ \lambda_f + \dfrac{\lambda_f - \lambda_u}{2\Delta T}[T - (T_m - \Delta T)] & (T_m - \Delta T) \le T \le (T_m + \Delta T) \\ \lambda_u & T > (T_m + \Delta T) \end{cases} \tag{3}$$

$$C_e = \begin{cases} C_f & T < (T_m - \Delta T) \\ \dfrac{C_u + C_f}{2} + \dfrac{L}{2\Delta T} & (T_m - \Delta T) \le T \le (T_m + \Delta T) \\ C_f & T > (T_m + \Delta T) \end{cases} \tag{4}$$

where subscripts f and u denote the frozen and unfrozen states, λ and C are the thermal conductivity and volumetric heat capacity of the media, and L is the latent heat per unit volume.

Geometric model

In this section, a practical Mohe–Daqing oil line transversal section at the Mohe site is chosen as computational model, as shown in Fig. 9. The foundation of geological conditions can be classified into two layers. From the depth of 0.0 m to 10.0 m, the soil type was clay and the lower layer was mainly decayed sandstone. Based on the geologic drilling data, the frozen types in these regions were usually ice-rich permafrost with a mean annual ground temperature of –1.0 °C. The permafrost exhibited a layered structure with thickness of 3.0 cm. The volumetric ice content was approximately 40% at the depth from –2.8 m to –4.6 m.

The oil pipe diameter was taken as 813 mm in the conceptual model. The embankment height of the accompanying road was assumed as 2.0 m. The width of the pavement is 10.0 m. The computation domain is extended to 30.0 m away from the side-slope foot of the embankment and to 30.0 m under the natural ground surface.

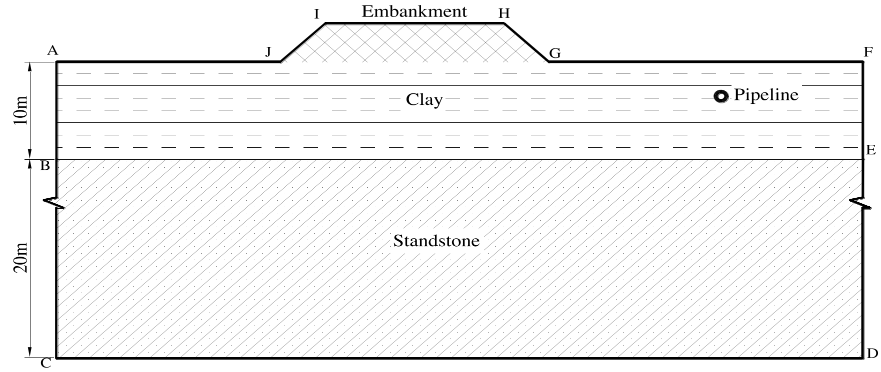


Fig. 9. Conceptual model of pipeline and accompanying road.

Boundary conditions and computational parameters

Based on the adherent layer theory and long-term observed temperature data from the Mohe test site, the upper boundary temperature can be expressed as the following sinusoidal function (Equation (5)):

$$T = T_s + \frac{0.07 \cdot t}{8760} + A\sin(\frac{2\pi t}{8760} + \frac{\pi}{2}) \tag{5}$$

where T_s is the annual surface temperature at the upper boundary, t is the service time of engineering, and A is the annual amplitude of the temperate. According to relevant literature: natural surface T_s is -1.0°C, embankment slope T_s is -0.5°C, asphalt pavement T_s is 3.0°C; natural surface A is 11.5°C, embankment slope A is 14.5°C, and asphalt pavement A is 15.15°C.

The lateral boundaries $\overline{AC}$ and $\overline{FD}$ were assumed to be adiabatic, and the geothermal gradient at boundary $\overline{CD}$ is 0.024 °C/m based on the measurement data. In Fig. 9, the upper boundaries of AJ and GF represent the natural surface, IJ and HG are the embankment slope, and HI is the asphalt pavement.

In Fig. 9, the conceptual model can be divided into three parts. Part I consists of embankment fill; part II, clay; and part III, decayed sandstone. The oil pipe was buried at a depth of 2.0 m below ground surface. The thermal parameters of media are shown in Table 2.

Table 2. Thermal parameters of media in oil pipe and accompanying road model.

	λ_f(W/m·k)	C_f(J/m^3·°C)	λ_u(W/m·k)	C_u(J/m^3·°C)	L(J/m^3)
Embankment fill	1.980	10^6×1.913	1.919	10^6×2.227	10^7×2.04
clay	1.472	10^6×1.764	1.211	10^6×2.403	10^7×6.03
sandstone	1.832	10^6×1.711	1.536	10^6×2.102	10^7×3.77

Initial condition

As the permafrost may have developed decades ago, the initial ground temperature is complex, which could be determined by trial computation. In the simulation process, the natural surface temperature functions, without considering warming, are used to carry out a series of trial computations. If the consecutive calculated results within two years of ground temperature have agreed with the measured data from a natural borehole, the ground temperature at this time is adopted as the initial condition.

To validate the reliability of the computational model and method, the measured data of the natural drill at the site of the Mohe–Daqing road were selected. In Fig. 10, the calculated data show a good agreement with the measured data. Therefore, the ground temperature filed at this time was assumed to be the initial condition.

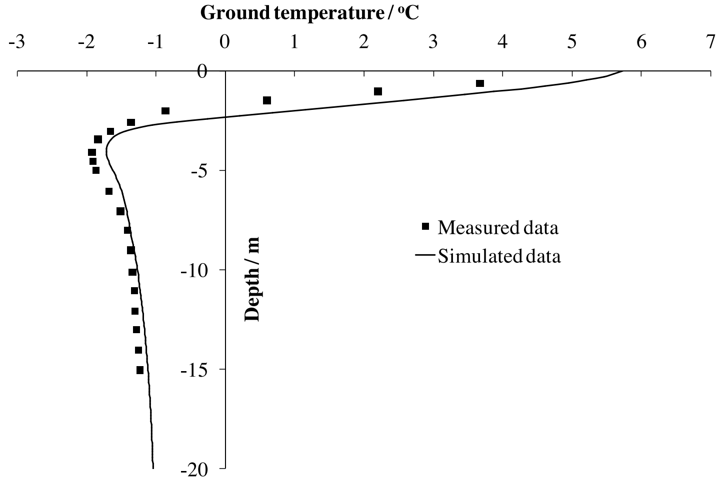


Fig. 10. Geotemperatue curves of measured data and simulated data.

Since the governing equations of the mathematical model are strongly nonlinear, a numerical solution was employed in this study. In the simulation, considering that most of the heat transfer occurs in the warmest time of the year, assume that the oil pipe and accompanying road construction were finished on July 15.

RESULTS AND ANALYSIS

Several studies have shown that the thermal budget of engineering is a crucial index for stability evaluation. To analyze the thermal state of oil pipe and accompanying road, the temperature fields within a total of 20 years after construction were simulated. The ground temperature, temperature difference, and temperature increase rate were used to evaluate the long-term thermal stability of the two engineering projects.

Thermal stability of oil pipeline

The development of a thaw circle and subsequent thaw settlement, which is harmful to the stability and safety of the oil pipeline, could be considered fully during the design process. Thus, laying a thermal insulation material around the pipe is one of the most frequently applied measures. Polyurethane rigid foam, which is widely used in buried oil pipeline engineering, has features of small bulk density, low thermal conductivity, and high compressive strength. In the calculation, the thermal insulation was in series with the surrounding soil based on thermal resistance series principle of the multilayered medium. The thermal conductivity of thermal insulation was 0.032 W/(m·k). The crude oil transported in MDOP was mainly imported from Russia with a condensation point lower than –15 °C. Therefore, the temperature of transportation is controlled between –10 and 15 °C. In the calculation, the temperatures of oil were taken as 5, 10, and 15 °C.

Fig. 11 compares the thaw rate curves of permafrost around the oil pipe without insulation at the depth of 2.0 m below the ground. The figure shows that the thaw rate reached a maximum value after 1 year of construction, and then the rate decreased over time. After 5 years of construction, the change in the thaw rate tends to be stable at 0.3 m/a. After 30 years of construction, the thaw rates of permafrost around warmer oil (oil temperatures are 10 and 15 °C) are close to 0. With oil temperature taken at 5 °C, however, the thaw rate of permafrost was less than 0 after 20 years of construction, which indicated a refreezing phenomenon of thawed soil around the oil pipe. Thus, the thaw rate of permafrost around the oil pipe reaches its maximum in the first 5 years of operation, which should be considered in the design and construction stage. Furthermore, the oil temperature has more influence on the thawing process of permafrost. In general, the lower the oil temperature, the lower the thaw rate, and the shorter the refreezing time of permafrost.

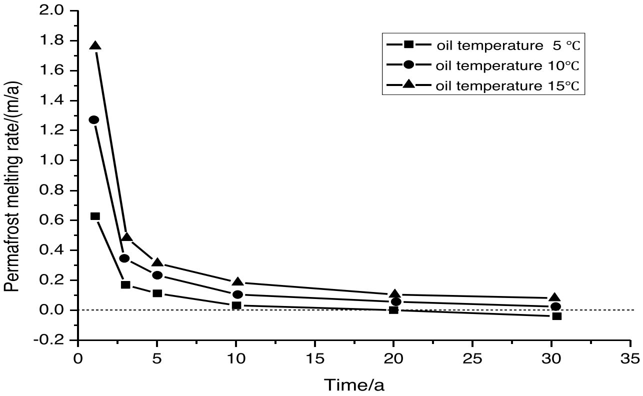


Fig. 11. Variation of thaw rates under different oil temperatures.

To investigate the influence of thermal insulation on the oil pipe, the thaw rates of permafrost around the oil pipe with thermal insulation are provided in Fig. 12. As illustrated in this figure, the thermal stability of the oil pipe had improved remarkably due to thermal insulation. The thaw depth was becoming stable when the insulation thickness increased to 5.0 cm after the first 5 years. This finding suggests that using thermal insulation such as polyurethane rigid foam is an efficient measure to control the thaw depth of permafrost around the oil pipe.

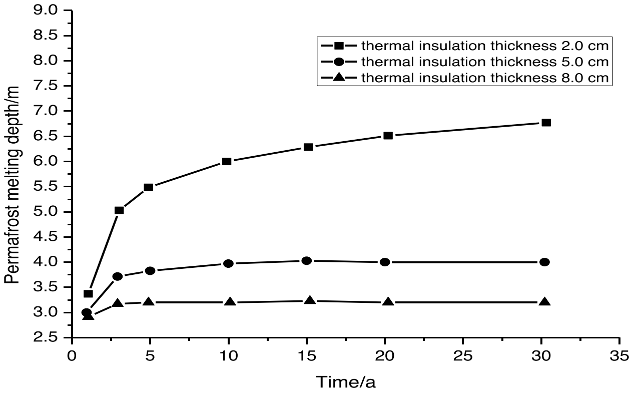
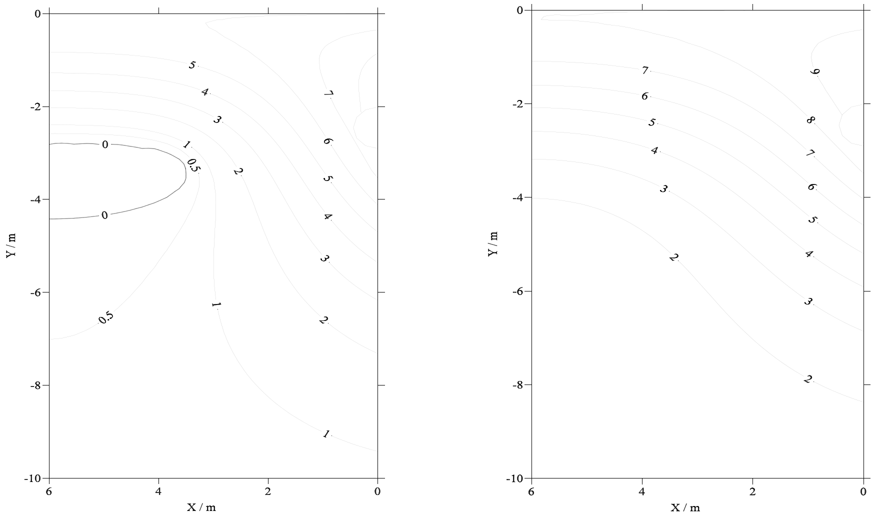


Fig. 12. Variation of maximum depth under oil pipe with different thermal insulation thicknesses.

To further illustrate the influence of thermal insulation and climate change on the stability of the oil pipe, the ground temperature fields around the oil pipe in October after 30 years of construction, both with and without an insulation layer, are shown in Figs. 13 and 14.

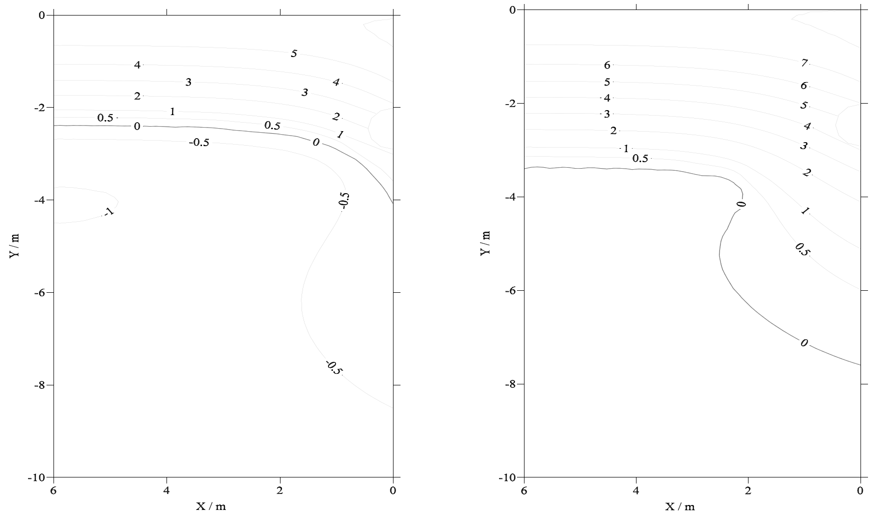
First, without the thermal insulation layer, the global warming effect could increase the thaw depth by a large margin. As shown in Figs. 13(a) and 13(b), in the horizontal direction, permafrost still exists at a distance of 4.0 m from the oil pipe, which means that the thermal influence distance of the oil pipe is about 4.0 m without considering the global warming effect. However, considering the global warming effect, the ground temperature would rise above 0 °C in the range of 6.0 m around the oil pipe. In fact, the thermal influence radius may exceed 6.0 m with continuous climate change.



(a) without considering global warming (b) considering global warming

Fig. 13. Ground temperature fields of oil pipe without thermal layers.

On the other hand, when placing a thermal insulation material around oil pipe, the thermal impact on permafrost could be neglected without considering the global warming effect. As indicated in Fig. 14(a), the 0 °C isotherms remained stable. Only in the vertical direction, the –0.5 °C isotherms near the oil pipe degenerated to the depth of 8.0 m. However, when considering the global warming effect (Fig. 14(b)), the 0 °C isotherms obviously fell 2.0 m away from the oil pipe in horizontal direction. Furthermore, the maximum thaw depth may reach 4.0 m, causing a higher thawing risk to the oil pipe.



(a) without considering global warming (b) considering global warming

Fig. 14. Ground temperature fields of oil pipe with thermal layers.

Regardless of the global warming effect, using thermal insulation material in the oil pipe is a highly effective measure to prevent thaw settlement of permafrost resulting from warm oil. Thus, the design idea and treatment principle of cooling temperature should be ensured to be running through the entire process in face of climate change. Moreover, a series of new-style structures should be invented according to the thermal character of the oil pipe.

Thermal stability of accompanying road

The strong heat absorption of black asphalt pavement would inevitably lead to thawing of permafrost, which may result in a series of engineering diseases and thaw hazards in these regions. This condition will be more serious with the effect of global warming.

In this section, the warming rates of ground temperature at different depths are shown in Fig. 15. As the figure shows, the warming rates of natural ground temperature decreased first and then increased. In detail, the warming rates were 0.07 and 0.062 °C/a at ground surface at the depth of 3.4 m, respectively. With the increase of depth, the limited value is close to 0.07 °C/a, which is in accordance with the warming rate of mean annual average temperature. By contrast, the warming rate curves under the embankment could be divided into three parts. With increase of depth, the warming rates of ground temperature under the embankment increased first and then decreased after reaching the maximum value. Lastly, the curves ascended again when the warming rate reached its minimum value. In addition, according to Fig. 15, a higher embankment would cause a higher warming rate because of the thermal resistance of the embankment fill, which could defend against thermal invasion from the ambient environment. The thicker the embankment fill is, the more obvious the thermal resistance effect becomes. As illustrated in Fig. 15, the maximum values of temperature warming rates changed from 0.084 °C/a to 0.075 °C/a when the embankment height increased from 3.0 m to 7.0 m, respectively.

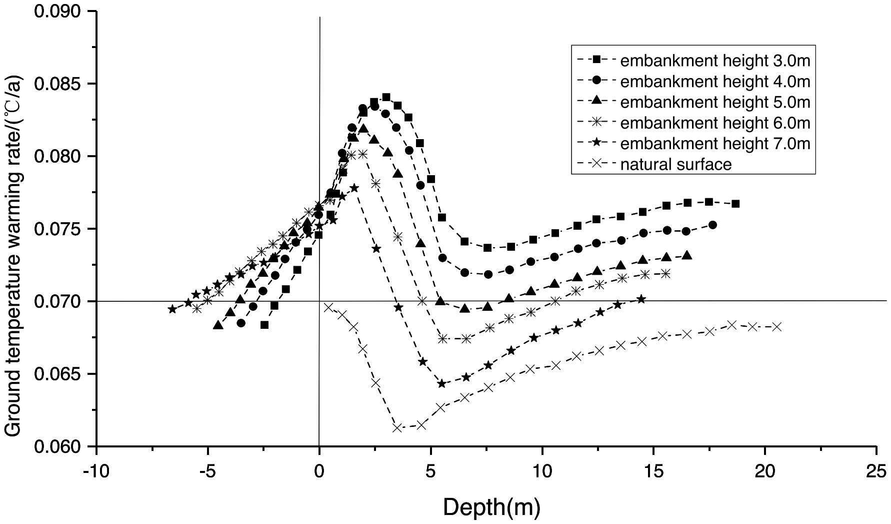
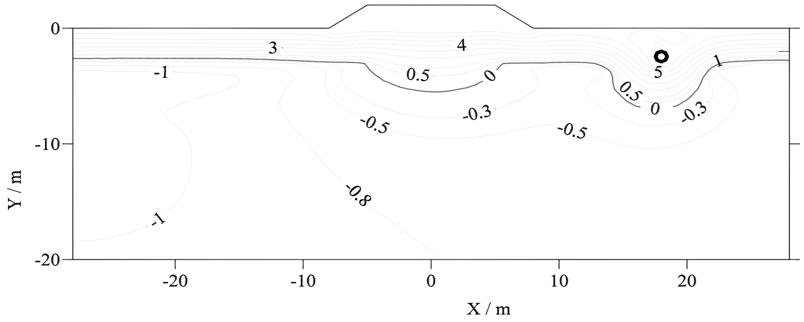


Fig.15. Variation of ground temperature warming rates under natural surface and embankments with different depths.

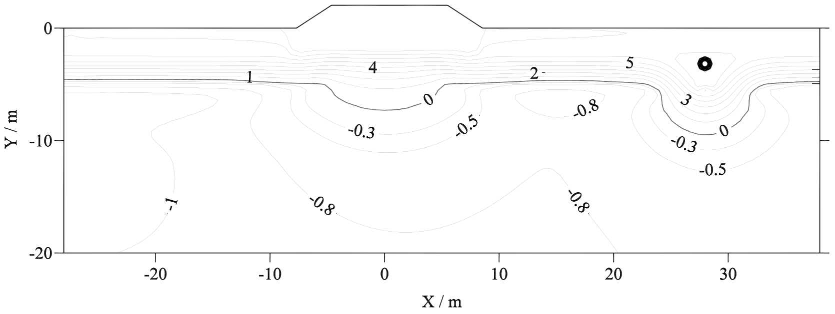
Analysis of thermal influence between oil pipe and accompanying road

The previous studies on the thermal stability of oil pipelines mainly focused on engineering itself and less on affiliated facilities. However, the thermal interaction between the oil pipeline and the accompanying road cannot be neglected in long-distance linear engineering in permafrost regions. To analyze this effect, the temperature fields of the oil pipe in different distances from the accompanying road were simulated. The oil pipe without thermal insulation layer was adopted to simulate the most adverse case.

The ground temperature fields around the oil pipeline and underneath the road embankment are given in Fig. 16 in October after 30 years of construction, with distances of 10.0 m and 20.0 m, respectively. As shown in Fig. 16(a), the 0 °C isotherm between the two engineering structures did not change significantly. However, the –0.5 °C isotherm obviously degenerated at the depth of 10.0 m, which means that a high-temperature zone formed, and thus, the foundation strength would obviously decay. Therefore, this zone would draw more attention. As shown in Fig. 16(b), the temperature field had certain improvements when the distance increased to 20.0 m. Similarly, the 0 °C isotherm changed slightly, maintaining its natural level. At the depth of 5.0 m to 8.0 m, a relatively low-temperature zone (lower than –0.8 °C) existed, thereby illustrating that a larger distance has greater benefit to improve the thermal stability of engineering.



(a) 10.0 m



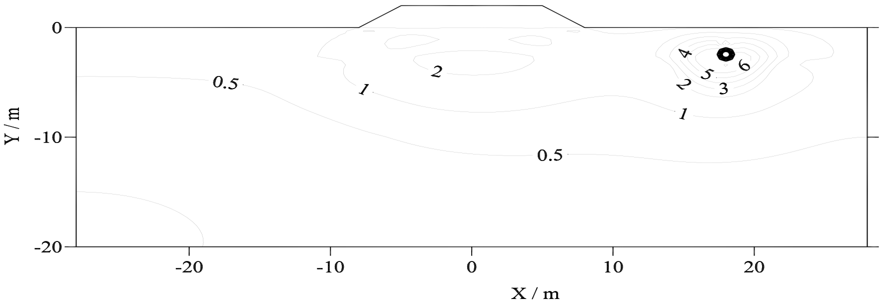
(b) 20.0 m

Fig. 16. Temperature fields of oil line and accompanying road at different distances.

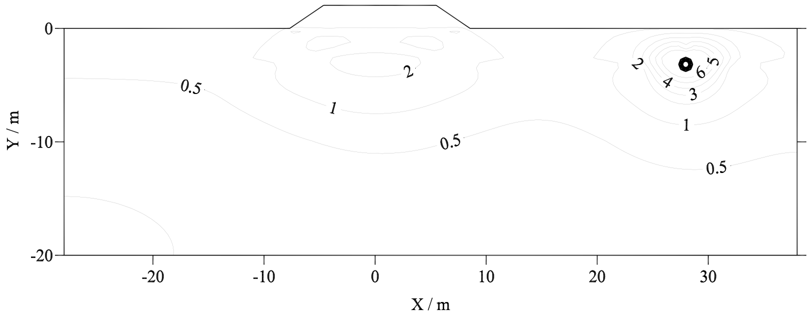
To further illustrate the thermal interaction between the oil pipe and the embankment, the temperature difference was introduced in previous studies. The temperature difference was defined as a change in ground temperature compared to conditions without engineering (i.e., oil pipe and embankment), which is given as a difference between ground temperature field (T_r) with an oil pipe or embankment and (T_w) without any engineering. It can be formulated mathematically in the equation (6):

$$\Delta T = T_r - T_w \tag{6}$$

The thermal influence on permafrost from the embankment or oil pipe depends on the value of ΔT. If ΔT is equal to 0 °C, it can be neglected. The temperature difference fields are shown in Fig. 17. For the distance of 10.0 and 20.0 m between the embankment and the oil pipe, the maximum temperature differences are approximately 2.0 °C and less than 1.0 °C, respectively, which indicated a smaller thermal impact on permafrost with the increasing distance.



(a) 10.0 m



(b) 20.0 m

Fig. 17. Temperature difference fields of oil line and accompanying road at different distances.

It can be inferred from the temperature fields that the thaw bulbs of the oil pipe and accompanying road have moved closer to each other during the operation period when the distance was relatively smaller, thereby resulting in an increase in ground temperature. Due to the thaw bulb offset, the embankment defects include an uneven settlement, longitudinal crack, and sliding collapse, which have extremely developed in these regions. In addition, the asymmetrical ground temperature of the oil pipe would increase the thaw depth and induce further thaw settlement risk. Particularly for an oil pipe that is nonparallel to an accompanying road, the settlement degree changes with the increase of distance, and thus, the construction difficulty is gradually increased in the transition section. However, a larger distance is not better because it could weaken the service function of the accompanying road to the oil pipeline in spite of a smaller thermal risk.

Some special engineering measures were recommended to ensure the stability of the oil pipe and accompanying road in these regions. For example, an oil pipe can be protected with a thermosiphon and thermal insulation layer. The safety distance between the oil pipe and accompanying road has not been specified and therefore requires further research.

CONCLUSIONS

The thermal condition of the oil pipe and accompanying road based on the Mohe–Daqing line of the China–Russia crude oil pipeline has been simulated. The thermal interaction analysis was also given in this paper. On the basis of the simulations, the following conclusions are presented:

(1) During the operation period, the buried oil pipeline had an obvious adverse influence on the permafrost around the pipe, especially with the effects of global warming and warmer oil.

(2) Placing thermal insulation material around the oil pipe is useful to defend against the thermal invasion to the permafrost. Many other active cooling measures should be adopted to improve the thermal stability.

(3) In the simulation, the coupling thermal effect of the oil pipe and accompanying road should not be neglected. The interaction zone between the engineering structures should be examined because it is a potential risk zone that induces engineering defects and diseases.

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دراسة حول الثبات الحراري للتربة الصقيعية بسبب المخاطر الجيولوجية لخط أنابيب النفط الخام الصيني الروسي

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الخلاصة

يمر خط أنابيب النفط Mohe - Daqing التابع لخط أنابيب النفط الخام الصيني الروسي عبر التربة الصقيعية بطول 441 كيلومتراً في مناطق خطوط العرض العليا. تتسبب التأثيرات الناتجة عن تكنولوجيا البناء وارتفاع درجة حرارة النفط والاحتباس الحراري في ارتفاع درجة حرارة الأرض وتسريع هدم التربة الصقيعية. في هذه الدراسة، تم دراسة تأثير المخاطر الجيولوجية على خط أنابيب النفط الخام الصيني الروسي الحالي والطرق المصاحبة له والتي أظهرت أن الهندسة الحالية قد تأثرت بذوبان الجليد. في ضوء هذه المشكلة، تمت محاكاة الثبات الحراري للتربة الصقيعية لخط الأنابيب والطريق المصاحب له استناداً إلى MDOP، مع الأخذ في الاعتبار درجات حرارة النفط المختلفة والاحتباس الحراري والعزل الحراري والمسافات المختلفة بين الاثنين. تشير النتائج الرقمية إلى أن درجة حرارة النفط كان لها تأثير كبير على معدل ذوبان التربة الصقيعية. إن وضع مواد العزل الحراري حول أنبوب النفط يمكن أن يقلل بشكل فعال أو حتى يتحكم في تدهور التربة الصقيعية. ومع هذا القياس، بقي عمق الذوبان مستقراً بعد 5 سنوات من البناء، وتم التحكم فيه على مسافة 3.0 متر عندما بلغت سماكة العزل الحراري 8.0 سم. كلما كانت المسافة بين أنبوب النفط والطريق المصاحب أكبر، كلما كان الاضطراب الحراري أقل. ولذلك، يمكن أن يعتمد الاستقرار الحراري لخط أنابيب النفط Mohe - Daqing بشكل إيجابي على درجة حرارة مناسبة للزيت لتوفير سماكة عزل حراري مناسبة، جنباً إلى جنب مع تحديد المسافة الأمثل بعيداً عن الطريق المصاحب له. ستوفر هذه الدراسة أيضاً دعماً نظرياً وتكنولوجياً أساسياً لتصميم خط أنابيب النفط في مناطق التربة الصقيعية الأخرى.