Research on Design Method for Thermal Insulation of Oil Pipeline in Permafrost Regions

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Abstract. The most important problems encountered in the design and operation of oil pipelines in permafrost regions are frost heaving and thawing settlement. In this paper, we conducted an investigation and analysis on the status of freezing damage of the operating oil pipelines. Based on the investigation and research, we calculated the temperature field of the oil pipeline and analysed the thawing ability under the conditions of the strain criterion. Finally, we proposed a design method for pipeline insulation and the maximum amount of thawing displacement that the pipeline can withstand. It has certain guiding significance for the thermal insulation design of oil pipelines in permafrost regions.

1 INTRODUCTION

The most important problems encountered in the design and operation of oil pipelines in permafrost regions are frost heaving and thawing settlement[1-10]. The design and construction of oil pipelines in permafrost regions has its own particularities. The operation of the oil pipeline has a huge impact on the hydrothermal conditions of frozen rock and soil around and along the line[11-25]. The change of the hydrothermal state of frozen and thawed soil directly affects its physical and mechanical characteristics and threatens the overall stability and structural integrity of the pipeline. Due to the differences in geological conditions, the types of frozen soil, and the differences in topography and geomorphology, the freezing and thawing process of the soil around the pipeline has obvious inhomogeneities, which determines the differences in soil frost heave and thawing settlement[26-36]. As a linear project, oil pipelines inevitably have to pass through different freezing and thawing differential deformation transition zones, and the pipes may be damaged due to the excessive frost heave or thawing of the pipeline foundation. Therefore, it is necessary to carry out thermal insulation research on oil pipelines in permafrost regions to guide practical engineering applications.

2 FROST DAMAGE SURVEY

At present, the Mo-da Line has officially operated for more than 3 years. According to field investigations and studies, some potential frost damage risks have been discovered, including frost heaving, thawing settlement and adverse frozen ground. The main problem is thawing settlement. During the pipeline design period, the inbound temperature provided by Russia varied from -6 to 10 °C, but the actual operating oil temperature was

above the positive temperature. The monitoring results of the oil temperature at each station from 2011 to 2012 show that the oil temperature of the pipeline is above 0 °C even in winter. The average annual oil temperature varies from 4.40 to 9.99°C, and the extreme oil temperatures during the year are 0.42 and 16.2°C. During the winter, several frost heaving points were excavated on the site. It was found that a certain range of the perimeter of the pipe was molten soil. The frost heave caused by the soil below the bottom of the pipe has not been found. From the results of oil temperature monitoring, it was found that the pipeline was operating at high temperature and the phenomenon of thawing was obvious. There are different degrees of melting or sinking along the line.

Table 1. Statistics of GPR detection results for typical melting zones

Pipeline mileage	Melting depth in November 2013 (m)	Preliminary calculations thaw settlement amount(m)	
		thawing settlement	strong thawing settlement
mdx40	2.5	0.08~0.25	0.25~0.63
mdx113	2.5		
mdx285	4.5	0.13~0.45	0.45~1.13
mdx304	3.0	0.09~0.3	0.3~0.75
mdx364	3.5	0.11~0.35	0.35~0.88
mdx391	3.5		

According to the thawing depth monitoring data (Table 1), it is possible to calculate the thawing amount corresponding to different thawing levels (about 0.45 to 1.1m), which is basically consistent with the site thawing monitoring data (0.5 to 0.88m). It can be known that the types of frozen soils in areas where the amount of thawing is obvious are generally thawing ~ strong thawing ice-rich ~ saturated frozen soil.

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3 CALCULATION MODEL OF PIPELINE TEMPERATURE FIELD

There may be different amounts of water (ice) frozen soil in various places along the pipeline, there may be frost-heavy soil layers. Therefore, the prediction and analysis of the freeze-thaw cycle in typical regions select clay that is not conducive to pipeline stability. The material parameters of the model vary according to the stratum profile and different water content (ice) content, and are selected from the original test data, as shown in Table 2.

Table 2. Thermophysical parameters of each soil layer

Geotechnical properties	Thermal Conductivity (w/m·°C)		Specific heat (J/kg·°C)	
	Frozen soil	Thawing soil	Frozen soil	Thawing soil
Subsoil	1.82	1.6	982	1273
Silty clay	2.12	1.42	1222	1608
Fully weathered sandstone	1.82	1.6	982	1273

In this study, polyurethane foam was used as the thermal insulation material, and the thermal conductivity was about 0.03W/(m·K). Based on this model, the development of the melting circle and the melting depth of the bottom of the pipeline under the conditions of different parallel spacing and with or without thermal insulation layer, and the soil around the pipeline under different frozen soil types are studied. It can be concluded that there are important reference values for the design of Moda second-line crude oil pipeline.

3.1 Without thermal insulation

The calculation and analysis are performed for six pitch schemes of 6m, 8m, 10m, 12m, 30m, and 50m, and the parallel spacing of the two pipes without thermal influence on each other are obtained when the insulation is not maintained.

Fig. 1. The process of melting depth of tube bottoms with different parallel spacings as a function of operating time

Through the study of the parallel spacing (Figure 1), it can be concluded that if the double pipes are parallel without any insulation measures, the parallel spacing needs to be at least 30 ~ 50m to avoid the superimposed effect of the double pipes on the thermal effects of frozen soil at the bottom of the pipes. Since this distance

is unlikely to be achieved, it is recommended that necessary insulation measures be taken to reduce the parallel spacing.

3.2 Thermal insulation of pipelines

Considering the Greater Xing'an Mountains forest area, in order to reduce felling and land occupation, the parallel distance should be reduced, and to reduce the thermal impact of double pipes on the frozen soil around the pipe, consider the temperature of the second line when the double pipe is 8m. Calculate and analyze the temperature field calculation of the different insulation schemes of the two pipes. The calculation results are shown in Table 3.

Table 3. Statistics of tube bottom melting depth under different insulation schemes

Insulation scheme	Insulation type	2nd year thaw depth /m	30th year thaw depth /m	50th year thaw depth /m
I	First line uninsulated	2.2	6.1	7.5
	Second-line insulation	0.3	1.9	2.6
II	First line insulated	0.3	1.7	2.3
	Second-line uninsulated	2.2	6.3	7.5
III	First line insulated	0.4	0.9	0.9
	Second-line insulation	0.3	1.0	1.0

Using this model, the temperature field of the pipeline under future heating conditions was calculated (Figure 2). It can be seen from the figure that after the oil temperature increases, when the pipe is provided with a thermal insulation layer, the maximum melting depth is increased from 2.0m to 9m.

Fig. 2. Melting depth curve of tube bottom in frozen soil area under new and old oil temperature

3.3 Analysis of Deformation Capability

From the summary table of the stress and strain calculation of the pipeline under different thawing displacements (Table 4), it can be seen that regardless of the type of frozen soil, as the soil displacement increases, the stress and strain value of the pipeline is also increase accordingly. The pipeline safety check was performed

according to the strain criterion. The maximum axial compressive strain and maximum tensile strain of the pipeline were within the allowable range (the maximum allowable compressive strain was 0.77% and the maximum allowable tensile strain was 1%). The pipeline strain check passed.

Table 4. Summary table of pipeline stress and strain calculation under different thawing displacements

Pipeline settlement /m	Effective stress /MPa	Equivalent stress /MPa	Maximum compressive strain	Maximum tensile strain
0.77	451	519	0.31%	0.17%
0.89	453	521	0.39%	0.20%
1.45	452	520	0.37%	0.20%
1.65	453	521	0.41%	0.21%

The results of multiple trial calculations are shown in Figure 3 below. From the table, it can be concluded that under the condition of 16mm wall thickness, the maximum thawing displacement ΔS that the pipeline can withstand is in the range of 2.0m ~ 2.2m.

Fig. 3. Strain change trend of D813 pipeline under different thawing displacements (under the condition of strain criterion)

4 CONCLUSIONS

In this paper, through research on the thermal insulation design method of oil pipelines in permafrost regions, we can draw many conclusions that have important reference value for pipeline design in permafrost regions. The main conclusions are as follows:

(1) The thermal effects of uninsulated pipes on frozen soil are very strong. The melting depth exceeds 7m, and the thaw is large (1.7m). On the one hand, the deformation of the pipeline is exacerbated, and on the other hand, the geomorphology and ecology are greatly destroyed. Considering the irreversibility of the frozen soil ecological environment, it is recommended that oil pipelines be considered for additional insulation.

(2) When the oil pipeline is added with an insulation layer, the melting depth is stable after 15 years, the maximum melting depth is controlled within 1m, and the thawing amount is only 0.2m.

(3) Under the condition of 16mm wall thickness, the maximum thawing displacement ΔS that the pipeline can withstand is in the range of 2.0m ~ 2.2m.

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