Analysis of ground temperature variation in differential settlement of China-Russia crude oil pipeline: field monitoring and numerical simulation

Guiquan Bi¹, Zhengmin Song¹², Yanhu Mu², Guoyu Li²

¹School of Civil Engineering, Lanzhou University of Technology, Lanzhou, Gansu 730050, China
²State Key Laboratory of Frozen Soils Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, 730000, China

*Corresponding author’s e-mail: 252222045@qq.com

Abstract. In vast areas of rich frozen soil, the intense heat exchange between the hot oil pipeline and surrounding soil results in the continuous melting of permafrost under the pipeline and the continuous sinking of the pipeline. Moreover, the settlement rate and depth of the pipeline are also different due to the influence of ice content and the thickness of rich frozen soil layer. Therefore, in this paper, based on the field measured data, by adopting the method of numerical simulation, the temperature rise process of the soil around the pipeline under the condition of different subsidence rate and different thickness of rich frozen soil layer is studied. The results show that with the increase of the thickness of the frozen soil layer, the degradation depth of the upper limit of the artificial frozen soil in the lower part of the pipeline increases gradually. Under the same thickness of the frozen soil layer, the influence of the settlement rate of the pipeline on the upper limit of the artificial frozen soil mainly concentrates on the initial operation stage of the pipeline; with the increase of the thickness of rich frozen soil layer, the upper limit difference of artificial frozen soil under different settlement rates of pipelines at the same time increases gradually. Of different sedimentation rate and the rich soil layer under the condition of ice ~6 m depth of geothermal heating process monitoring, the geothermal heating process can be divided into three stages: melting stage (I), rapid heating stage (II), slow heating stage(III). With the increase of the settling depth, the duration of the phase I and II is significantly reduced, the heating rate is significantly promoted, the duration of phase III is increased significantly and the heating rate is gradually reduced.

1. Introduction
The Sino-Russian crude oil pipeline was built in 2010 and put into operation in 2011. The annual oil transporting capacity is 15 million tons to 30 million tons, which is an important energy pipeline in China. China's CROCP is 933.11 kilometers long, including 441 kilometers of discontinuous, sporadic and isolated permafrost zones, of which 119 kilometers are warm and ice-rich permafrost zones[1]. Because of frequent forest fires and other security risks, oil and gas pipeline construction usually adopts the conventional buried type, and the buried depth is about 1.5m. Based on the long-term construction experience of the United States, Russia, Canada and other countries, it is shown that there are great risks in the construction of conventional buried pipelines in permafrost regions under the
condition of high temperature operation, especially in ice-rich and ice-saturated permafrost. The thermal effects of underground large-diameter oil and gas pipelines have caused many engineering problems, such as permafrost degradation, soil liquefaction, thawing settlement and ground subsidence. The pipeline deformation and rupture caused by this will seriously endanger the normal operation of the pipeline system[2-3]. At present, a large number of field observations, laboratory experiments and numerical simulation studies have been carried out for pipeline operation. Xu et al[4] studied the development of freeze-thaw zone and the displacement and strain of pipeline during pipeline operation by carrying out routine buried indoor model test. The results show that with the increase of operation period, the thermal insulation material can effectively slow down the development rate of thawed soil area. When the ambient temperature decreases, the axial strain of pipeline increases gradually with the frost heave of soil. When the temperature returns, the soil thaws and the stress-strain releases. Wu, Li, Zhang[5-7] can carry out the numerical simulation study of the thermal interaction between conventional buried pipelines and surrounding soil. It is known that wrapping thermal insulation material can effectively slow down the development rate of the melting zone in the lower part of the pipeline and reduce the melting subsidence rate of the pipeline. Under the influence of frost heave, the maximum stress point appears at the junction of the non-frost heave zone and the transition zone. However, there are few studies on the heat exchange process between pipeline and surrounding soil due to the different thickness and ice content of frozen soil in the process of pipeline melting and subsidence.

Based on the measured data of Gagdage monitoring section and the settlement value of pipeline obtained by pipeline excavation, this paper carries out the simulation calculation of long-term development of ground temperature under different annual settlement rate and different settlement depth. By studying the process of ground temperature rise under the coupling condition of pipeline settlement and ground temperature under different ice content and thickness of frozen soil, this paper aims to provide some guidance for engineering construction and operation.

2. On-site monitoring

The field monitoring section is located 0.6 km south of Gagdage Pumping Station (50°28′14.23″N, 124°13′31.75″E, 484m above sea level). Previous studies have shown that the permafrost type is sporadic, discontinuous and discontinuous. Permafrost around the pumping station accounts for about 30%, annual average temperature is -2.15 degree Celsius, and active layer thickness is about 2.0m. Because of the surface damage and low vegetation coverage along the pipeline, the permafrost along the pipeline is extremely unstable.

According to geological survey data, the soil layer near the pumping station is gravel sand, clay and weathered granite from top to bottom. The buried depth along the pipeline is -1.6m, and no thermal insulation material is wrapped. The temperature sensor layout of geothermal monitoring section is shown in figure 1. The location of T1 monitoring holes is 2.0 m away from the center of the pipeline, the spacing of shallow (0~4 m) temperature probes is 0.5 m, the spacing of deep (4~20m) temperature probes is 1.0 m, the maximum depth is -20m, the distance of T2 monitoring holes to the center of the pipeline is 16.6 m, the spacing of shallow (0~5m) temperature probes is 0.5m, and the spacing of deep (5~20 m) temperature probes is 1.0 m, the maximum. The depth is -20m. The temperature probe is manufactured by the State Key Laboratory of Permafrost Engineering, Chinese Academy of Sciences, with an accuracy of less than 0.05 degree Celsius and a data acquisition interval of 2 hours per time. The sketch of geothermal monitoring section is shown in figure 1.
Figure 1. Ground temperature monitoring section diagram

By monitoring the oil temperature at the outlet of Gagdage Pumping Station, it is known that the annual average oil temperature in the pipeline is about 7.65 degrees Celsius. According to the long-term temperature observations at a gas phase Observatory in Gagdage, the annual average temperature is about -2.15 degree Celsius, the annual amplitude can reach 21 degree Celsius, the annual average wind speed is about 2.2 m/s, and the annual rainfall is about 532 mm. Because the buried depth of the pipeline is -1.6m, the oil temperature in the pipeline shows a similar change trend with the environmental temperature affected by the environmental temperature and the upper filling of the pipeline, and the fluctuation range is about 3.5 degree Celsius. However, due to the influence of filling in the upper part of the pipeline, the change of oil temperature in the pipeline shows obvious hysteresis. As can be seen from figure 2, the phase difference between oil temperature and environmental temperature in the pipeline is about π/3.

Short-term temperature monitoring results show that the upper limit of artificial permafrost at T2 detection hole is less affected by crude oil pipeline. After 6 years of pipeline operation, the upper limit of artificial permafrost remains at -2m depth. However, the upper limit of artificial permafrost at T1 monitoring hole changes significantly. From the figure 3 below, we can see that after 6 years of pipeline operation, the upper limit of artificial permafrost at T1 can reach -7.8m, and the annual average degradation rate reaches 0.96 m/a, and it can be seen from the graph that with the operation of the pipeline, the decline rate of this depth decreases.
Figure 3. Upper limit variation of artificial frozen soil in T1 and T2 geothermal monitoring system (2014~2017)

3. Heat transfer model

3.1. Numerical model

In order to study the heating process of the lower part of pipeline caused by pipeline settlement under different ice content and thickness of frozen soil, three kinds of pipeline settlement rates and three kinds of ice-rich soil thickness were studied by numerical simulation. The calculation model was shown in figure 4. According to the different heat transfer characteristics in different media regions, the model can be divided into two parts: the solid domain and the fluid domain. For the solid domain, the thermal conductivity is much larger than the convective heat transfer coefficient. Therefore, the convective heat transfer process in the solid domain can be neglected. The heat transfer control equation of the model can be simplified as follows:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_e^*} \left( \lambda_e^* \frac{\partial T}{\partial x} + \lambda_e^* \frac{\partial T}{\partial y} \right)$$

In the formula, $\rho$ is the density of soil layer, $T$ is the temperature / °C, $t$ is the time / s, $x$, $y$ is the space variable, $C_e^*$, $\lambda_e^*$ are the equivalent volume heat capacity and the equivalent thermal conductivity of the medium respectively. The concrete expressions are as follows:

$$C_e^* = \left\{ \begin{array}{ll}
C_r + \frac{C_u - C_r}{T_2 - T_1} (T - T_1) + \frac{L}{(1+W)} \frac{\partial W_1}{\partial T} & \text{if } T < T_1 \\
C_r & \text{if } T_1 \leq T < T_2 \\
C_u & \text{if } T \geq T_2
\end{array} \right. \quad (2)$$

$$\lambda_e^* = \left\{ \begin{array}{ll}
\lambda_f + \frac{\lambda_f - \lambda_u}{T_2 - T_1} [T - T_1] & \text{if } T < T_1 \\
\lambda_u & \text{if } T_1 \leq T < T_2 \\
\lambda_u & \text{if } T \geq T_2
\end{array} \right. \quad (3)$$

3.2. Physical model

The computational physical model is designed according to the buried depth of the pipeline. The buried depth of the pipe top is -1.6m, the diameter of the pipe is 814mm, and the depth of the model soil is 20m. It extends 2m along the center of the pipeline to both sides. The distribution and thickness of the soil layer are shown in figure 4. The vertical profile of the soil is divided into three layers: gravel sand: 0~2.5m; clay: -2.5m~10 m; weathered granite: -10m~20m; $h$ is the thickness of the rich frozen soil layer. In this paper, the thickness of rich frozen soil layer is 0.6m, 1.6m and 2.6m. The settlement rates of pipelines in rich frozen soil layer are 0.25m/a, 0.35m/a and 0.45m/a, respectively.
3.3. Boundary condition

According to the relevant research data, the range of temperature rise in the future 50 years in Northeast China can reach 2.4 degree Celsius. After considering the "boundary layer" effect and snow cover effect, the natural surface and pipeline temperature boundary can be expressed as follows:

Natural surface AB temperature boundary:

\[ T_n = -0.7 + 12 \sin \left( \frac{2\pi t}{8760} + \frac{\pi}{2} \right) + \frac{2.4t}{50 \times 365 \times 24} \]  

Temperature boundary of oil pipeline:

\[ T_0 = 7.65 + 3.5 \sin \left( \frac{2\pi t}{8760} + \frac{\pi}{6} \right) \]  

In the formula, \( C_f \) and \( C_u \) are the volumetric heat capacities of the frozen and unfrozen water-bearing media, and the thermal conductivity of the frozen water-bearing media is the thermal conductivity of the frozen water-bearing media.

\( L \) is the latent heat of phase change, \( W_i \) is the ice content of soil layer, \( T_1 \) and \( T_2 \) are the temperature of phase change interval of ice-water. The thermal calculation parameters of each soil layer are shown in Table 1 and Table 2.

![Diagram of the conventionally buried pipeline](image)

**Table 1. Characteristics of soil layer and related thermal parameters**

| Soil layer     | depth (m) | Dry density (kg·m⁻³) | Water content (%) | Thermal conductivity (J·m⁻¹·h⁻¹·K⁻¹) | Heat capacity (J·kg⁻¹·K⁻¹) |
|----------------|-----------|----------------------|-------------------|-------------------------------------|-----------------------------|
|                |           |                      |                   | freezing                           | thawing                     |
| Gravel sand    | 0~ -2.5   | 1800                 | 15                | 6552                               | 5760                        |
| clay           | -2.5~ -10 | 1280                 | 35                | 6022                               | 3932                        |
| Weathered granite | -10~ -20 | 1800                 | 15                | 6552                               | 5760                        |

**Table 2. Mass heat capacity at different temperature intervals (J·kg⁻¹·K⁻¹)**

| Soil layer     | Temperature/°C | -20~-10 | -10~ -5 | -5~ -3 | -3~ -2 | -2~ -1 | -1~ -0.5 | -0.5~ -0.2 | -0.2~ -0 | 0~ 20  |
|----------------|----------------|---------|---------|--------|--------|--------|----------|------------|----------|--------|
| Gravel sand clay | 977            | 1152    | 1776    | 3362   | 5572   | 18693  | 30344    | 66718      | 1266    |
| clay           | 1275           | 1771    | 2742    | 6550   | 6596   | 11598  | 34750    | 187588     | 1730    |
| Weathered granite | 982            | 1476    | 2364    | 3658   | 6160   | 16080  | 39562    | 1267       | 1272    |

3.4. Model Verification

Through field excavation of oil pipeline, it is known that the settlement of pipeline near monitoring section can reach 1.4 m and the annual average settlement rate is 0.35 m/a after 4 years of pipeline operation. Therefore, in the process of numerical simulation, the numerical model of heat exchange process between pipeline and surrounding soil is validated by setting the pipeline downward
movement rate of 0.35 m/a, and the comparison between numerical simulation and field monitoring is made. The figure is shown in Figure 5.

It can be seen from the graph that after six years of pipeline operation, the upper limit of artificial frozen soil at T1 monitoring hole can reach -8m, and the annual average degradation rate is about 1.0m/a. According to the results of field monitoring and numerical simulation, the difference of artificial frozen soil upper limit is not more than 0.1m, which can better reflect the warming process of soil around pipeline caused by pipeline subsidence. However, the numerical simulation results of shallow soil are different from the field monitoring results. This is because the shallow soil contains root, fur, peat soil and other substances, which changes the internal structure and composition of the soil. The influence of this effect can not be considered in the numerical model, so the results of field monitoring and numerical calculation are different in shallow soil.

4. Analysis of Differential Settlement Effect of Hot Oil Pipeline

4.1 Difference analysis of artificial permafrost upper limit under different annual settlement rates and thickness conditions of rich frozen soil

Combining the above field monitoring data with the preliminary comparison of the numerical simulation results, the coupling degree is better. Based on this, this paper studies the difference of ground temperature variation under different ice content and different thickness of frozen soil layer by using different subsidence rate and depth of pipeline. Firstly, when the subsidence depth is 3 m, the upper limit of artificial frozen soil under pipeline in pipeline. Degradation trend analysis within effective operation life (50 years). By comparing the degradation rates of 0.25m/a, 0.35m/a and 0.45m/a, it can be found that the increase of pipeline subsidence rate leads to a great difference in the upper limit of artificial permafrost at the lower part of the pipeline in the initial stage of pipeline operation. Therefore, the difference between the upper limit of artificial permafrost with settlement rates of 0.25m/a and 0.45m/a is given in Figure 6a. According to the figure, the difference of the upper limit of artificial frozen soil in the lower part of the pipeline is mainly concentrated in the first five years of pipeline operation, and it can be seen from the 6th day that when the pipeline is in operation for one year, the difference of pipeline settlement is the largest, reaching 0.2m. Then, as the pipeline continues to operate, the difference decreases gradually, and tends to zero when the pipeline runs to 5a. By calculating the horizontal and vertical development of the melting zone in the lower part of the pipeline, it is known that after 50 years of operation, the degradation depth of the upper limit of artificial frozen soil in the lower part of the pipeline can reach -11.5 m, the annual average degradation
rate is about 0.18 m/a, the horizontal radius of the melting zone can reach 11 m, and the annual average development rate can reach 0.22 m/a.

When the settlement depth is 4 m, the numerical results show that (figure 6b.), the difference duration of the upper limit of artificial frozen soil in the lower part of the pipeline increases to 20 years, and from figure 6d, it can be seen that after 4 years of pipeline operation, the difference reaches the maximum, reaching 0.45 m. Then, with the operation of the pipeline, the difference decreases, and tends to zero after 20 years of operation. When the pipeline is in operation for 50 years, the maximum degradation depth of the upper limit of artificial permafrost in the lower part of the pipeline can reach 13.2 m, the annual average degradation rate is about 0.22 m/a, the horizontal radius of the melting circle around the pipeline can reach about 12 m, and the annual average French rate is about 0.24 m/a.

When the settlement depth reaches 5 m, the degradation rate and depth of the artificial permafrost upper limit increase further. According to Figure 6c, the maximum degradation depth of the artificial permafrost upper limit can reach -15 m after 50 years of pipeline operation, and the annual average degradation rate is about 0.26 m/a. The horizontal development radius of the melting circle around the pipeline can reach about 13 m. From the 6th day, it can be seen that with the increase of settlement depth, the difference of artificial frozen soil upper limit under different pipeline settlement rates increases further. When the pipeline is operated for 6 a, the difference reaches the maximum value of 0.7 m.

Figure 6. Upper limit variation of artificial frozen soil at different settlement depths and settlement rates

By comparing the position of artificial frozen soil upper limit under different annual settlement rate and different settlement depth, as shown in figure 7, it can be found that the degradation rate of artificial frozen soil upper limit under pipeline can be divided into three stages: severe degradation stage (I), transition stage (II) and slow degradation stage (III); the degradation rate of different stages is affected by pipeline settlement rate and settlement depth in duration. When the settlement rate of pipeline is 0.25 m/a, the degradation rate of artificial permafrost upper limit is about 0.95 m/a in severe degradation stage, and the duration of severe degradation stage can reach about 2 a, 6 a and 10 a in different settlement depth conditions respectively. When the settlement rate is 0.45 m/a, the degradation rate of artificial permafrost upper limit can reach 1.15 m/a, and the duration can reach about 1 a, 4 a and 6 a respectively.
By comparing the duration of transition stage (II) under the same settlement depth and different settlement rates, it can be found that the duration of transition stage (II) decreases with the increase of settlement rate. When the settlement rate is 0.25m/a and the settlement depth is 3m, 4m and 5m, the duration of transition stage (II) is 8a, 14a and 14a, respectively. When the settlement rate is 0.45m/a, the duration of transition stage (II) is significantly shortened, reaching 4a, 6a and 10a, respectively. After entering the stage of slow degradation (III), the degradation rate of artificial frozen soil upper limit under different settlement depths and rates is basically the same, which is about 0.125 m/a.

Figure 7. Variation curves of upper limit depth of artificial frozen soil at different settlement depths and different settlement rates.

4.2 Analysis of difference of temperature rise under different annual settlement rate and thickness of frozen soil

Figure 8 (a~c) shows that when the soil is in the melting stage (I), the difference of the duration of pipeline under different settlement rates increases gradually. When the settlement depth of pipeline is -3 m, the influence of the settlement rate of pipeline is less. When the settlement depth of pipeline is -4 m, the duration of different settlement rates of pipeline is 5a, 4.3a, 4a, and the maximum time difference is 1a. When the degree of subsidence reaches -5m, the duration at different pipeline subsidence rates is 5a, 4.3a and 3.5a respectively, and the maximum time difference is 1.5a.

By comparing the annual heating rate difference of different stages and different settlement depths, it can be seen that with the increase of settlement depth, the heating rate of stage I and II increases gradually, and the heating rate of stage III decreases gradually. This is because the sinking of pipeline causes the deep soil of pipeline to be more directly affected by the heating oil pipeline, and the temperature rising range of the soil at the same depth of the lower part is larger. Influenced by the oil temperature of crude oil pipeline, the temperature of soil is limited, and the overall temperature of soil is close to the oil temperature in pipeline, which eventually leads to the gradual decrease of temperature rising rate in stage III with the increase of the depth of pipeline subsidence.
Figure 8. Geothermal heating curve at -6m depth at different settlement depths and settlement rates

5. Conclusions
According to the field survey data, the first four years of pipeline operation resulted in large pipeline settlement, the settlement amount was 1.4m, and the average annual settlement rate was 0.35 m/a. Based on this, the soil heating process under different settlement rate and different thickness of frozen soil layer was studied. The results are as follows:

According to the numerical simulation of settlement rate of different pipelines under the condition of 3m settlement depth, the difference of upper limit of artificial frozen soil under different settlement rate is mainly concentrated in the initial stage of pipeline operation (5a). In the 2nd year after pipeline operation, the difference of settlement of upper limit of artificial frozen soil under different pipeline settlement rate is the largest, and the maximum difference of settlement can reach 0.2m. By comparing the warming effect of soil at -6m depth, it can be seen that when the settlement depth of pipeline is 3m, the warming range of soil at different settlement rates has little difference.

When the settlement depth of the pipeline is 4 m, the difference of degradation rate of artificial frozen soil upper limit in the lower part of the pipeline is gradually increased under the influence of the settlement rate of the pipeline. After four years of pipeline operation, the maximum difference of artificial frozen soil upper limit under different pipeline settlement rate is 0.45m. After 20 years of pipeline operation, the degradation range of artificial frozen soil upper limit caused by the difference of pipeline settlement rate tends to be the same. After 50 years of pipeline operation, the maximum downward displacement depth of artificial frozen soil upper limit under pipeline can reach -13.2m.

With the further increase of the pipeline settlement depth (5m), the upper limit of artificial frozen soil in the lower part of the pipeline is most affected by the settlement rate of the pipeline. After six years of pipeline operation, the difference between the upper limit of artificial frozen soil in the lower part of the pipeline and the subsidence rate of different pipelines reaches the maximum value, about 0.7m. With the increase of the pipeline settlement depth, the upper limit of artificial frozen soil in the lower part of the pipeline can be moved down after 50 years of pipeline operation. It reaches -15m.

By comparing the heating effect of soil at different settlement rates and depths of pipeline at -6m depth, it can be seen that when the settlement depth is -3m, the difference of pipeline heating caused
by uneven settlement rate of pipeline is small; with the increase of settlement depth, the influence of pipeline settlement rate increases gradually.

With the increase of the settlement depth of pipeline, there are obvious differences in the heating stage of soil in the lower part of pipeline. The duration of stage I and II is obviously shortened, and the heating rate is obviously increased. The duration of stage III is obviously increased, but the heating rate is gradually reduced.

Acknowledgements
We sincerely appreciate the financial support from National Natural Science Foundation of China (No.51568043, 41772325, 41630636) and State Key Laboratory of Frozen Soil Engineering (No. SKLFSE201008)

References
[1] Huijun Jin, Jiaqian Hao, Xiaoli Chang, Jianming Zhang, Qihao Yu, Jilin Qi. (2010) Zonation and assessment of frozen-ground conditions for engineering geology along the China-Russia crude oil pipeline route from Mo’he to Daqing, Northeastern China. J. Cold Regions Science and Technology., 65(2): 226-233.
[2] Li, C.J., Jiang, M.Z., Ji, G.F., (2000) Thermal-stress computation of the buried heated-oil pipeline in permafrost regions. J. Southwest Petrol. Inst. 22 (1), 77–79.
[3] Jin, H.J., Brewer, M.C., (2005) Experiences and lessons learned in the engineering design and construction in the Alaska arctic. J. Glaciol. Geocryol. 27 (1), 140–145.
[4] Guofang Xu, Jilin Qi, Huijun Jin. (2010) Model test study on influence of freezing and thawing on the crude oil pipeline in cold regions. J. Cold Regions Science and Technology., 64: 262–270.
[5] Guoyu Li, Yu Sheng, Huijun Jin. (2010) Development of freezing-thawing processes of foundation soils surrounding the China-Russia Crude Oil Pipeline in the permafrost areas under a warming climate. J. Cold Regions Science and Technology., 64: 226–234.
[6] Jianming Zhang, Guangzhou Qu, Huijun Jin. (2010) Estimates on thermal effects of the China-Russia crude oil pipeline in permafrost regions. J. Cold Regions Science and Technology., 64: 243–247.
[7] Yaping Wu, Yu Sheng, Yong Wang. (2010) Stresses and deformations in a buried oil pipeline subject to differential frost heave in permafrost regions[J]. Cold Regions Science and Technology, 64: 256–261.