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Permafrost thawing along the China-Russia Crude Oil Pipeline and countermeasures: A case study in Jiagedaqi, Northeast China

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ABSTRACT

The China-Russia Crude Oil Pipeline (CRCOP) traverses 441-km-long permafrost zones in northeastern China. Since the pipeline operation in 2011, significant ground surface subsidence occurred within the trench of the pipeline in warm and ice-rich permafrost zones. Oil temperatures from three pump stations were obtained and the soil temperatures around the pipe at two cross sections along the CRCOP in Jiagedaqi, northeast China were monitored during the period from 2011 to 2017. With the date records, permafrost thawing and thaw bulb development around the pipe were investigated in this study, as well as the cooling effect of thermosyphons experimentally installed around the pipe. Results showed that the mean monthly oil temperature ranged from 0.4 to 17.9 °C and increased slowly with operation time increase. Due to thermal effect of the warm oil, the artificial permafrost table near the pipe was approximately 5.9 m greater than that in the natural ground 5 years after pipeline operation. A thaw bulb developed around the pipe and expanded at a rate of more than 1.0 m/a in depth. Following the permafrost thawing, ground subsidence around the pipe was significant. The buried depth of the pipe declined with a rate of approximately 0.35 m/a during the study period. To mitigate the permafrost thawing and the pipe settlement, a pair of thermosyphons were experimentally installed at the two sides of the pipe in March 2015. After 2 years of installation, the shallow foundation soils were cooled down and the thaw bulb was partially re-frozen. However, there was still a thawed layer beneath the pipe. Long-term thermal regime of foundation soils under the cooling effect of the thermosyphons needs further investigation.

1. Introduction

Oil and gas pipelines built in permafrost zones are always affected by permafrost thawing (Schiermeier, 2003). The permafrost thawing around the pipelines can be triggered by warm oil/gas flow, trench excavation, vegetation removal and water ponding within the trench. For example, the Nadym-Pur-Taz natural-gas pipeline in northwest Siberia had floated upwards due to permafrost thawing and water accumulation around the pipeline (Seligman, 2000). The Norman Wells pipeline also experienced a significant settlement caused by underlying permafrost thawing (Nixon and Burgess, 1999; Smith et al., 2008).

The China-Russia Crude Oil Pipeline (CRCOP) was built between 2009 and 2010, and began official operation on January 1, 2011. The length of CRCOP in China is 933.11 km, of which 441 km is in discontinuous, sporadic and isolated permafrost zones and 512 km in deep seasonal frost zones. Within these permafrost zones, warm and ice-rich permafrost sections is roughly 119-km-long, and 42% of them is covered by peat soils. The CRCOP has a diameter of 813 mm, with a wall thickness of 11.9 mm. The buried depth of the pipe ranges from −1.6 to −2.0 m, near the permafrost table in the natural ground. A three-layer polyethylene structure was used for anti-corrosion, including epoxy primer, synthetic adhesive coating and a polyethylene layer from outside to inside.

Many researches have been conducted on thermal regime of foundation soils and mechanical behaviors of the pipe along the CRCOP in permafrost zones. Wen et al. (2010) calculated the stresses and deformations of the pipeline induced by differential frost heave and thaw settlement using a thermal elastoplastic computation model. Xu et al. (2010) conducted a model test to study the thaw bulb development around the pipe and the displacement, axial strain and stress of the pipe. Li et al. (2010a, 2010b) predicted the oil temperature and the thaw bulb development around the pipe along the CRCOP based on a quasi-three-dimensional computational model. Yu et al. (2014) used a coupled model of heat transfer and seepage to evaluate the effects of warm oil pipe on permafrost foundation. Wang et al. (2016a) investigated the thermal regime of foundation soils around the pipe using

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ground-penetrating radar. However, field monitoring on thermal regime of foundation soils around the pipe along the CRCOP has yet been reported at present.

In this study, about six-year records of oil temperatures from three pump stations of the CRCOP were obtained and soil temperatures around the pipe at two cross sections along the CRCOP in Jiagedaqi, northeast China were monitored. Permafrost thawing and thaw bulb development around the pipe were investigated based on the long-term data records. At one cross section, a pair of thermosyphones were experimentally installed at the two sides of the pipe. As a high effective heat transfer device, thermosyphon has been widely used for engineering infrastructures in permafrost zones (Wu et al., 2010; Zhang et al., 2011; Ma et al., 2012; Mu et al., 2016; Yu et al., 2016a, 2016b; Pei et al., 2017; Fang et al., 2018). Along the Trans Alaska oil pipeline, heat piles were used extensively at most of the above-ground sections to ensure the pipeline's stability and performed well up to present (Johnson and Hegdal, 2008). In this study, the cooling effect of the two thermosyphones in foundation soils of the oil pipe were also investigated based on soil temperature monitoring.

2. Site description and methods

The study site (KP 391 km + 600 m of the CRCOP in China) was located in a permafrost wetland, approximately 0.6 km south of the Jiagedaqi pump station (50°28′14.23″N, 124°13′31.75″E, and 484 m in altitude). According to a weather station in Jiagedaqi, the mean annual air temperature is −1.2 °C and the average annual precipitation is 524 mm. Engineering geological investigation shows that the depth of permafrost table is approximately −2.0 m and the mean annual ground temperature is −0.7 °C at the study site. The permafrost is warm, ice-rich and thaw-unstable. The vegetation coverage is dense, primarily consisting of mud sedge. The shallow geological stratum is peat, clayey sand, fine-grained sand and weathered granite from the surface downward. The pipeline was uninsulated and buried about 1.6 m in depth relative to the natural ground surface.

A monitoring cross section perpendicular to the pipeline was established at the study site and named as "cross section 1-1" in this study (Fig. 1a). In the cross section, two temperature boreholes (T1 and T2) were drilled and installed both with a 20-m-long thermistor cable in March 2014 to measure soil temperatures near the pipe. The two boreholes are 2.0 and 16.6 m away from the pipeline centerline,

Table 1
Detail parameters of the thermosyphons experimentally installed near the pipe.

Parameter	Value	Parameter	Value
Length of condenser section	2.5 m	Inner diameter of tube	79 mm
Length of evaporator section	6.0 m	Fin thickness	1.5 mm
Length of adiabatic section	0.5 m	Fin height	25 mm
Outer diameter of tube	89 mm	Fin space	10 mm

respectively. The thermistor cable in T1 has 25 thermistor sensors with an interval of 0.5 m from the ground surface (0.0 m) to −4.0 m depth and an interval of 1.0 m from −4.0 to −20.0 m depth. The interval of thermistor sensors in T2 was 0.5 m above the depth of −5.0 m, and 1.0 m below. Soil temperatures in this section were collected manually every month.

Another monitoring cross section was constructed 20 m away from the cross section 1-1, named as cross section 2-2 in this study. At the cross section, as shown in Fig. 1b, a pair of 9-m-long thermosyphons were experimentally installed at the two sides of the pipe in March 2015. The distance between the thermosyphons and the pipe centerline is both 1.5 m. The working fluid of the thermosyphons is ammonia and the detailed parameters of the thermosyphons are listed in Table 1. Three temperature boreholes were drilled (T3, T4 and T5) 0.5, 1.5 and 2.5 m away from the thermosyphon at the same side of the pipe in this section (Fig. 1b). The depth of the three boreholes are 15, 10 and 15 m, respectively. In each boreholes, a thermal cable were installed to measure the soil temperatures. In both T3 and T5, the thermal cables have 20 thermistor sensors, with a 0.5 m interval from 0.0 to −4.0 m depth and a 1.0 m interval below. While in T4, the thermal cable has 11 thermistor sensors in total, with an interval of 1.0 m. All the thermistors were manufactured by the State Key Laboratory of Frozen Soil Engineering, Chinese Academy of Sciences and have an accuracy of ± 0.05 °C. Soil temperature data in this section were collected automatically every 2 h by a datalogger.

3. Results and analyses

3.1. Oil temperatures at three pump stations

Three pump stations were set up in Mohe, Tahe and Jiagedaqi from north to south along the CRCOP in permafrost zones. Fig. 2 shows oil

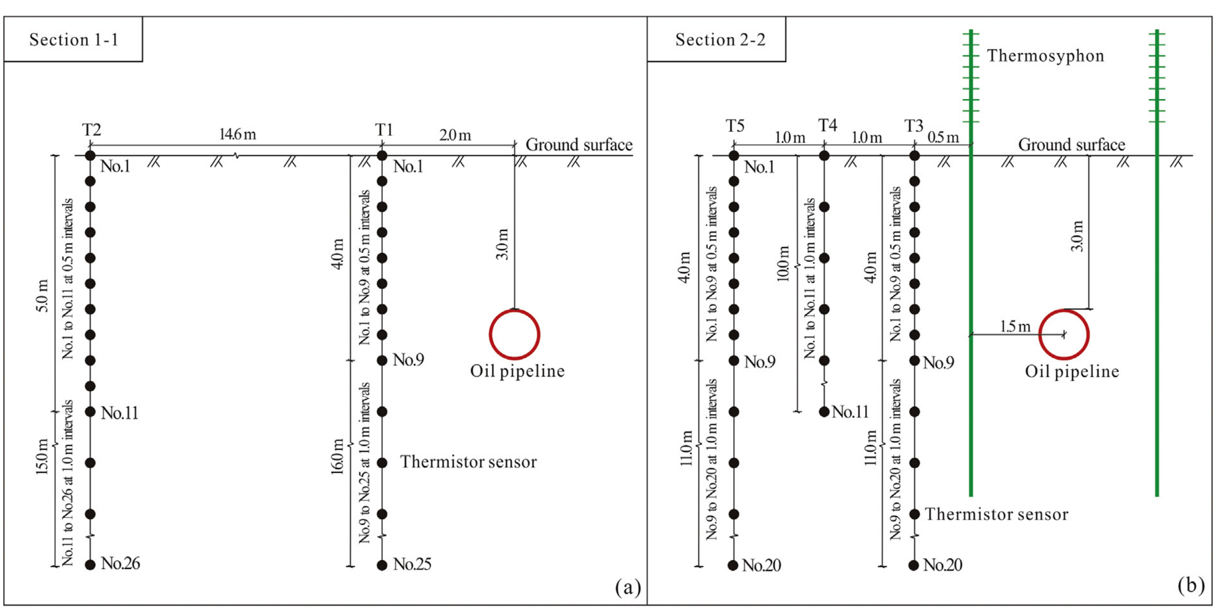

Fig. 1. Lay out of temperature boreholes and thermosyphones in cross section 1-1 (a) and cross section 2-2 (b).