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Pipe-laying Technology in a Subarctic Permafrost Region — A Case Study for the China-Russia Crude Oil Pipeline from Mo'he to Daqing, Northern Northeast China

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ABSTRACT
This paper summarized some pipe-laying technology experiences and lessons of the China-Russia Crude Oil Pipeline (CRCOP). The main principle on frost hazards mitigation and pipeline route selection is "bypassing" and "protection" of permafrost with mitigative measures. Another supplementary principle is pre-thawing or clearance of permafrost. The mitigative measures mainly include the increase of pipe wall thickness, external thermal insulation, drainage control, re-vegetation, and refilling with the thaw-stable (or non-frost-susceptible) soils. Numerical simulations, field investigations and ground-penetrating radar surveys have provided many key parameters and characteristics of the pipeline and its foundation soils. A strain-based pipeline design and a modified conventional burial were proposed and adopted for the CRCOP.

RÉSUMÉ
Cet article résume quelques expériences et leçons concernant les technologies employées pour poser la canalisation de l'oléoduc de pétrole brut entre la Chine et la Russie. Le principe de base pour la sélection du tracé de l'oléoduc et l'atténuation des risques de gel est l'emploi de mesures d'atténuation pour "contourner" et "protéger" le pergélisol. Un autre principe utile est la pré-décongélation ou le dégagement du pergélisol. Les mesures d'atténuation comprennent principalement l'augmentation de l'épaisseur de la paroi de la canalisation, l'isolation thermique externe, le contrôle du drainage, la végétalisation et le remplissage avec des sols insensibles au dégel (ou non gélifs). Des simulations numériques, des enquêtes de terrain et des enquêtes de radar à pénétration du sol ont fourni de nombreux paramètres et caractéristiques importants du pipeline et de ses sols d'assise. Une conception du pipeline axée sur la déformation, ainsi qu'un enterrement classique modifié ont été proposés et adoptés pour l'oléoduc de pétrole brut entre la Chine et la Russie.

1 INTRODUCTION

In subarctic permafrost regions, appropriate understanding of pipe-laying technology clearly represents an essential component of the overall design and construction of new pipelines. The China-Russia Crude Oil Pipeline (CRCOP) is a recent example.

The CRCOP was built to transport Siberian crude oil across 1,030 km of frozen-ground from Skovorodino, Amur Prefecture, Russia to Daqing, Heilongjiang Province, Northeast China (Figure 1). The Chinese portion of the CRCOP crosses 441 km of permafrost zones along the eastern flank of the Da Xing'anling (Hinggan) Mountains from Mo'he to Urqi (Figure 1), in which approximately 120 km is underlain by warm (>-1 °C) and ice-rich permafrost, with many frost hazards along the CRCOP route (PetroChina Petroleum Planning Institute, 2005; Daqing Oilfield Engineering Company (DOE), PetroChina Co., Ltd., 2008a, b). Using an X-65 pipe steel, the pipeline has a diameter of 813 mm, design pressures of 8-10 MPa, and a design annual throughput of 15 million tons to transport crude oil originally estimated

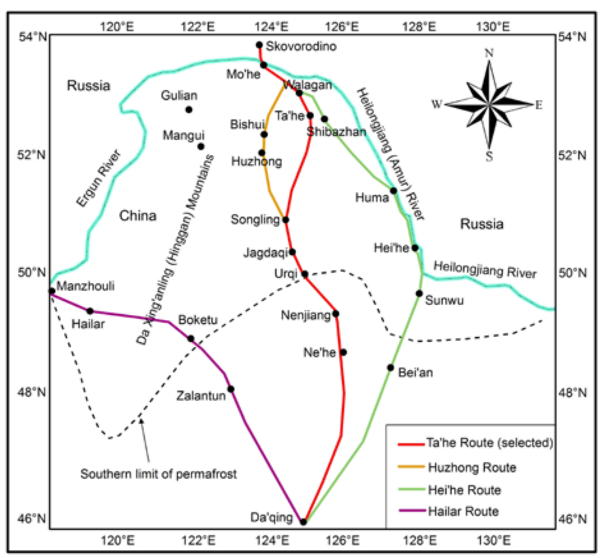

Figure 1. Alternatives and the finalized route for the CRCOP

to be in relatively low temperatures (-6.4 °C to +3.6 °C) in northern Northeast China with air temperatures fluctuating between -52.3 °C to +39.8 °C (PetroChina Petroleum Planning Institute, 2005; DOE, 2008a; Jin, 2010; Jin et al., 2010). The active construction period was 18 months (from May 2009 to October 2010). After two months of testing and trial operation, the formal operation began in January 2011.

The researches on pipe-laying technology have fallen short in permafrost regions in the world (Day, 1998; Seligman, 2000; Jin et al., 2005; Oswell, 2011). Lacking of earlier experiences for a crude oil pipeline construction in permafrost regions in China, appropriate design and construction of crude oil pipeline foundation soils with adequate consideration for the mitigation of frost hazards became the key technical issue for the CRCOP project (Jin et al., 2005). In order to solve the technical problems, research on pipe-laying technology in permafrost areas were carried out. In subarctic permafrost regions, the study of pipe-laying technology is mainly focused on pipeline route selection, construction mode design, numerical modeling and simulations, geotechnical investigations, hazards mitigation, and environmental protection and contingency plans for environmental disasters. This study has filled the historical gaps per se, and will provide a better basis for the design, construction, operation and maintenance of oil and gas pipelines in permafrost areas in the future.

2 PIPELINE ROUTE SELECTION PRINCIPLES

The selection of pipeline routes should mainly take into account of permafrost features, ecological environments, technical criteria for design and building the pipeline, access roads and other related engineered structures. The main principle of pipeline route selection is avoidance of geological hazards (Day, 1998; Oswell, 2011). For selecting the pipeline route, those areas with high risks of thaw settlement and frost hazards should be bypassed if at all possible, and the areas with highly possible occurrence of primary and secondary periglacial geohazards should be avoided. The avoidance needs careful identification of potentially problematic terrains or frost hazards. For example, the CRCOP finally selected the middle line (Ta'he route) from three alternative routes shown in Figure 1, mainly considering the shortest possible length in order to minimize costs and freezing/thawing problems. It was possible because the detailed geological survey along the alternative routes and the historical data had reported no near-surface buried ice wedges or lenses whose thawing might produce significant differential settlement over short distances and possible rupture of the pipeline (Jin, 2010). The selected route is also relatively richer in engineering geological and permafrost data, and consequently less costly (Jin, 2010). In addition, thermal and mechanical characteristics of the operating infrastructures should be considered. The new pipeline should keep a safe distance from the existing projects in order to avoid those undesired thermal and mechanical interactions between the pipeline and existing infrastructures.

3 NUMERICAL COMPUTATIONAL MODELS

To predict the geothermal and mechanical impacts of the CRCOP construction and operations on permafrost terrains, according the features of the CRCOP, a new numerical computational model was established in a semi-3-dimensional environment for analyzing the thermal regimes of the pipeline-soil system under fluctuating oil temperatures (Li et al., 2010a, b; Wen et al., 2010; Wu et al., 2010; Zhang et al., 2010), and the possible spatiotemporal changes in oil temperatures were predicted for the next 50 years (Li et al., 2010a).

The results indicated that the oil temperature were mainly controlled by the inlet oil temperatures, pump heating, throughput of oil transport, and ambient soil temperatures of the pipeline (Li et al., 2010a); the freeze-thaw states of the pipeline foundation soils were largely determined by climate and its changes, soil moisture contents, soil types and pipeline throughput and design configurations, as well as the mitigative measures for frost hazards (Li et al., 2010b; Zhang et al., 2010); the possible changes in the freeze-thaw cylinders around and under the pipeline along the CRCOP route (Li et al., 2010b; Zhang et al., 2010); changes in effective stress and strain of pipeline foundation soils were analyzed under different insulation configurations, oil pressures, pipewall thickness and the lengths of the transition of frozen-unfrozen foundation soils (Wen et al., 2010; Wu et al., 2010); the key design parameters, such as the constraint differential deformations for pipe buckling and allowable deformations of pipeline foundation soils, pipewall thickness and burial depths of pipe top, and insulation thickness (Li et al., 2010a, b; Zhang et al., 2010; Wen et al., 2010; Wu et al., 2010). Many of these results were adopted and extensively applied in the design and building of the pipeline.

The studies also revealed that the strain from thaw settlement of pipeline foundation soils would be accumulative (Wen et al., 2010); when traversing slopes underlain by fine-grained soils, the large and persistent difference in pipe and soil temperatures could result in hydraulic channels of the suprapermafrost water, subsequently enhanced erosion and drainage, and resultant geohazards such as icing and frost mounds, and thaw subsidence, along the pipeline (DOE, 2008 a, b; Wu et al., 2010); due to the concentration of stress, large deformations could result at the transition zones of frozen-unfrozen interfaces and across adverse periglacial phenomena such as frost mounds, therefore they are the key segments for permafrost hazard mitigation(DOE, 2008 a, b; Wu et al., 2010; Wen et al., 2010). These results have been proved through the recent field investigations (Li et al., 2015; Wang et al., 2015a) and ground-penetrating radar (GPR) surveys (Wang et al., 2015b) along the CRCOP route in permafrost areas.

4 FIELD INVESTIGATIONS AND GROUND-

PENETRATING RADAR (GPR) SURVEYS

The field investigations have been undertaken since the principle routes of the CRCOP have been set to provide information on climate, terrain, geology, vegetation, ground temperatures, presence or absence of permafrost, permafrost table and base, soil moisture content, groundwater, soil characterization and another site-specific features. About 500 boreholes, with depth of 5 m to 20 m, were drilled and cored for the CRCOP project in 2007-2008 (Jin, 2010). The frost hazards (Figure 2), such as thaw settlement, frost heave, frost mounds and icings, generally occurred at the sites in lowland marshes or those underlain by ice-rich, warm permafrost after the operation of the CRCOP (Li et al., 2015; Wang et al., 2015a). The thaw settlement occurred more extensively, frequently and severely in permafrost areas along the CRCOP route (Li et al., 2015; Wang et al., 2015a). The construction and operation of the CRCOP broke the hydrothermal balance of the ground which caused differential frost heave and thaw settlement of the foundation soils around and under the pipeline and the accumulation of the differential displacement (Wang et al., 2015a).

Figure 2. The example of frost hazards along the CRCOP

Ground-penetrating radar (GPR) is effective, non-destructive, and convenient for evaluating the spatiotemporal extent and development processes of the freeze-thaw states of pipeline foundation soils and the underlying permafrost (Wang et al., 2015b). Significant thaw settlement of some of the CRCOP foundation soils has occurred since the pipeline began operation in January 2011 (Li et al., 2015; Wang et al., 2015a). To evaluate the engineering safety and long-term stability of pipeline foundations, GPR technique was used for detecting the freeze-thaw states of pipeline foundation soils in permafrost zones along the CRCOP route (Wang et al., 2015b). From April 2012 to November 2013, a total of 2,780 m of GPR profiles and 62 cross sections (perpendicular to the CRCOP route) were obtained at eight GPR study sites on various terrains and vegetative coverage, with different thermal insulation configurations around the pipe, and with and without thermosyphons installed. The GPR profiles were interpreted and cross-checked with data from drilling, hand-dug pit excavations, and ground temperature measurements. The results showed that the foundation soils around the pipeline were thawing, with maximum thaw depths under the pipeline of about 1.1 m to 4.5 m from the pipe bottom and increased maximum thaw depths of 0.5 m to 3.7 m during the period of this study. However, GPR profiles from the areas with dense vegetative coverage, and with pipe insulation of 80-mm-thick extruded polystyrene (XPS), and also with vertical thermosyphons installed, showed that permafrost foundation soils were better thermally protected, with only minor thaw settlement. Until November 2013, the measured thaw depths under the pipe in insulated areas was generally 1.1 m to 2.1 m from the pipe bottom, and less than the 2.3 m to 4.5 m in un-insulated sections, and about 1.1 m in the area with thermosyphons and less than the 2.0 m in the nearby area without. The increases in thaw depth beneath the pipe bottom were generally less than 30% in areas with an insulated pipeline, and less than the percentage increase of areas without insulation (more than 48%). The percentage increase in the thaw depths of the pipeline segment with thermosyphons was also smaller (27% m < 30%).

The thermal states of pipeline foundation soils and the underlying permafrost varied markedly with different terrains. The drainage patterns and engineering activities, especially the heating from operating oil flows at an annual average oil temperature of 7.7 °C, with a range of 0.7 °C to 20.4 °C, along the pipeline route may have been responsible for the extensive and substantial thaw subsidence in the ice-rich permafrost zones. Additionally, there was positive feedback between the thaw subsidence of ground surface in the vicinity of the pipeline route and the thaw settlement of the pipeline foundation soils. The greater the earth surface subsidence, the more surface water ponding and soil disturbances, and even greater progressive thawing. Therefore, it is recommended that some measures, such as better operational control, improved re-vegetation, better controls of ground surface subsidence, and foundation soils and drainage, better insulation or thermosyphons at some pipeline segments with severe settlements, and excavating and refilling with thaw-stable soils if absolutely necessary, for stabilizing the pipeline foundation soils (Wang et al., 2015b).

5 HAZARD MITIGATION MEASURES AND ENVIRONMENTAL PROTECTION

In permafrost regions, the main frost hazards include (differential) frost heave and differential settlement of pipeline foundation soils (Lachenbruch, 1970; Jin et al., 2005). The disturbance of pipeline construction on permafrost environment may possibly impact the long-term stability of pipeline foundation soils (Seligman, 2000). The main principle on the mitigation of frost hazards is "bypassing" and "protection" of the permafrost soils and mitigative measures for controlling significant deformation caused by frost heave and thaw settlement of pipeline foundation soils and the underlying permafrost soils (Oswell, 2011).

There are two "rules of thumb" on using permafrost soil as the pipe foundation. The first principle is the protection of permafrost soils, such as those mitigative measures for reducing the thermal and hydraulic influences of the pipeline system on the permafrost environment. The second is pre-thawing or clearance of permafrost soils when economically justified, particularly in the southern margins of permafrost zones. After a comparative study and due to the project economics, allowable active construction period, and technological viability on various construction modes, a modified burial of the pipeline was adopted for the CRCOP project (PetroChina Petroleum Planning Institute, 2005; DOE, 2008a; Jin et al., 2010). The most effective way for controlling the large thaw settlement and frost heave is to increase the pipe wall thickness (the range of the CRCOP wall thickness is from 12 mm to 17 mm), in addition to the consideration for ensuring the pipeline safety for the design internal pressure. The other effective ways also include external thermal insulation of the pipe and to refill the ambient soils with the thaw-stable (or non-frost-susceptible) soils (about 0.3 m to 0.5 m depth of soils under the CRCOP was refilled at some segments with high-ice-content permafrost). To ensure the permafrost slope stability at some critical segments, a permafrost protection construction mode was also realized by surface insulation, such as woodchip layers (Figure 3).

Figure 3. Woodchip layers of a slope surface insulation along the CRCOP on March 23, 2014

According to the study on the protection of permafrost environment, the influences of pipeline construction and operation on the permafrost environment is analyzed (DOE, 2008a, b). The environmental protection measures were proposed as follows:

(1) Bypassing measures, while selecting pipeline route try to bypass the areas with high risks of hazardous periglacial phenomena (see the “pipeline route selection principles” section in this paper);

(2) The pipeline construction should be mostly carried out in winter, and the bilateral and environmental damage due to the clearance of the pipeline right of way should be reduced to the minimum possible (Figure 4);

Figure 4. Winter construction of the CRCOP (photographed on November 19, 2009)

(3) The environmental impact on permafrost area caused by pipeline construction and operation should be reduced economically. For example, the thermal insulation measure shall be adopted to reduce the heat exchange between pipe and permafrost soils and with other aquatic environments (Figure 5);

Figure 5. Thermal insulation of the CRCOP near Amuer, northern Heilongjiang Province, China (photographed on April 15, 2012)

(4) Re-vegetation shall be implemented as soon as possible and periodically checked (Figure 6).

Figure 6. The re-vegetation information at the CRCOP Mile Post MDX304 Km + 687 m

6 STRAIN-BASED PIPELINE DESIGN

The stress-based traditional pipeline design generally cost higher in comparison with the strain-based pipeline design (Zhou et al., 2006). The strain-based pipeline design can maintain pipeline safety and integrity to some extent when reach the limit strain (Zhou et al., 2006). Strain-based pipeline design was proposed and adopted for the CRCOP due to the large anticipated deformations of pipeline and its foundations soils subject to frost heave and thaw settlement and other geological hazards which could induce excessive stresses and strains on the pipeline (DOE, 2008a, b). This was on the basis of thorough thermal and stress/strain analyses of CRCOP, economically available steel type, and strict environmental stipulations for wetlands, forests and potable water sources for northern Northeast China Plain. It was recommended that control or enhanced drainage and refills of thaw-stable soils should be undertaken for the modified burial construction mode, and proper extension of the frozen-unfrozen transition zones for lowering the effective stress on the ice-rich permafrost slopes.

7 RETROSPECT AND PROSPECT

Most of the results from the study were extensively adopted by the CRCOP construction and operation. It has been put into operation since November 2010 after 18 months of active construction period. The proposed principles for pipeline design, construction and operation have been proven reasonably effective. However, due to the much-higher inlet crude oil temperatures from Russia, the thaw settlement has exceeded the previous estimates. Some additional studies and mitigative measures deem necessary after a systematic evaluation of the operation risks under the present conditions.

In retrospect, the much-higher-than-anticipated oil-flow temperature was the major contributor to the large and rapidly-developing thaw settlement, and other adverse environmental factors on the permafrost slopes and wetlands also contributed indirectly to the hazardous operating environment, such as the thermal erosion and hydraulic channeling when pipeline skirting or along the fine-grained permafrost slopes and water ponding on the disturbed surfaces in wetlands in or close to the pipeline right-of-way.

In prospect, the second CRCOP will be soon built along the similar route for higher throughput and the China-Russia Natural Gas Line from Hei'he to Daqing is already under a feasibility study and at the stage of route selection and surveying for engineering geology. They are all to be operating at above-zero or much higher temperatures of oil and gas (about 10 °C to 20 °C) across hundreds of kilometers of warm, ice-rich and discontinuous, and therefore different thaw settlement of foundation soils will be the primary concerns. Therefore, the relevant studies and the monitoring of the practical thermal and strain/stress states of the pipe-soils systems have showed their crucial importance for a safe, stable and economical design, construction and operation of many pipelines to come. The improving monitoring systems and data sharing, as well as the experiences and lessons learned would undoubtedly help the better and more environmentally friendly oil and gas pipelines in permafrost regions in China and beyond.

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