Remediation of a Settlement and Heave Anomaly on a Pipeline in the Northern Region of Canada – an Update

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ABSTRACT
The first completely buried oil pipeline in the discontinuous/sporadic permafrost zone of Canada was constructed in the winters of 1983 and 1985. Since 1989, settlement and heave have been detected along the pipeline at a particular small creek crossing. In 2014, a borehole geotechnical investigation and assessment were completed. Subsequent monitoring revealed that the pipeline continued to experience strain which eventually caused a wrinkle in the pipeline. In February 2017, a section of pipeline approximately 90 m long, including the wrinkle, was replaced. During the replacement work, additional thermistors and piezometers were installed at the site, including a pipe thermistor directly on the pipeline to provide ongoing monitoring. This update on the original paper presents the monitoring information between 2014 and 2016, findings of the replacement work, details on the pipe wrinkle and subsequent monitoring.

RÉSUMÉ
Le premier oléoduc entièrement enfoui dans la zone de pergélisol discontinu / sporadique du Canada a été construit durant les hivers de 1983 et de 1985. Depuis 1989, des tassements et des soulèvements ont été détectés où l'oléoduc traverse un petit ruisseau. En 2014, une étude géotechnique par forage et une évaluation géotechnique ont été complétées. Une surveillance subséquente a révélé que le pipeline continuait de subir des contraintes, lesquelles ont éventuellement causer un flambage local mineur de la conduite. En février 2017, une section de pipeline d'environ 90 m de long a été remplacée, incluant la partie de conduite flambée. Pendant les travaux de remplacement, des thermistances et des piézomètres supplémentaires ont été installés sur le site, y compris une thermistance placée directement sur le tuyau pour assurer une surveillance continue. Cet article constitue une mise à jour de la version originale. L'article présente les résultats de la surveillance effectuée entre 2014 et 2016 et décrit les travaux de remplacement de la conduite, incluant des détails sur la partie de conduite flambée et la surveillance subséquente.

1 INTRODUCTION

An 869-km crude oil pipeline in the northern region of Canada was constructed during the winters of 1983 and 1985. The pipeline was the first completely buried oil pipeline constructed in a sporadic/discontinuous permafrost zone.

At a particular site, pipe movement from its original position was first detected in 1989 near a small creek crossing. Monitoring data indicated that an approximately 30 m long section of pipe on the north side of the creek had been subjected to ongoing settlement of up to 1 m from 1989 to 2013. An adjacent 20 m long section of pipeline had experienced up to 0.25 m of heave during the same time.

Historical data review and a geotechnical field investigation were completed in 2014. Eight boreholes were advanced with soils logging completed in six of the boreholes. Three vibrating wire piezometers and six thermistor cables were installed to monitor ground temperature and piezometric conditions.

A 2-dimensional geothermal model was developed to predict potential for future settlement of the pipeline and to back-calculate the potential thickness of the ice-rich permafrost layer that may have been present originally near the settling pipe section.

Subsequent monitoring using in-line inspection tools revealed that the pipeline continued to experience strain which eventually caused a wrinkle in the pipeline. In February 2017, the affected sections of the pipeline were excavated and replaced. During the excavation, a wrinkle was visible adjacent to a girth weld, approximately 10 m north of the creek. This wrinkle was located where a section of thick-walled pipe connected to regular-thickness pipe. Following removal of the pipe segment, laser mapping and laboratory macro photograph analysis were completed of the wrinkle.

A paper was presented summarizing the field works and geotechnical assessments conducted in 2014 (Hsieh et al., 2017). This is an updated paper presenting the monitoring information between 2014 and 2016, findings of the replacement work, and details on the pipe wrinkle.

2 SITE DESCRIPTION

The section of affected pipeline is buried within a cleared right-of-way, adjacent to a small creek. Surficial geology maps of the area indicate the site is situated close to the eastern boundary of lacustrine plains with depression zones created by thermokarst processes (Natural Resources Canada, 2009).

The creek is approximately 2 m wide within a small creek valley that is approximately 3 m deep. The area within 10 m north of the creek was relatively flat. The slope south of the creek was approximately 2.7 m higher than the thalweg of the creek. The crest of the south slope was approximately 15 m south of the creek. Southwards, the land sloped gently away from the creek.

3 PREVIOUS INVESTIGATIONS

3.1 Historical Data Review

Boreholes were not advanced as part of the original geotechnical design as the slopes adjacent to the creek were less than 5 m. An in-line inspection (ILI) caliper tool equipped with inertial positioning has been used annually since 1989 to measure the pipeline position, geometric anomalies, and pipe strain.

For the purposes of historical data review and geothermal modelling, the pipeline was subdivided into three sections based on relative movement to the pipe:

- Section I: pipe section beyond 16 m north side of the creek;
- Section II: pipe section within 16 m north side of the creek;
- Section III: south side of the creek.

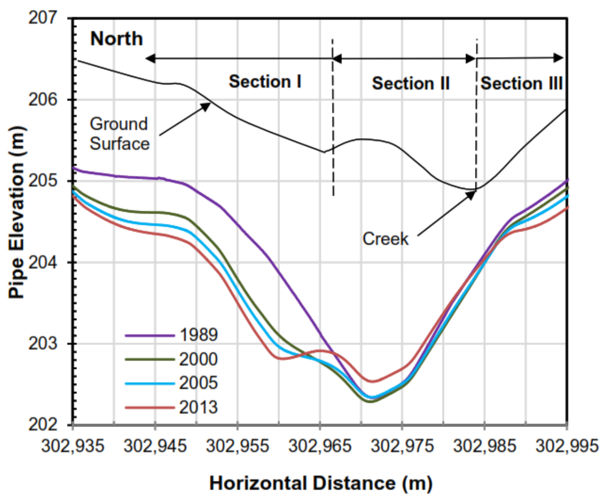

Figure 1. Measured Pipe Elevation – ILI Data

Between 1989 and 2000, varying degrees of settlement was detected in all sections. From 2000 to 2013, upward movements were detected in the pipe in Section II while settlement continued in Sections I and III at varying rates.

Comparison of pipe strains in 1989 and 2013 revealed that there were no significant increases in pipe strain for most of Sections I through III. An exception to this was approximately 24 m north of the creek where the vertical strain changed from negative to positive within the above noted time. A negative pipe strain indicates the pipe is subjected to settling (convex bending) whereas a positive pipe strain indicates heaving (concave bending).

Historical temperature data from a set of four of five thermistor beads attached to the pipeline indicated that the pipeline temperature (including non-operating periods up to several days in duration) generally fluctuated from about 8°C in the summer to -1°C in the winter. From 2010 to 2013, temperatures up to 13°C were recorded in the summer. In 2009 and 2012, winter season temperatures were below -2.5°C.

Weighted averages of climate data from Environment Canada weather stations closest to the site (270 km north and 200 km south) indicated that the mean annual air temperature had warmed up by approximately 1.5°C between 1985 and 2012. Snow fall, snowfall thickness on the ground, and weighted averages of monthly air temperatures were also collected for use in thermal modelling discussed in Section 3.3.

3.2 Field Investigation

In 2014, a geotechnical field investigation was completed and included eight boreholes, six of which were logged and sampled. Three vibrating wire piezometers and six thermistor cables were installed to monitor ground temperature and piezometric conditions within the pipeline right-of-way.

A consistent soil profile of silty clay was encountered in all boreholes. Laboratory testing indicated the silty clay layer to be firm, medium to high plastic, massive, grey, with trace oxidation, and moist.

Lenses of ground ice up to 300 mm thick were encountered in four of the eight boreholes. The permafrost table was found to be approximately 6 to 6.5 m below the ground surface.

A topographic survey of the ground surface and depth of cover survey was completed on both sides of the creek and found that the pipe burial depth varied from 0.9 to 2.9 m, with the deepest section located 10 to 14 m north of the creek.

3.3 Geothermal Modelling

Geothermal modeling was completed for a selected location within Section I that had experienced approximately 1.1 m of settlement between 1989 and 2013. Sections II and III were not analyzed as the pipe settlement in these regions were minor according to the ILI measurements. The modelling was intended to predict potential for future thaw settlement and thaw depth along the pipe in Section I. SIMPTEMP, a 2D geothermal modelling program, was used to simulate a period of 45 years, from the winter of 1985 to winter of 2030.

The modelling predicted that the maximum thaw depth in Section I would be in the order of 12 m in 2029, resulting in an additional settlement up to 0.4 m in the next 10 to 15 years.

4 INSTRUMENTATION MONITORING

Instruments installed during the 2014 geotechnical field investigation were monitored quarterly until August 2016. Ground temperatures were measured using thermistor cables and the presence of frozen soils were confirmed by measurements ±0.1°C.

Piezometric pressures recorded by vibrating wire piezometers corresponded to hydrostatic pressures at a height of 2 to 6 m above the respective ground surface. Following installation, piezometric levels remained relatively stable and significant increases or decreases in pore pressure were not noted.

5 ILI DATA FROM 2013 TO 2016

Percent of bending strain accumulation from 1989 to 2016 and wrinkle height as well as ovality after 2009 are plotted in Figure 2. An in-line inspection (ILI) caliper tool with bending strain measurement capability has been used annually since 1994 on this pipeline segment, usually in the summer or early fall months. The ovality and onset of a wrinkle became significant in 2009, and is plotted thereafter in terms of percentage of OD. The 2% wrinkle formation at approximately 1.9% bending strain is consistent with other >2% wrinkles in NPS 12 pipe in this wall thickness range. The pipeline was required to be replaced because the 2% wrinkle criteria was exceeded.

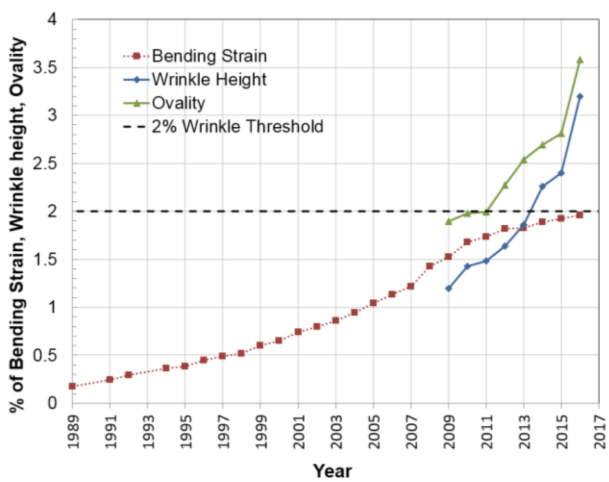

Figure 2. ILI Data Trends Near the Creek

Ovality and wrinkle formation appear to correlate with bending strain, with an acceleration in 2011 when bending strain exceeded 1.7%. Typical pipeline internal pressure at this location is 2,450 kPa with very little pressure variation.

6 FIELD OBSERVATIONS DURING WRINKLE REPAIR

6.1 Methodology of Pipe replacement

Five excavations were completed in February 2017 to expose and replace approximately 60 m of pipeline on the north side of the creek and 30 m of pipeline on the south side of the creek. During preparations for replacement work, all instruments installed in 2014 were destroyed.

Two track-mounted excavators were used to expose the pipeline within five zones of excavations.

Prior to excavation, vacuum holes were completed at intervals along the pipeline alignment to determine the depth of the pipeline at all trench locations. Snow and top soil were removed.

Trenches were dug directly adjacent to both sides of the pipeline to the pipe invert. After overburden was removed using an excavator with extensive guidance from a ground crew, the pipeline was exposed by hand with shovels. Trench walls were back-sloped to approximately 45 degrees and barricades were placed around the open excavations.

6.2 Pipeline Condition

The exterior coating of the pipe was observed to be in good condition during excavation, except for the area around a girth weld between the thick-walled and regular pipe sections. This weld was located within the middle zone, approximately 10 m north of the creek, at the location of the wrinkle. At this location, the black sleeve around the pipe was deformed on the underside of the pipe at the wrinkle location. Foam wrap was noted to be wrapped around the pipeline south of this weld towards the creek.

Within the middle zone, the pipeline was observed to sag, with the lowest point located approximately 15 m north of the creek. Approximately 0.5 to 1 m of horizontal displacement was also noted across the extent of the excavation. Figure 3 illustrates the horizontal displacement & field bend in proximity to the wrinkle.

Figure 3. Horizontal Displacement of the Pipe

6.3 Subsoil Conditions

Soils exposed during excavation were consistent with soils logging completed during the 2014 geotechnical investigation. The soil profile included approximately 0.2 m of topsoil mixed with some angular gravel and cobbles, overtop of a silty clay layer which continued to the final depth in all excavations.

The silty clay was logged in the field as medium to high plastic and dark brown to dark grey. Some isolated pockets of organics were noted in the drain up bell hole. Pockets of light brown silty clay mottling were noted in the north and south isolation bell holes and the north tie in hole.

A silty to clayey gravel unit was encountered directly over the pipeline in the drain up bell hole. The unit was approximately 1 m wide and traced the orientation of the pipeline across the length of excavation. Cobbles and boulders up to 0.4 m diameter were observed within the unit with some resting directly on the pipeline.

Samples were collected in each excavation, approximately every 0.5 m to the final depth of excavation.

6.4 Permafrost Conditions

Permafrost was not encountered within any of the excavations. In all excavations, the soil was noted to be frozen 0.3 to 0.4 m below ground surface but was thawed to the depth of excavation.

6.5 Groundwater Conditions

Prior to excavation, water was observed to be frozen approximately 0.8 m below the ground surface within one of the vacuum holes at the drain up bell hole location.

Free water was observed dripping within the gravel unit directly above the pipeline at the south end of the drain up bell hole, at the location of the foam wrap. The day following excavation, 0.2 m of water was pooled at the bottom of the excavation.

6.6 Laboratory Testing

Laboratory testing, including natural moisture content of grab samples, particle size distribution analyses and Atterberg limit testes were completed on samples collected from within the excavations. The soil surrounding the pipeline contained, on average, 52% silt and 48% clay. Moisture contents varied from 13.9 to 29 % with an average of 24%. The average liquid limit was 50% and the average plastic limit was 30%, which are classified as medium to high plastic clay as per MUSCS.

6.7 Instrumentation

Following replacement of the pipeline, a pipe thermistor cable was wrapped around the pipeline prior to backfill. Four thermistor cables with switch boxes and three vibrating wire piezometers were installed in five boreholes to continue to monitor temperature and piezometric conditions surrounding the pipeline.

Since installation, the thermistors have recorded frozen ground between 6 and 9 m below ground elevation. This is consistent with the thermistors installed during the 2014 field investigation. Minimal change in temperature has been recorded between installation (March 2017) and the most recent readings.

Piezometer data from the instruments installed in March 2017 indicated ground water levels directly north and south of the creek were between 0.5 and 2 m above the ground elevation. Piezometric levels recorded by the southern-most instrument (approximately 20 m south of the creek) were between 7 and 8 m above ground elevation. All three piezometers have recorded a decreasing piezometric level since installation.

The thermistor installed around the replacement pipe section has recorded temperatures between -0.3 and -0.1°C since installation.

7 ANALYSIS OF WRINKLE

A laboratory photograph of the wrinkle and girth weld after removal of the polyethylene coating and shrink sleeve is shown in Figure 4. The wrinkle height was found to be about 13.7 cm. The pipe has been rotated approximately 180 degrees in Figure 4 showing the wrinkle at the top for photographic convenience. The field-discovered wrinkle orientation was actually at the six o'clock position. The wrinkle formed close to the center of a field bend of radius 93.5D, 1.3 degrees right and 1.9 degrees down, just upstream of a transition weld to heavier walled pipe.

Figure 4. Pipe with wrinkle (top of photograph)

Measurement of the minimum radius of curvature associated with the buckle using the procedures outlined in ASME B31.8R gave a minimum radius of curvature of 29.8 mm and a calculated local strain value of 16.8%. The laser strain mapping of the wrinkle is shown in Figures 5 and 6.

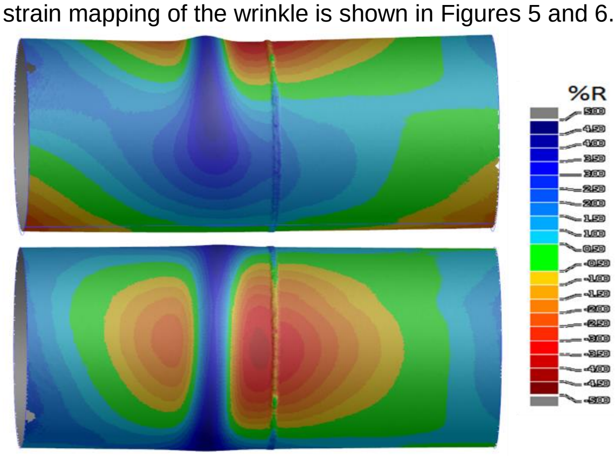

Figure 5. Laser mapping of the Wrinkle, Elevation and Plan views

Upstream and downstream ovality measurements were recorded. The upstream pipe adjacent to the feature had a top-bottom diameter of 327.1 mm, and a 3 to 9 o'clock diameter of 322.9 mm. The downstream heavy wall pipe adjacent to the feature had a top-bottom diameter of 326.4 mm and a 3 to 9 o'clock diameter of 321.2 mm. The calculated ovality after formation of the wrinkle is 1.3% upstream and 1.6% downstream of the wrinkle feature. The upstream peak ovality, $(D_{max} – D_{min}) / D_{nominal}$, reported by ILI in 2013, just before the wrinkle formed, was 2.54%.

The pipe was found to be free of corrosion, cracking, or mechanical damage features in proximity to the wrinkle. Basic mechanical properties and chemistry of the X52 pipe material met all CSA Z245.1 requirements with an average longitudinal elongation of 39%.

Both upstream and downstream pipe joints exhibited excellent toughness, including a minimum full-scale equivalent toughness of 135 Joules in the pipe joint with a minimum local wall bend radius and 102 Joules across the girth weld with wrinkle.

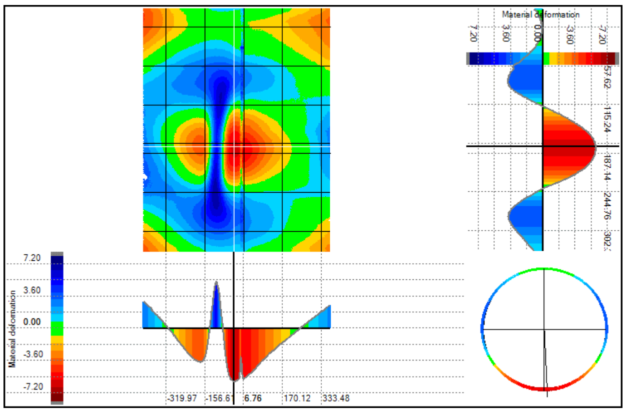

Figure 6. Laser Measurement of the Wrinkle Feature

A summary of the allowable compression strain analysis methods and the associated computational result is shown in Table 1. The observed threshold for wrinkle onset in 6.9 mm wall thickness NPS 12 pipe (five wrinkles) is 1.9% bending strain based on the in-line inspection tool measurements. The diameter to wall thickness ratio is 46.5 for the wrinkled pipe joint.

Table 1. Comparison of Compressive Strain Limit Estimating Methods

Source	Percent Compression Strain
American Lifeline Alliance [1]	0.822
Murphey-Langner API RP 1111[2,8]	1.076
Murphey-Langner Sherman [11]	0.741
British Standards [3]	0.695
Gresnigt [7]	0.829
CSA Z662-11 [4] (P_e=0)	0.849
C-FER Equation [13]	0.806
DNV Equation [5,12]	1.676
Dorey Equation [6] rounded yield, GW	1.022
Dorey Equation plateau yield	0.848

The DNV equation most closely matches the observed onset of compression wrinkles on this pipeline, with all other methods erring conservatively.

8 CONCLUSION

A holistic assessment approach to an externally loaded pipeline segment was found to be valuable. After integrating the historical monitoring data, annual ILI surveys, geothermal modeling, and a 2014 geotechnical field investigation, it was predicted that continued pipe settlement and heave along the segment of pipeline would continue, and formation of a wrinkle was imminent.

ILI data confirmed that a pipe wrinkle had formed at approximately 10 m north of the creek. In February 2017, an approximate 90 m length section of pipeline was excavated and replaced to remove the wrinkle and remediate the strain accumulation. The exposed section of pipeline had displaced both horizontally and vertically from the original installation location, confirming the ILI and ground instrumentation measurements.

A section of the pipeline containing the wrinkle was sent to a laboratory for analysis. Wrinkle and material characterization measurements confirmed the ILI measurements and material chemistry and properties were within specification values. There were no crack indications in the wrinkle which had a calculated local plastic deformation strain of 16.8%. This limits the wrinkle consequence to serviceability, which mimics prior experience with wrinkles on this Grade X52 pipeline. Mathematical strain capacity models were found to trend conservatively for this pipeline segment.

This example confirms that periodic in-line inspections can play a critical role in predicting pipeline maintenance, and can be correlated with geotechnical assessments. A correlation between ovality severity and wrinkle onset was observed from ILI measurement, and could form the basis for more accurate future predictions of wrinkle onset.

9 DISCLAIMER

10 REFERENCES

American Lifelines Alliance, 2005. Guidelines for the Design of Buried Steel Pipe, July 2001 (with addenda through February 2005)

API, 2011. Recommended Practice for the Design, Construction, Operation, and Maintainance of Offshore

BSI, 2004. Code of Practice for Pipelines – Part 1: Steel Pipelines on Land. British Standards Institution, PD 8010-1:2004.

CSA, 2011. Oil and Gas Pipeline Systems. CSA Z662-11, Canadian Standards Association, Mississauga, Ontario.

DNV. 2012. Submarine pipeline systems. DNV Offshore Standard DNV-OS-F101, Det Norske Veritas Classification A/S.

Dorey, A.B., Cheng, J.J.R., and Murray, D.W. 1994. Critical Buckling Strains for Energy Pipelines. Structural Engineering Report No. 237, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta.

Gresnigt, A.M., 1986. Plastic Design of Buried Steel Pipelines in Settlement Areas. Heron, Vol. 31, No. 4, The Netherlands.

Hydrocarbon Pipelines (Limit State Design). API RP 1111, Fourth Edition, American Petroleum Institute.

Hsieh, E., Tchekhovski, A, Brodland, B., Song, P., 2017. Settlement and Heave Anomaly on a Pipeline in the Northern Region of Canada, 70th Canadian Geotechnical Conference: *GeoOttawa 2017*.

Natural Resources Canada, 2009. Open File 6014, Surficial Geology, Wrigley (95O/SW), Northwest Territories, Scale 1:100 000.

Sherman, D.R., 1976. Tests of Circular Steel Tubes in Bending. ASCE Journal of the Structural Division.

Yoosef-Ghodsi, N., Julak, G.L. and Murray, D.W., 1994. Behaviour of Girth-Welded Line Pipe. Department of Civil Engineering, University of Alberta, Structural Engineering Report No. 203.

Zimmerman, T.J.E., Stephens, M.J., DeGeer, D.D. and Chen, Q. 1995. Compressive Strain Limits for Buried Pipelines. Proceedings of the 1995 Offshore Mechanics and Arctic Engineering Conference, Denmark.