# Long-term Field Observations of Cyclical and Cumulative Pipe and Ground Movements in Permafrost Terrain, Norman Wells Pipeline, Northwest Territories Canada

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ABSTRACT
Pipe and ground movements have been documented since the mid 1990s at two permafrost sites in the first 5 km of the Norman Wells Pipeline route to investigate the effect of seasonal cycling of oil inlet temperature. Seasonal pipe movements of about 0.2-0.5 m have occurred in response to heave and settlement related to the cyclical pipe and ground temperatures. At one site, where pipe uplift initially occurred in response to the cyclical pipe temperature, a gravel berm has been effective in reversing the upward movement and in reducing seasonal movements. Cumulative pipe settlement up to 0.3 m has occurred at the other site and likely resulted from increasing thaw penetration. Cumulative ground settlement has been greater than 0.3 m.

RÉSUMÉ
Les mouvements de la conduite et du sol ont été documentés à partir de 1994 à deux sites le long des cinq premiers kilomètres de l'oléoduc Norman Wells. Des mouvements saisonniers de la conduite d'environ 0,2 à 0,5 m surviennent en réaction au soulèvement et au tassement provoqués par le cycle saisonnier des températures aux entrées du pétrole A l'un des sites, un soulèvement de la conduite fut d'abord observé, mais l'emplacement d'une couche de gravier réussit à renverser le mouvement vers le haut à long terme et à réduire les mouvements saisonniers. Un tassement cumulatif de la conduite allant jusqu'à 0,3 m est survenu à l'autre site, probablement en raison du dégel continu en dessous de la conduite. Le tassement cumulatif du sol peut dépasser 0,3 m.

## 1 INTRODUCTION

The Norman Wells Pipeline, in operation since 1985, is the first completely buried ambient oil pipeline in permafrost terrain in North America. The environmental and engineering design of the pipeline utilized novel approaches in order to deal with potential issues of thaw settlement and frost heave. A collaborative monitoring project, between the government and the pipeline operator, Enbridge Pipelines (NW) Inc., has facilitated documentation and improved understanding of the interactions and impact of the pipeline project on permafrost and terrain conditions.

Over the pipeline's operating life, average annual oil temperatures entering the line have been maintained slightly below 0°C. Initially this was achieved through constant chilling of the oil throughout the year. In 1993, a seasonal chilling cycle was introduced (to address operational challenges due to waxing) resulting in summer temperatures rising above 0°C and winter temperatures dropping below 0°C while maintaining a mean annual temperature near 0°C. The fine-grained soils in the first few kilometres of the pipeline route are thaw and frost susceptible. Field surveys conducted at the northern end of the pipeline, at (kilometre post) KP2 and KP5 have generated data on seasonal and cumulative pipe and ground movements in response to both right-of-way clearing and pipeline operation. In particular the data collected have facilitated an assessment of impacts of changes in the pipe inlet temperature regime that have been effective since 1993 and also the effectiveness of remedial action taken in 1997 in response to increasing pipe uplift at KP5. This paper presents an update to observations previously reported at these two sites (Burgess et al. 1998, 2000; Nixon and Burgess 1999), of both pipe and ground surface movements.

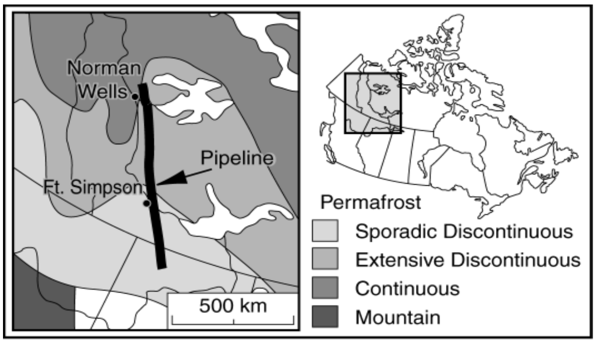


Figure 1. Location of Norman Wells Pipeline and permafrost zones in the region.

## 2 BACKGROUND

### 2.1 Project Setting

The 869 km pipeline route crosses the discontinuous permafrost zone (Figure 1) and unconsolidated

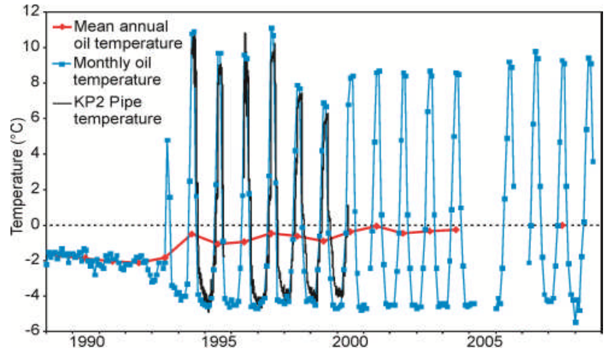


Figure 2. Monthly and mean annual oil temperatures exiting the Norman Wells pump station and mean daily external pipe wall temperatures at KP2.

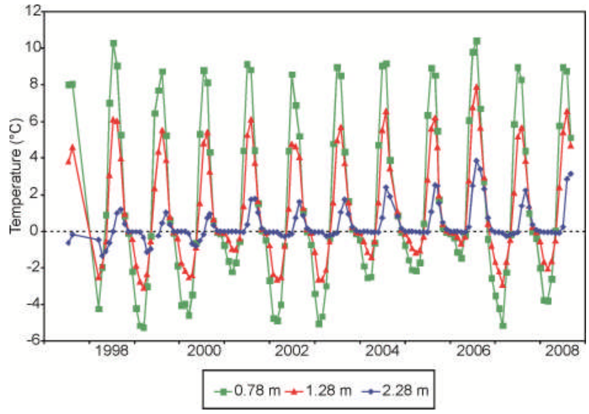


Figure 3. Mean monthly ground temperatures for depths to 2.3 m near KP12, a cleared firebreak adjacent to the town of Norman Wells.

Quaternary deposits of the Mackenzie Valley and Alberta Plateau. Lacustrine sediments and tills are dominant over the northern half of the route with tills and organic soils becoming dominant in the south. The fine-grained lactustrine sediments and frozen organic soils are generally ice-rich and thaw sensitive exhibiting thaw strains of greater than 20% (Burgess and Smith 2003). Undisturbed permafrost temperatures range from -2 to -1°C in the northern part of the route and above -1°C in the south. Permafrost in the northern portion of the route, of interest in this paper, is up to 50 m thick.

The pipeline is a small diameter (30 cm) ambient temperature pipeline. It was buried with an initial average depth of cover of about 1 m. Oil entering the line is chilled at Norman Wells with no chilling elsewhere along the route. From the start of operation until 1993, the oil was chilled to a constant temperature of about -1°C throughout the year. Since 1993, temperatures cycle from -4°C in winter to 12°C in summer, maintaining an average annual temperature between 0°C and -1°C (Figure 2). The seasonal variation in oil temperature approximates the seasonal variation in ground temperatures observed at depths of about 1 m for cleared terrain (Figure 3) with similar ground surface conditions as the pipeline right-of-way (ROW). Additional information on project setting, design, terrain and geotechnical performance can be found in Naviq & AMEC (2007) and Smith et al. (2008b).

### 2.2 Study Sites

This paper focuses on two study sites in the first 5 km of the pipeline route, KP2 and KP5. The short distance between these sites and the Norman Wells pump station ensures minimal attenuation of the seasonal oil temperature cycle.

The KP2 study site was established in 1994 to examine pipe-soil interaction across a soil transition under the new seasonal pipe temperature regime. It is 100 m in length and located on slightly elevated lacustrine terrain partially surrounded by wetlands (Burgess et al. 1998). There is a textural transition at the site with the silty-clay becoming thicker from (pipeline) north to south where it may extend below a depth of 4 m. At the north end of the site, a 40 cm organic layer overlies a 1-1.5 m layer of silty clay, below which coarser silty sand is present. Visible ice contents range from 10 to 50% in the upper 4 m of the ground with ice contents generally being greater with distance along the pipe.

The KP5 study site is about 100 m in length and located in level terrain. It was selected for investigation following observed pipe uplift (to above the ground surface) in the early-mid 1990s. Surficial materials are similar to that at KP2 with a surface organic layer up to 0.4 m over silty-clayey lacustrine sediments which overlie till (Burgess et al. 2000). Several springs have been observed adjacent to the ROW which are likely related to ground water discharge through taliks, from higher elevations in the mountains to the north where permafrost is absent (Taylor et al. 1998). Perennial cross-ROW flow occurs at the site and icings up to 50 cm thick are observed to form in winter.

Uplift of a 20 m segment of the pipeline at KP5 was observed in the early 1990s (Burgess et al. 2000). Uplift gradually increased over time resulting in total movement of >1 m by 1997 when the pipe became exposed 0.5 m above the ground surface. A detailed discussion regarding the possible mechanism of the uplift (Nixon and Burgess 1999) indicates that a combination of high axial stresses and a relatively small amount of seasonal frost heave likely triggered uplift buckling. The low soil resistance associated with the low-density thawed soils was also a contributing factor. Field surveys of pipe and soil movements and temperatures at the site were initiated in 1995. In 1997, remedial action, which consisted principally of the placement of a gravel berm, was taken by the pipeline operator to curtail pipe movement. Regular field surveys continue to monitor the response to the remediation.

### 2.3 Instrumentation and Methodology

A detailed description of instrumentation and techniques utilized in the field investigations can be found in Burgess et al. (1998, 2000). A brief overview is provided below.

Ground temperatures are monitored at a number of locations close to the pipe at both KP2 and KP5. Boreholes were drilled 1-2 m from the pipe and thermistor cables were installed to depths of generally less than 5 m.

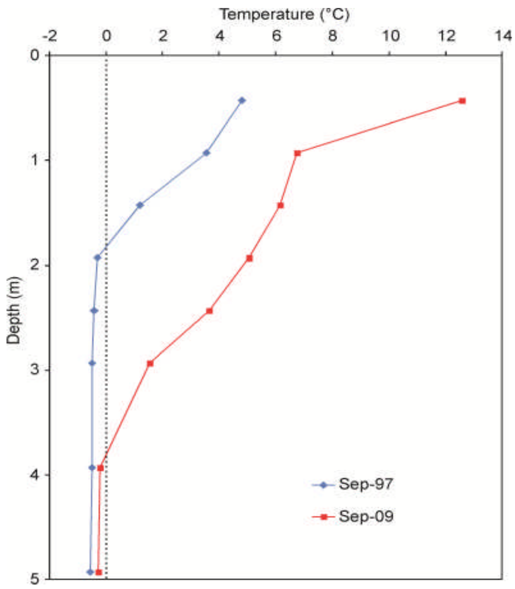


Figure 4. Ground temperatures at KP2 at pipeline south end of site (80 m position).

Temperature cables were also installed off-ROW to provide information on the thermal conditions in adjacent undisturbed terrain. Some cables were attached to eight-channel data loggers to provide continuous measurements. The measurement system allows for an accuracy and precision of ±0.1°C or better. Thermistors connected to a single channel logger were also installed on the pipe wall to record the pipe temperature. However, these ceased to operate after a few years.

Level surveys are conducted to monitor vertical pipe and ground surface movements. At KP2 access tubes (0.15 m diameter) were installed in holes excavated to the top of the pipe. These tubes are in direct contact with the pipe and positioned at 2 m intervals over a 60 m long segment of the line. These pipes allow placement of the survey rod directly on the pipe. At KP5, steel rods were welded by Enbridge to saddles placed on the pipe over the length of the uplift section and a short distance on either side. The top of the rods are above the ground surface and level surveys of their position allow determination of the pipe elevation. Pipe position is also determined between rod locations where possible through inserting a metal probe down to the pipe and placing the survey rod on top of it. Permanent local benchmarks have been installed at both study sites. These consist of a steel pipe anchored to a depth of 10 m in permafrost at the edge of the ROW. Level surveying is conducted with an electronic total station with a vertical resolution of 2-5 mm and an accuracy of 5-10 mm.

Thermal data collection, datalogger servicing and pipe and ground surface elevation surveys have been done during site visits since the establishment of the study sites. Initially site visits were conducted twice a year, in June and September. Since 2001, only one annual visit is made in September, approximating the time of maximum annual thaw penetration.

## 3 OBSERVATIONS

### 3.1 KP2

Temperatures measured on the external wall of the pipe at KP2 between 1993 and 2000 are shown in Figure 2. The temperatures are indeed close to those of the oil inlet temperature indicating that there is minimal attenuation over 2 km. These temperatures are also similar to ground temperatures expected to occur at about 1 m depth for cleared terrain (e.g. near KP12, Figure 3).

September ground temperatures measured between 1997 and 2009 at temperature cables about 1.5 m from the pipe (Figure 4) indicate that thaw depths have increased by more than 1.5 m during this period and are now greater than 3.5 m. The cable however is located at the lower lying southern end where the thermal regime may be affected by the enlarging adjacent wetland area. Thaw depths therefore may not be representative of those in the elevated portion of the site. Although no recent data are available from cables located in the elevated section, observations in similar soils at KP0.2 indicate that thaw

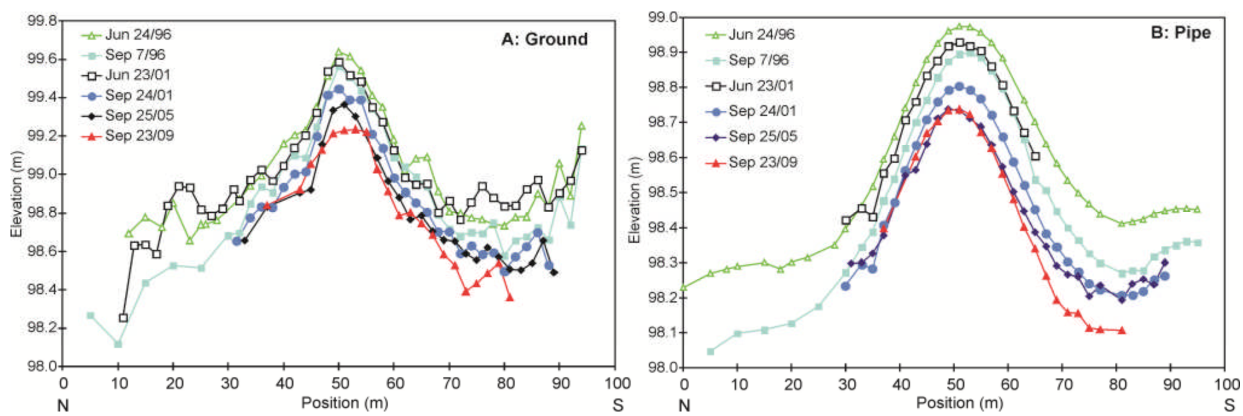


Figure 5. Ground surface (A) and Pipe (B) elevation (relative to local datum) at KP2 for selected dates during the monitoring period. N and S refer to pipeline north and south respectively. Note different vertical scales for A and B.

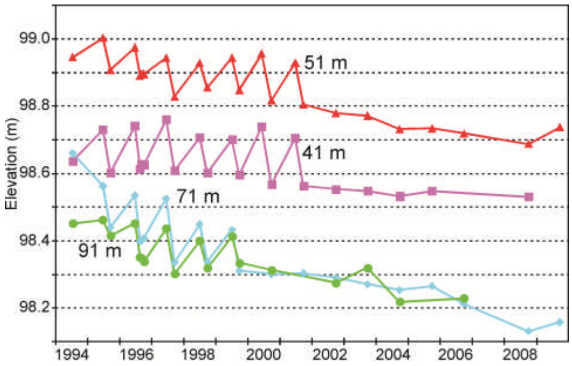

Figure 6. Pipe elevation (relative to local datum) over time at selected locations at KP2. Note spring and fall surveys prior to 2001; fall only thereafter.

depths near the pipe have increased over time and are now greater than 4 m (Burgess and Smith 2003).

The results of pipe and ground elevation surveys conducted between 1994 and 2009 are shown in Figure 5. The ground surface profile indicates that there is a topographic rise of close to 1 m over the length of the study site. The pipe profile also follows the general topographic profile with a maximum difference in elevation between the north end of the section (position 0 m) and the pipe apex at about 51 m of about 0.75 m. The general pipe curvature likely originated at the time of installation with pipe laying following the natural topography (Burgess et al. 1998).

Surveys of the ground elevation along the pipe centre line (Figure 5A) conducted up until 2001, show seasonal ground surface movements that may be up to 0.17 m. The soft, often wet soils in the trench over the pipe and the fact that the ground surface surveys did not necessarily re-occupy the same points would reduce the accuracy of the results. Over the monitoring period there has been a net downward movement of the ground surface which can be in excess of 0.30 m at some locations along the pipe. There is also visual evidence of settlement in the pipeline trench area that includes ponding of water within the trench.

June and September surveys conducted until 2001 show seasonal movements of the pipe of up to about 0.2 m (Figure 5B) which follow the annual freeze (heave) and thaw (settlement) cycle. The timing of the surveys may have been such that neither the maximum nor minimum elevations were captured, leading to underestimates of the seasonal amplitude (both for the ground and pipe movements). Unlike the ground surface surveys, the pipe elevation surveys re-occupy the same points leading to better accuracy in the observed estimates of seasonal movement. During the monitoring period, however, there has been an overall movement of the pipe downward.

Pipe elevation through time for selected points along the pipe is shown in Figure 6. Seasonal movements have generally been smaller near the pipe apex (maximum of 0.14 m at the 51 m position) compared to 10 to 20 m away from the apex where maximum seasonal movement has been about 0.19 m. Greater seasonal movements of up to 0.22 m were observed at the north end (10 m position, not shown) in the first few years of the monitoring period before conditions became too wet to continue repeat measurements (Burgess et al. 1998). The amount of seasonal movement varies from year to year. Some of this variation, as previously noted, may be due to slight variations in timing of surveys each year and the timing of the maximum heave and settlement.

The net downward movement of the pipe is clearly shown in Figure 6. Analysis of the September pipe elevations between 1995 and 2008 at three positions along the pipe indicates that the pipe has moved downward by 0.10 m at 41 m, 0.22 m at 51 m and 0.31 m at 71 m. At the 91 m position, where measurements were made until 2006, downward movement is estimated to be at least 0.19 m. The average rate of net downward movement at the 51 m position has been 1.6 cm per year over the monitoring period.

In fall 2009, pipe elevation at 51 m and 71 m was 0.05 m and 0.02 m higher than it was in 2008. However, the results over the entire monitoring record show that it is not unusual for the pipe not to settle back to the same position (or deeper) it did the previous year. The survey in 2009 was also conducted slightly earlier than that in 2008 and the period of maximum thaw may not have been captured by the survey. Also, September ground temperature measurements at the 80 m position indicate that thaw depths were greater at the time of the 2008 surveys compared to 2009 and this may explain the lack of net downward movement in the pipe between the 2008 and 2009 observation periods.

## 3.2 KP5

The results of surveys of pipe and ground elevation along the pipeline centreline at KP5 are shown in Figure 7. The pipe profile clearly shows the curvature of the pipe over the uplift/buckled section. The pipe would not have been laid down with any marked curvature at this location where the terrain is essentially level. Prior to remediation the uplifted section of the pipe was about 50 cm above the ground surface with a 10 cm draping of overlying uplifted soil and seasonal pipe movements were observed. Following remediation in late 1997 which included placement of a gravel berm, the pipe apex was about 0.59 m below the berm ground surface. Seasonal pipe movements are still evident post remediation as is a net downward movement of the pipe over time.

Analysis of the pipe elevation through time at selected points along the pipe (Figure 8) facilitates a better assessment of seasonal movements and the cumulative changes in elevation over the monitoring period. In 1997, prior to remediation, seasonal movement at the pipe apex (Rod 5) was 0.48 m. Following remediation, the maximum seasonal movement recorded at the pipe apex is about 0.16 m. A decrease in seasonal movement following remediation also has appeared to occur at the edge of the gravel berm (Rod 3). As was the case with KP2, the amount of seasonal movement varies from year to year and survey timing may not capture the full range.

A net downward movement of the pipe since 1998 is also shown in Figure 8. Analysis of September pipe elevations from the first year following remediation until 2009 indicates a net downward movement of 0.24 m near at the pipe apex, 0.23 m at the edge of the gravel berm

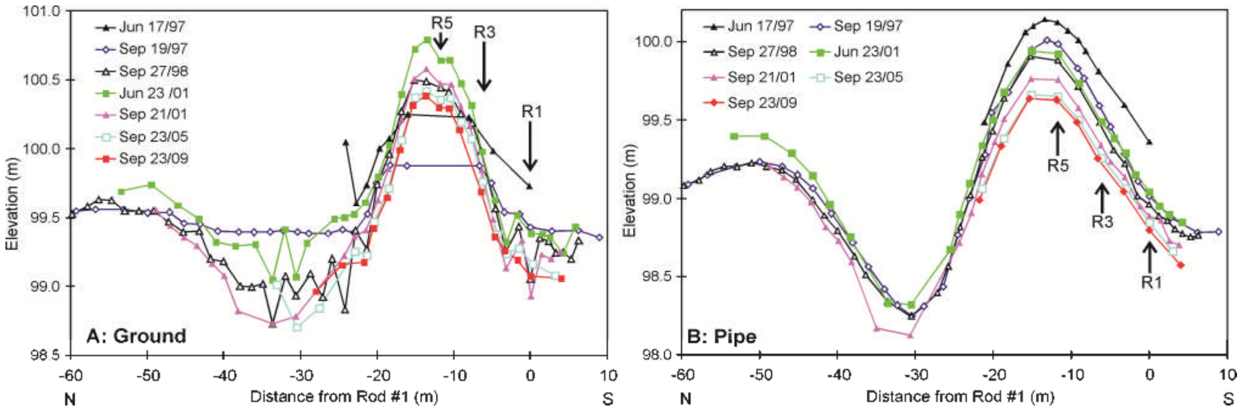


Figure 7. Ground (A) and pipe (B) elevation (relative to local datum) at KP5 for selected dates. N and S refer to pipeline north and south respectively. Rod positions shown in Figure 8 are indicated by R1, R2, R3. Note, vertical scales for A and B are different.

and 0.16 m about 5 m south of the berm (Rod 1). The rate of downward movement has been about 2.5 cm per year at the pipe apex. However the rate of downward movement has declined over time. The rate of downward movement for the first 5 years following remediation (1998-2003) at Rod 5 was about 4 cm per year but it declined to about 1 cm per year between 2003 and 2009. Downward movement since 2006 has only been at a rate of about 0.2 cm per year.

Ground surveys (Figure 7A) indicate that there is some evidence of seasonal ground surface movements along the pipe centerline adjacent to the gravel berm. However, given the accuracy of the surveys and the irregular nature of the ground surface it is more difficult to provide an assessment of seasonal ground movements compared to that of the pipe. In general there appears to be ongoing settlement of the ground surface and associated with this has been increased ponding of water within the trench on either side of the berm. From 1998 to 2009 there has been a net downward movement of the gravel berm surface of about 0.15 m.

Ground temperature measurements indicate that prior to placement of the berm, in fall 1997, the ground near the pipe apex was unfrozen to depths greater than 3.5 m (Figure 9). Data from other temperature cables on either side of the pipe uplift section, indicate that permafrost does exist at the site below depths of 3 m although it is at temperatures very close to 0°C (Burgess et al. 2000). Frozen conditions were initially re-established in the ground beneath the berm and this aggraded permafrost existed for the first 5 years following placement of the gravel. However, ground temperatures subsequently gradually increased and by 2005, unfrozen conditions once again existed down to a depth of 3 m (the depth of deepest temperature sensor).

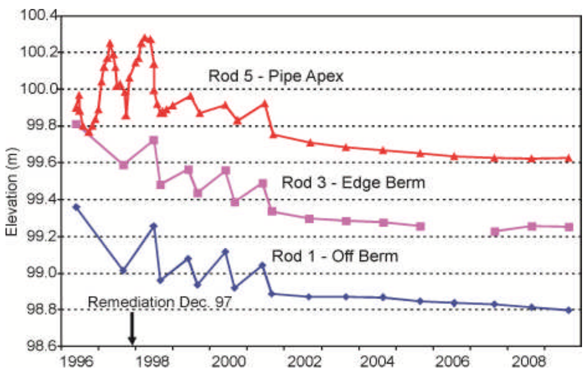


Figure 8. Pipe elevation (relative to local datum) over time at selected positions at KP5. See Figure 7 for rod location. Higher frequency measurements were made by Enbridge at Rod 5 at the beginning of the monitoring period. Note, only fall measurements after 2001.

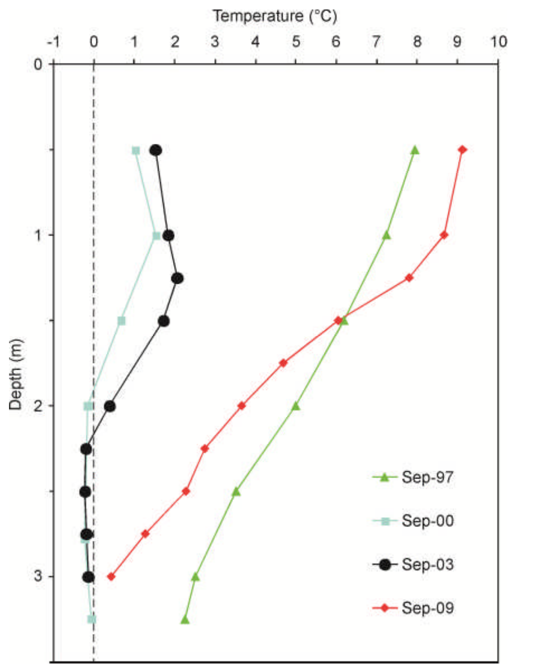


Figure 9. Ground temperatures beneath the berm at KP5. Temperatures for 1997 are prior to berm placement.

## 4 DISCUSSION

Pipe wall temperatures at KP2 since the seasonal cycling of oil temperature commenced have reached summer temperatures that have been as high as 11°C and winter temperatures of about -4°C (Figure 2). Prior to the initiation of this seasonal cycle in 1993 when there was a constant chilling of oil, the ground adjacent to the pipe at KP2 would have experienced pipe temperatures that remained below 0°C throughout the year. The new seasonal fluctuations of pipe temperature above and below the freezing point would cause thaw settlement and frost heave which would be responsible for seasonal pipe and ground movements in the trench observed at KP2. Elsewhere, farther down the route, where the pipe thermal regime had, since 1985 adopted an ambient seasonal ground temperature cycle, the ground near the pipe would also be experiencing a seasonal temperature cycle (e.g. Figure 3) and seasonal ground movements would also be expected. However, the design and temporal frequency of surveys at other sites further from the Norman Wells pump station (e.g. Burgess and Smith 2003) have not been sufficient or detailed enough to determine if the seasonal pipe movements at KP2 since 1994 are greater than that occurring elsewhere along the route.

Interannual variability in the magnitude of seasonal pipe and ground movements has been observed at KP2. These variations may in part be due to variations in oil and pipe wall temperatures (Figure 2). Interannual variability in climate, particularly air temperature and snow depths leading to variable ground thermal conditions could also be a factor. Elsewhere along the pipeline ROW where the influence of the pipe is minimal, or under natural conditions, interannual variability in thaw depth has been observed (Burgess and Smith 2003; Smith et al. 2009). Although controlled fluctuations in pipe temperature at the northern end of route would be a major factor influencing the ground thermal regime close to the pipe, and therefore seasonal pipe and ground movements, climate is a secondary factor.

Although average annual oil inlet temperatures have generally remained below 0°C, there has been some increase since 1994 (Figure 2). A general warming of the ground near the pipe over time would result in increased thaw penetration which in turn would lead to ground and pipe settlement. At KP2 for example, ground temperatures measured next to the pipe at the 80 m position (Figure 4) and elsewhere at the site indicate that thaw depths have increased over time. This net warming of the surrounding ground over time, would explain the observed general downward movement of the pipe and the ground surface on which are superimposed the seasonal movements. The observed downward ground movement is consistent with observations acquired elsewhere at the northern end of the pipeline route. At KP0.2 for example, increases in thaw depth on-ROW in similar fine–grained material have been in excess of 3 m since the commencement of operation (Burgess and Smith 2003; Smith and Riseborough 2010). Ground settlement at KP0.2 has been over 1 m in the trench area and about 0.5 m across the ROW (based on updated observations from Burgess and Smith 2003). The cumulative downward pipe movement at KP0.2 is estimated at more than 0.5 m.

There appears to be a greater downward movement of the pipe at the south end of the KP2 site (e.g. 71 m and 91 m position in figure 6) compared to that in the central section (e.g. 41 and 51 m position). The expansion of the surrounding wetland likely is influencing the ground thermal regime at either end of the site resulting in greater summer thaw and wetter conditions which may result in greater pipe movement.

Clearing of vegetation and removal of the surface organic layer during pipeline construction can also result in warmer ground conditions and increased thaw penetration over time. Observations elsewhere along the route indicate that long-term warming beneath the ROW has occurred resulting in thaw and subsequent ground settlement (Burgess and Smith, 2003; Smith et al. 2008a, b; Smith and Riseborough 2010). Increased thaw penetration over time is also observed in other cleared areas unrelated to the pipeline such as the firebreak near KP12 (Figure 3). Further analysis of the ground temperature data presented in Figure 3 indicates that mean annual ground temperatures at a depth 1.28 m have increased about 0.1°C per year following clearing and that thaw depths have increased by about 2 m over the monitoring period. Level surveys across the ROW at KP2 also record ongoing surface settlement several metres away from the pipe which would be related more to clearing than effects of the pipe.

Effects of clearance of vegetation and ROW preparation therefore may be combined with those related to the pipe temperature resulting in the ongoing warming and thawing of the ground and net settlement of both the pipe and the ground surface. A decreasing rate of downward pipe and ground movements over time has also been observed at KP2 as well as elsewhere along the pipeline route. This is likely associated with a decreasing rate of thaw penetration over time as the ground thermal regime adjusts to the initial thermal disturbance of the pipe and/or ROW clearing. The effects of climate however, are also superimposed on these other disturbances to the ground thermal regime. In the case of ongoing climate warming at a rate of 0.5°C/year for example, gradual thawing of the ground would continue, albeit at a slower rate, that may be only 10-20% of that due to ROW clearing (Smith and Riseborough 2010), resulting in long-term cumulative settlement.

The situation at KP5 is more complex than that at KP2. The change in the pipe operating regime was a primary driver for uplift of the pipe at KP5. Higher frequency surveys of the pipe elevation (Figure 8) by the pipeline operator prior to December 1997 indicated seasonal movements of about 0.4 m at the pipe apex (Rod 5) and a net upward movement of the pipe. The placement of the gravel berm at KP5 has reversed and curtailed the pipe movements. Seasonal pipe movements were also reduced after placement of the berm, for example, at the pipe apex, to about a third of those occurring prior to remediation (Figure 8). The gravel berm offers more resistance to movement than the naturally occurring wet low density soils present at this site. The gravel berm also altered the ground surface conditions, affecting the ground thermal regime and the amount of freeze and thaw that occurs in the underlying frost susceptible soils.

There has also been a net downward movement of the pipe at KP5 following placement of the berm (Figure 8). The overall rate of downward movement at Rod 5 for example is about 2.5 cm per year which is greater than that observed in the central portion of the KP2 site (51 m position) where it is about 1.6 cm per year over the monitoring period. The weight of the berm itself is likely largely responsible for the downward movement of the pipe. Additional thawing of the ground at depths below 3.5 m could also be a contributing factor (Figure 9). Downward movement of the pipe is also observed on either side of the berm (Figures 7B, 8). The pipe is likely being pulled down in wet, low strength soils as the berm pushes the pipe near the apex downwards.

## 5 SUMMARY

Pipe and ground movements since the mid 1990s have been documented for two sites (KP2 and KP5) at the northern end of the Norman Wells Pipeline corridor following the introduction of a seasonal chilling cycle at the inlet in Norman Wells. The fine-grained soils at these sites are susceptible to both frost heave and thaw settlement Seasonal pipe movements at KP2 of about 0.2 m are associated with seasonal freezing and thawing at KP2. Greater seasonal movements of 0.4 to 0.5 m were initially observed in the uplift section of the pipe at KP5 but these were reduced to less than 0.2 m following remediation and placement of a gravel berm.

Although seasonal movements of both the pipe and the ground surface have been observed, there has been cumulative downward movement of the pipe during the 13-15 year monitoring period of up to 0.3 m at KP2. This is likely related to ongoing thaw beneath the right-of-way. Greater downward movement of the pipe is observed at the south end of the site and this is likely related to the wetter conditions associated with the encroaching wetland.

At KP5, net upward pipe movement prior to emplacement of the gravel berm was reversed to net downward movement, subsequent to remediation, at an initial rate of about 4 cm per year but declining to less than 1 cm per year. The higher initial rate of downward movement at KP5 compared to KP2 reflects the effect of the berm or load on the pipe.

The cyclical pipe temperature is the principal factor affecting the ground thermal regime adjacent to the pipe and responsible for the observed pipe and overlying ground movements at these sites within a few kilometers of the start of the pipeline. However, other factors such as the effects of vegetation clearing, disturbance to soils in the trench and climate variability and change are likely smaller but contributing factors.

## ACKNOWLEDGEMENTS

Support for this project has been provided by Natural Resources Canada, the Program for Energy Research and Development, Northern Energy Development Initiative, Enbridge Pipelines (NW) Inc. and Indian and Northern Affairs Canada. Numerous colleagues at the Geological Survey of Canada have assisted with the field data collection (including most recently, D. Riseborough). J. Chartand assisted with data management and preparation of figures. ESS Contribution Number 20100064.

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