Pipelines in permafrost: geotechnical issues and lessons

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ABSTRACT
Geotechnical input to the design, construction and operations of pipelines in permafrost may differ significantly from pipelines in temperate terrain. The general remoteness and terrain fragility of permafrost regions are key issues that challenge geotechnical inputs. Specific geotechnical issues that necessitate input include pipeline routing, slope stability, thaw settlement and frost heave, ditching, buoyancy control and upheaval buckling.

This paper examines the history of pipeline development in Canada north of the 60th latitude and highlights key design issues and some of the technical developments over the past 40 years of design, construction and operations of pipelines in permafrost regions. Advances have been made in areas such as geothermal modeling, slope stability assessments, terrain mapping technologies, thaw settlement and frost heave prediction, monitoring and predicting pipeline strain demand.

RÉSUMÉ
L'apport de la géotechnique pour la conception, la construction et les opérations des pipelines dans le pergélisol peut différer considérablement de l'apport de la géotechnique des pipelines en terrain tempéré. L'éloignement général et la fragilité du terrain des régions de pergélisol sont des questions clés qui défient l'apport de la géotechnique. Les problèmes spécifiques de géotechnique qui nécessitent un apport comprennent la route du pipeline, la stabilité de la pente, le tassement dû au dégel et le soulèvement par le gel, le creusement de la tranchée, le contrôle de la flottabilité, la déformation par soulèvement et ainsi que d'autres phénomènes.

Ce document examine l'histoire du développement des pipelines au Nord du 60° de latitude au Canada et met l'accent sur certains problèmes clés de conception et sur certains développements techniques au cours des 40 années de conception, de construction et d'opérations de pipelines dans les régions de pergélisol. Des progrès ont été réalisés dans les domaines tels que la modélisation géothermique, les évaluations de stabilité des talus, les technologies de relief cartographique, la prédiction du tassement dû au dégel et du soulèvement par le gel, la surveillance et la prévision de la demande de déformation du pipeline.

PREFACE

It is worthy to note at the beginning of this paper that Dr. Robert (Bob) Hardy, for whom this lecture recognizes, was a pioneer in the advancement of geotechnical engineering into permafrost terrain. Bob Hardy, as an academic and consultant worked on a variety of permafrost issues related to northern pipelines in the late 1960s and through the 1970s. He also worked on many of the very first civil engineering projects in permafrost terrain including the Alaska Highway, the Arctic railway project, and several of the very early Mackenzie Valley pipeline studies. His initial engineering work and research lead to many of the geotechnical design strategies that are used today.

If the likes of Bob Hardy, Roger Brown, Ed Johnston and Ross McKay represent the pioneers (or first generation) of permafrost engineering and science, then the second generation of permafrost engineers may include the likes of Ed McRoberts, Norbert Morgenstern, Bill Slusarchuk, Alan Hanna, Jack Clark, Derick Nixon, Don Hayley, Wayne Savingy, Mike Metz, Bucky Tart and many others. I have benefited enormously from the mentoring and tutoring that many of the second generation have provided. So in this respect, I represent the third generation of permafrost engineers.

I hope this paper provides some value to younger engineers and scientists who will follow; that is, the succeeding generations.

1 INTRODUCTION

Geotechnical aspects of pipeline design and construction in many regions of the world typically represents only a very minor component of the overall design effort. Pipeline construction in southern Canada is a classic example. In this region, geotechnical input may be limited to foundation design at facilities, the occasional slope, and investigations for horizontal direction drill crossings of major rivers. Elsewhere, such as in very mountainous regions, the geotechnical engineer may be involved in limited aspects of the pipeline project, including routing and geological hazard identification and mitigation through construction and operational monitoring. Examples abound of the geotechnical/geological contributions made to the safe operations of pipelines in locations such as northeast British Columbia, the South American Cordillera and southwestern United States where active earthquake faults are present. One other region that has benefited from the input of geotechnical engineers and related geo-professionals on pipeline projects is permafrost terrain. Since the late 1960s in North America geo-professionals have been at the forefront of the design, construction and operation of pipeline projects in cold regions. One important case history to illustrate the value of geo-professionals in the design of projects in permafrost is the Trans Alaska Pipeline System. It is believed that some significant cost overruns were the direct result of inadequate geotechnical and geological information during the design process.

The input of geo-professionals in northern pipeline design, construction and operation has not always been welcomed or successful. In some cases the input of geo-professionals has been viewed as an expensive evil, with no upside; in other cases, notwithstanding their good intentions, design strategies have fallen short and additional interventions have been needed to address some geo-process or hazard. This paper explores the development of geotechnical input to pipelines in permafrost, particularly in North America, and describes the design process and some of the lessons learned from the design of numerous northern pipelines, and from the operational experience of the few that have been constructed.

2 PIPELINE HISTORY NORTH OF 60°

2.1 Early Pipelines

Oil was first discovered at Norman Wells (65.28° N) on August 24, 1920 (Bones and Mahnic, 1984). At the time, the discovery represented the most northern discovery in the world. A small refinery was constructed in Norman Wells to provide petroleum products to communities along the Mackenzie River; during World War 2 oil production was expanded. To supply the war effort and as part of a larger Alaska defense strategy the US Army proposed that a pipeline be constructed from Norman Wells to Whitehorse and onwards to Alaska. The CANOL pipeline was constructed in 1943 to 1944. The 100 mm diameter and 960 km long pipeline, laid on wooden timbers on the ground surface transported about 175 m^3 of oil per day (Figure 1). From the Whitehorse refinery the pipeline carried refined product to a military base near Fairbanks Alaska, following the Alaska Highway, which was under construction. The pipeline generally performed poorly, being too small for the demand, being laid on the ground without consideration of the thermal disturbances and seasonal freeze-thaw cycles. Several pipeline ruptures occurred with significant losses of oil (MacNaughton, Macey, Monro Gray, McCracken, and Nowlan, 2007). The pipeline operated for about one year before being shut down and abandoned. The equipment, pump stations and facilities were sold as surplus in 1947.

Other components of the CANOL project included laterals from Whitehorse to Watson Lake and Skagway, Alaska. The Skagway-Whitehorse-Fairbanks section continued to transport refined products until about 1958.

The post-war Haines to Fairbanks pipeline carried refined petroleum products to supply the American armed forces. The project was authorized under the US Canada Treaty Number 20, signed by Canada on June 30, 1953 (Hollinger, 2003) and allowed the pipeline to operate for 20 years. The 250 mm diameter pipeline was constructed between 1953 and 1955. The right-of-way was about 15 m wide and 1000 km long. Initial operations began in 1956, but were suspended shortly after start-up because the water used to pressure test the pipeline had frozen solid and would not allow petroleum to pass the blockages. It took some six months to resolve (Holligner, 2003). After removing over 120 ice plugs, the pipeline operated without major interruption for 15 years. Because the majority of the pipeline was laid on the ground surface, leak detection was generally straight forward. Thermal disturbance of the right-of-way caused permafrost degradation and thaw settlement that had to be remediation by infilling the sagged sections with fill while protecting the pipeline from damage. The pipeline was essentially shut down permanently in 1972. Studies to revive the pipeline for other uses, including natural gas transport carried on until about 1978.

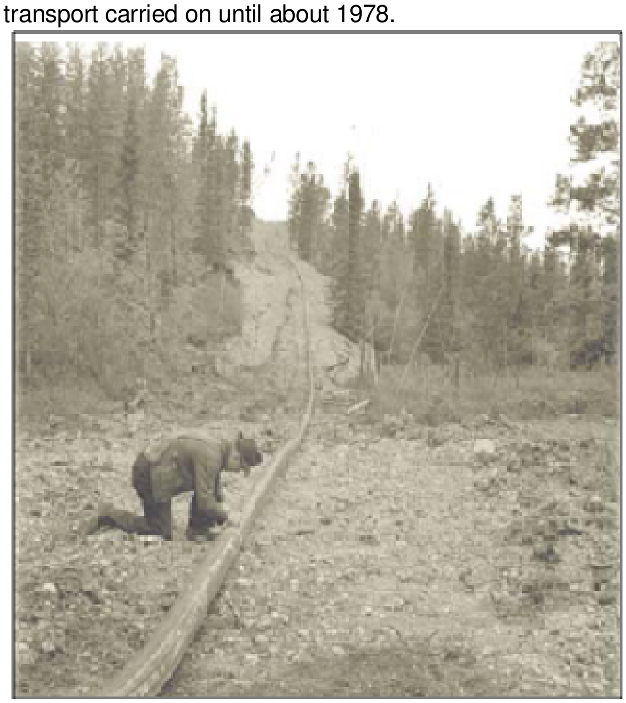


Figure. 1. View of CANOL pipeline being inspected. (Photo acknowledgement: Harry Rowed: National Film Board of Canada/Library and Archives Canada/PA-174542.)

2.2 Post 1970 Canadian Pipeline Studies and Projects

Figure 2 shows the linear corridors in northern Canada that have been the subject of pipeline routing studies. Literally hundreds of potential routes and tens of thousands of square kilometers of terrain have been

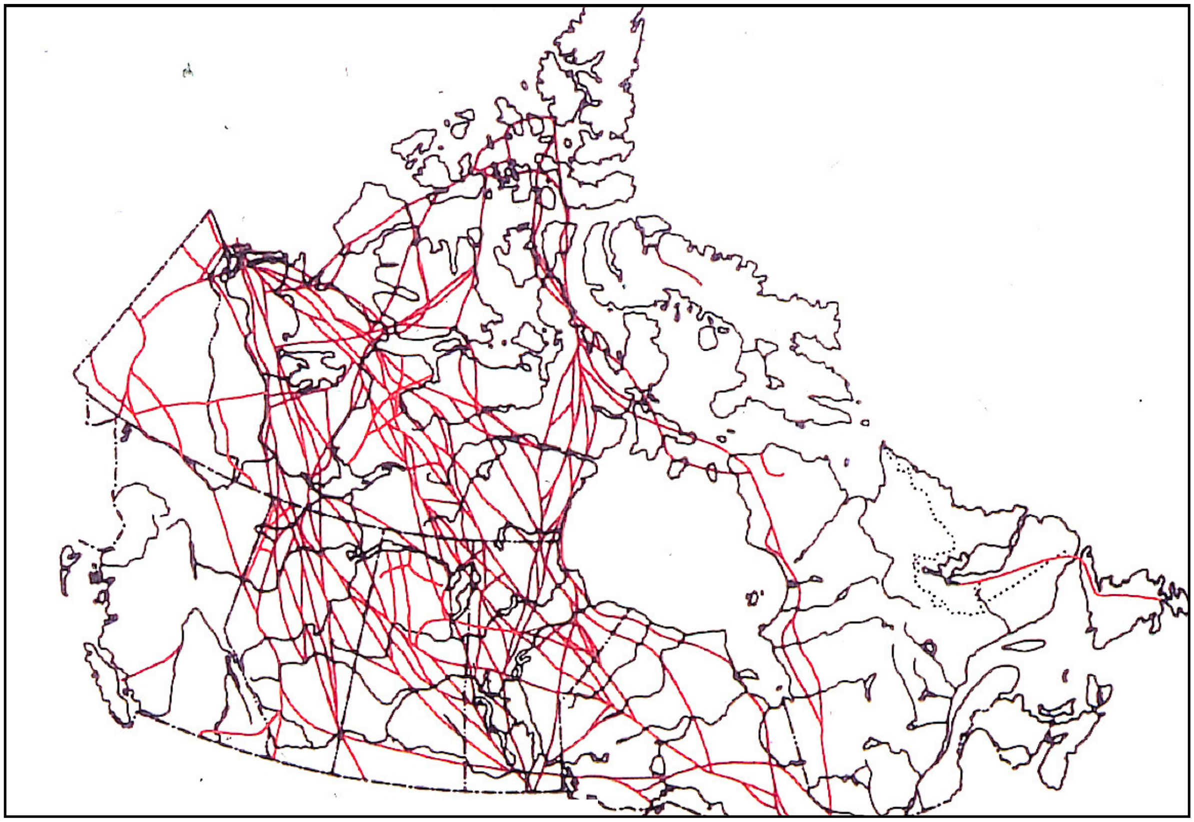


Figure 2. Northern Canadian pipeline study corridors. (Map courtesy of J.D. Mollard and Associates Ltd.)

mapped for possible northern pipeline routes. Table 1 list some of the larger projects proposed between 1970 and 2010.

The need for northern pipelines was spurred by the exploration for oil and gas in northern Canada and Alaska in the late 1960s. The Prudhoe oil field was discovered in March 1968. This discovery precipitated the design and construction of the Trans-Alaska oil pipeline.

In Canada, oil or gas discoveries were made in 1969 at Atkinson Point and in 1970 at Parsons Lake, NT. Within several years substantial on-shore discoveries were made on Richards Island and Niglintgak Island. These discoveries initiated planning for export pipelines along the Mackenzie Valley. It was initially assumed that an oil pipeline would be constructed first and a gas pipeline would follow along the same corridor. However, by about 1974 the impetus for a gas pipeline had eclipsed the oil pipeline (Berger, 1977).

The 1970s gas pipelines planned for the Mackenzie Valley were the subject of a public inquiry from 1974 to 1977; the Mackenzie Valley pipeline inquiry, chaired by Mr. Justice Thomas Berger. The project proponents were Canadian Arctic Gas Study Limited and Foothills Pipeline Limited. This inquiry was, in many respects, unprecedented in its scope and breadth. The most important issues raised by Berger were socio-economic. Significantly, his report recommended a moratorium on a major pipeline in the Mackenzie Valley for ten years to allow the native land claim process to be resolved (Berger, 1977). Regarding the engineering issues, considerable discussion and evidence was presented at the public hearings regarding geotechnical and terrain issues. In his final report, Berger devoted a chapter each to geotechnical and terrain considerations, representing over 20 pages of text. Two important issues addressed were frost heave and slope stability. These topics are addressed in detail below.

The Polar Gas Project was initiated in 1972 and continued through the early 1990s. It was a consortium of exploration and pipeline companies with a mandate to study the most feasible means of transporting natural gas from the high arctic islands in Canada (Kaustinen, 1983). The construction of a pipeline would involve several deep water crossings between arctic islands, such as between Melville Island and Victoria Island, and between Victoria Island and the Canadian mainland. In 1977, Polar Gas filed a regulatory application with the National Energy Board for a pipeline originating on Melville Island and connecting to an existing pipeline near Lake Superior in Ontario. The route would run inland from the west coast of Hudson's Bay through Nunavut and Manitoba (Kaustinen, 1981). Considerable research in arctic onshore and marine pipeline design and construction were undertaken by the proponents. Full scale pipeline trenching studies were conducted on Melville Island, and also near Churchill, Manitoba.

The Norman Wells oil pipeline was proposed as a relatively benign project compared to the Mackenzie Valley gas pipeline, which was the subject of the Berger inquiry. This pipeline, being under the jurisdiction of the National Energy Board (by virtue of it being trans-boundary), was designed in the early 1980s. It was the

Table 1. Significant northern Canadian pipeline studies.

Project	Routing	Study or Operating Dates	Comments
Mackenzie Oil Project	Canadian Beaufort Sea to Edmonton	1971 - 1973	
Canadian Arctic Gas Project (CAGSL)	Alaska and Canadian Beaufort Sea to Lower 48 States	1969 – 1977	Initially formed as the Northwest Project in 1969. Study suspended following Berger Inquiry moratorium on pipelines in the Mackenzie Valley.
Foothills Pipeline Project	Mackenzie Delta to Alberta, in competition to the Canadian Arctic gas project.	1975 - 1977	The study was suspended and then revised to the so-called Dempster Lateral to transport gas from Mackenzie Delta to the Alaska Highway gas pipeline.
Polar Gas Project (East)	Canadian Arctic Islands along west coast of Hudson Bay to Manitoba, and into Lower 48 States.	1972 – 1980s	
Alaska Highway Gas Pipeline Project	Prudhoe Bay through interior Alaska through Yukon, BC and Alberta with connection to California.	1977 – 1983	Initially proposed by Northwest Alaska and Foothills pipelines (South Yukon) Ltd. Pipeline project permitted by US and Canadian governments, but never built. Permits presently held by TransCanada Pipelines Limited.
Polar Gas Project (West)	Canadian Beaufort Sea through Mackenzie Valley into Alberta, and to Lower 48 States.	1972 – 1980s	
Norman Wells oil pipeline	Norman Wells NT to Zama, AB	1980 to present	Existing 300 mm oil pipeline began operations in April 1985 and continues to transport crude oil to Alberta.
Ikhil gas pipeline	Ikhil gas field to Inuvik (50 km)	1998 to present	Operating 120 mm diameter gas pipeline to supply natural gas to the Town of Inuvik, NT.
Alaska Gas Producers Pipeline Team	Prudhoe Bay through interior Alaska through Yukon, BC into Alberta	2001 – 2002	Producers sponsored study of two route, the over-the-top CAGSL route, and the Alaska Highway route.
Arctic Resources Company	Prudhoe Bay along the Yukon Coastal plain to Mackenzie Delta and south through Mackenzie Valley to Alberta	2001 – 2002	Independent study proposing to operate the pipeline similar to a municipal infrastructure project, with 100% debt financing.
TransCanada Pipelines Limited and ExxonMobil Corporation	Prudhoe Bay through interior Alaska through Yukon, BC into Alberta	2008 – present	Project study under enabling legislation by Alaska State (Alaska Gas Inducement Act). Project is a resurrection of the Foothills Pipeline Alaska Highway project.
Denali – The Alaska Gas Pipeline	Prudhoe Bay through interior Alaska through Yukon, BC into Alberta	2008 – present	Project study sponsored by ConocoPhillips and BP Exploration. Pipeline study in competition with the TransCanada Pipelines Limited project.

first northern pipeline approved and constructed in Canada. It was constructed between 1983 and 1985, and started operating in April 1985. The project relied on a great deal of engineering and Arctic construction expertise that had been developed in the 1970s related to the various gas pipeline projects. A unique aspect of the project was that the oil did not require any heating to facilitate the transport of the oil, having a flow point well below -10°C. The design strategy was to utilize existing disturbed linear corridors to the maximum extent possible. This was intended to reduce the amount of thaw settlement that might develop since the disturbed terrain may have already experience some thermal degradation. Thaw sensitive slopes were insulated with a layer of locally supplied wood chips to help control the thawing of the permafrost.

The Ikhil gas pipeline is a small diameter gas pipeline from the Caribou Hills area of the Mackenzie Delta to the Town of Inuvik. It was initiated in 1995 and began operation in 1999. The impetus for the pipeline was to provide natural gas for power and heating in Inuvik, replacing the existing diesel electrical generation and imported home heating oils. The pipeline is fully buried in continuous permafrost except at one stream crossing where the pipeline is above ground supported on steel support trusses (KavikAXYS, 2007).

The Mackenzie Gas Project (MGP) proposed to construct a pipeline from the Mackenzie Delta to northern Alberta. The project began engineering in about 2004 and suspended engineering design in 2008 at the end of regulatory hearings. The gas produced on the Mackenzie Delta would be transported to a gas treatment plant near Inuvik where the natural gas liquids would be removed. The lean gas would be transported in a 760 mm diameter pipeline to Alberta, while the liquids would be transported in a 200 mm diameter pipeline to Norman Wells where the liquids would be injected into the Norman Wells pipeline. The pipeline system had an estimated cost in 2008 of about $8 billion (CDN). The pipeline would be fully buried.

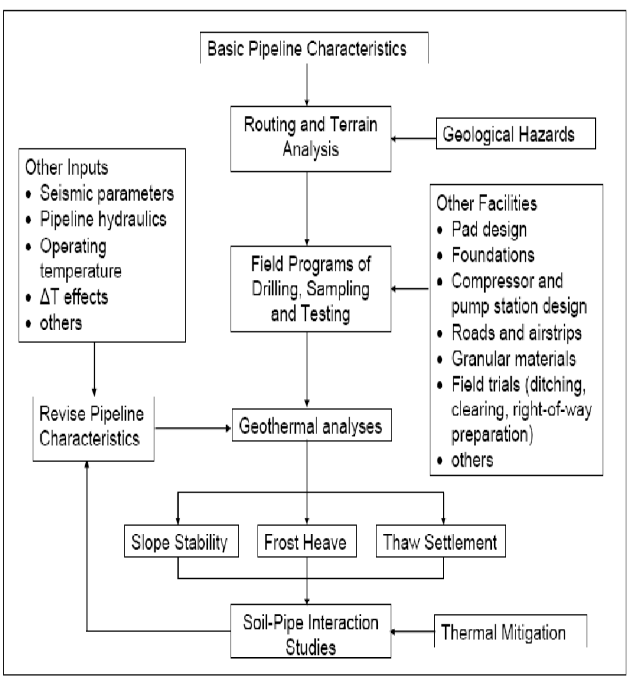


Figure 3. Simplified flowchart of geotechnical input to cold regions pipeline design (modified from Oswell, 2002).

Numerous proponents have proposed a gas pipeline through the interior of Alaska and then along the Alaska Highway between Fairbanks and northern Alberta. The initial study was proposed by Foothills Pipelines Limited and Northwest Alaska in the late 1970s and has been restudied in the early 2000s and again at the present time. The basic premise for all the studies are the same: a 1.2 m diameter gas pipeline to transport up to 5 billion cubic feet of natural gas per day to southern markets. In the case of the Foothills project (now owned by TransCanada Pipeline Limited), a treaty between Canada and the United States confirmed the necessity of the pipeline and granted Foothills a right to construct and operate the pipeline in Canada.

3 GEOTECHNICAL DESIGN ISSUES FOR PIPELINES IN PERMAFROST

3.1 The process

Figure 3 presents a simplified flowchart of the geotechnical design process. The flowchart is intended to highlight some of the key components relative to geotechnical issues. While it addresses several of the key components of an arctic pipeline design, some important, minor and auxiliary issues are omitted for brevity.

Figure 3 will be used to guide the following discussion regarding key aspects of geotechnical input to permafrost pipeline design.

3.1.1 Route Definition

Early definition of the route and the important geological features are critical activities that should not be under estimated or delayed. Detailed route reconnaissance early in the design process will be of significant value later in the project. Consideration of the limitations of the pipeline will also be critical to the success of the routing work. For example, the Norman Wells oil pipeline project took the practical decision to follow previously disturbed linear corridors, principally the Canadian National Telegraph cut line. In some cases the resulting pipeline route was not the shortest possible length. This was feasible for the Norman Wells pipeline because of its smaller diameter and relative flexibility. For larger diameter pipelines, such as those proposed for Canadian Arctic Gas and the MGP, this decision may not be an option because the size and stiffness of the pipe would lead to costs greater than the possible benefit derived from increasing pipeline length to follow existing linear corridors.

The thermal characteristics of the operating pipeline also need to be considered. For liquid pipelines requiring product heating maximizing unfrozen or thaw-stable terrain should be a priority. For ambient pipelines or chilled pipelines maximizing frozen terrain may be important, but not necessarily a priority. For gas pipelines, route selection also needs to consider the so-called "last point of cold flow". This location is the point on the route where the gas is no longer actively chilled or cooled to below freezing but may be discharged from a compressor station at a mean annual temperature warmer than freezing. The issue becomes more complicated because of decompression cooling of natural gas as it travels between compressor stations. This cooling is known as the Joules-Thomson effect, and can result in gas temperatures dropping well below freezing immediately upstream of a compressor station. Hence, it may be undesirable to locate a compressor station immediately downstream of a major river crossing because the gas passing under the river may induce the formation of a frost bulb within the thawed zone beneath the river bed and initiate frost heave in the soils.

It is interesting to note how the design philosophy regarding the last point of cold flow has evolved over the past 40 years. Design details presented at the 1970s Berger hearings for the Mackenzie Valley gas pipelines proposed that the last point of cold flow would be between Fort Simpson NT and the Alberta-Northwest Territories boundary. For the MGP with preliminary engineering in the mid 2000s, the last point of cold flow was proposed to be near Fort Good Hope NT, some 600 km north of Fort Simpson. The decision to move the last point of cold flow north came from the relative uncertainties and difficulties associated with the design for, and mitigation of, frost heave effects as opposed to the similar issues related to thaw settlement. Present-day designers facing a choice of confronting frost heave or thaw settlement have chosen to confront thaw settlement.

An important principle in linear development routing is avoidance. This applies to most geological hazards. It is often more expedient and economic to route the pipeline around identified hazards rather than to try to design a mitigation plan for construction and operations. Identification of these hazards is another reason for early and thorough route characterization (Oswell, O'Hashi, and Hirata, 2003).

Terrain analysis should be completed in conjunction with routing. Understanding the surface geology will provide insights into the permafrost conditions and hence help define potentially problematic terrain units. For example, experience in the Mackenzie Valley has shown that lacustrine deposits are generally associated with higher ice contents than till/moraine soils. In addition, geological hazards, such as existing landslides, and tectonic faults may be identified.

3.1.2 Geotechnical Investigations

Site specific characterization to establish the engineering and geothermal properties of representative soils along the proposed route should be undertaken after the principle route has been set. The purpose of this work is to ground truth the terrain mapping, and to provide information on ground temperatures, presence or absence of permafrost, ice content, and soil characterization.

Given the general remoteness of northern pipelines and the fragility of the terrain, geotechnical programs may need to rely on helicopter portable drill rigs and drill rigs mounted on low-ground pressure vehicles. The accessibility for conventional truck mounted drill rigs may be limited.

The number of boreholes that have been drilled for legacy pipeline projects along the Mackenzie Valley and the Alaska Highway routes is quite extraordinary. Along the length of the Mackenzie Valley, over 8,000 boreholes were drilled in the 1970s and 1980s for the purpose of defining soil conditions along the route, at facility sites, for borrow sources and other locations. For the Foothills pipeline project along the Alaska highway, over 1,000 boreholes are known to have been drilled between 1976 and 1983 along the route within Yukon and alone (some 1500 km) for route and facility site characterization, not including borrow sources. Over 10,000 boreholes have been drilled since the early 1970s along the TransAlaska oil pipeline.

Geophysical methods can provide important information on the permafrost conditions along the route. Electrical resistivity/conductivity equipment is very useful in mapping the location of frozen-unfrozen interfaces. Unfrozen soils have a higher electrical conductivity than frozen soils, although consideration of the soil is also needed. Sandy soils will display a lower conductivity than fine grained soils, independent of the thermal conditions. An understanding of the vegetation types at the survey site provides a useful adjunct to the geophysical data.[1]

Ground penetrating radar (GPR) has value in mapping the seasonal thaw depth in permafrost, although the success depends on the soil mineralogy. GPR surveys have also been conducted to map thermal conditions under wood chip insulated slopes (Burgess, Robinson, Moorman, Judge and Fridel, 1995).

As with any field investigative method, ground truthing and verification is needed. On the Norman Wells pipeline project, Nixon, Saunders and Smith (1991) reported that the number of frozen-unfrozen interfaces identified by geophysical methods were much higher than what was visually observed in the pipeline trench during construction.

3.1.3 Geothermal modeling

The advent of computer based numeral analytical methods in the 1970s lead to significant advances in the ability of geotechnical engineers to predict the geothermal impact of pipelines on permafrost terrain. In Canada J.F. Nixon and C.T. Huang were at the forefront of geothermal modeling during the initial Mackenzie Valley and Alaska Highway pipeline projects. Their work in modeling the

[1] It was reported that during the geophysical surveys for one pipeline project in the Mackenzie Valley the geophysical field crews were asked to record the species of trees at the survey sites. The field crews identified the trees as "fir trees", which the office engineering team interpreted literally, not realizing that the field teams could not distinguish between spruce trees that prefer wetter fine grained soils and for example, pine trees that prefer better grained, sandier soils. These facts lead to confusion in the interpretation of the geophysical data.

geothermal reaction of pipeline construction and operations are well documented and form the basis for much the geothermal modeling conducted at present (Hwang, 1972, 1976, 1977; Nixon, 1983). Advances continue to be made. Nixon (1996) developed a pseudo-three dimensional geothermal model for pipelines. The basic scheme is illustrated in Figure 4. The scheme consists of a series of conventional two dimensional numerical grids that are connected by one dimensional numerical grids. The output from one two dimensional grid becomes the input for the next one dimensional grid, which in turn becomes the input for the next two dimensional grid. By closely spacing the two dimensional grids the effects of ground thermal regime variations can be simulated. This scheme has recently been used to predict pipeline temperatures along a proposed Russia to China oil pipeline (Li, Sheng, Jin, Ma, Qi, Wen, Zhang,Mu, Bi, 2009).

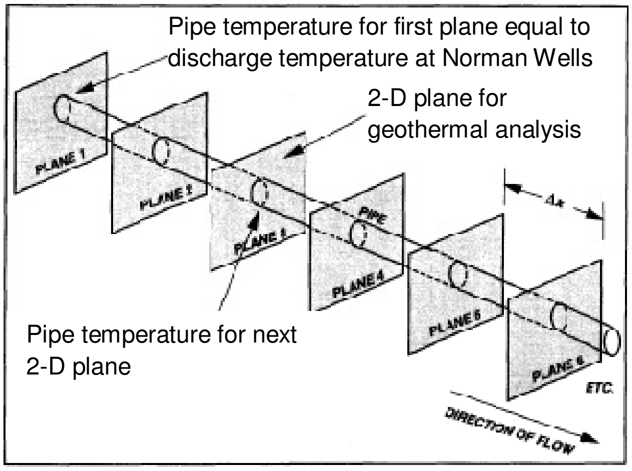
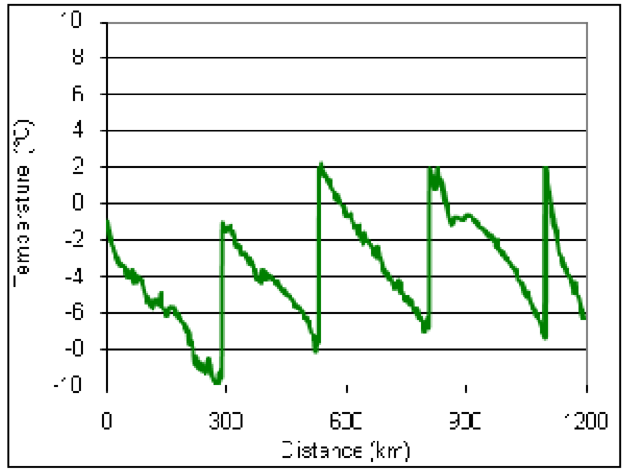
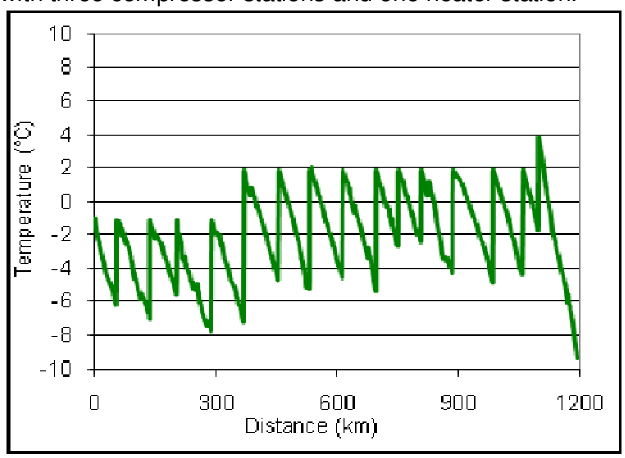


Figure 4. Concept of pseudo three dimensional geothermal model for pipelines. (from Nixon and MacInnes, 1996).

Applications of geothermal modeling in cold region pipelines are extensive. The thermal response of the ground to the surface disturbance, ditching and operation of the pipeline needs to be carefully predicted to ensure the appropriate design mitigations are implemented. This also includes the prediction of pipeline temperatures along the route and identification of those pipeline sections that operate cold in unfrozen terrain and those pipeline sections that operate warm in frozen terrain. Furthermore, as the pipeline capacity may change over the life of a project, understanding the temporal variations is important. Figure 5 illustrates this issue. Figure 5a shows the expected pipeline temperature variation along the route of the Mackenzie Gas Project (MGP) pipeline under initial start-up conditions. But, as the system is expanded to transport more gas, additional compressor stations will be constructed and put into service; Figure 5b, shows the temperature variation along the route with the fully developed system. Comparison of Figure 5a and 5b shows how some pipeline sections that were initially operating cold would eventually be operating warm. Thus for the geotechnical design the full lifecycle of the project should be considered.



(a) Proposed Mackenzie gas pipeline temperature profile with three compressor stations and one heater station.



(b) Proposed Mackenzie gas pipeline temperature profile with 14 compressor stations and one heater station.

Figure 5. Pipeline temperature profile proposed for the Mackenzie gas pipeline (adapted from Colt-KBR, 2006)

Geothermal modeling also provides estimates on the long-term changes in the ground thermal regime as a result of construction and operation of the pipeline. Figure 6 presents the results of geothermal modeling of the MGP pipeline at one location. Figure 6 illustrates the effect of climate warming on long-term permafrost degradation. This graph shows that over about 25 years, climate warming at a rate of 0.08 °C/year will result in one additional metre of thawing compared to no climate warming, all else being equal. Figure 7 shows the effect of surface insulation on the long-term thaw depth; the insulation is presented as the R_T value, which is the ratio of insulation thickness to its thermal conductivity. Clearly, as the thickness of the insulation or R_T value increases the thaw depth decreases.

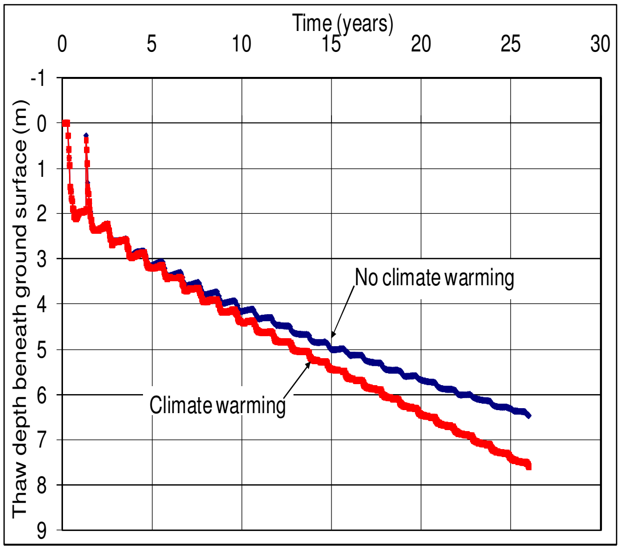


Figure 6. Modeling results of long term geothermal changes in the ground as a result of right-of-way clearing, and climate warming for the Norman Wells region.

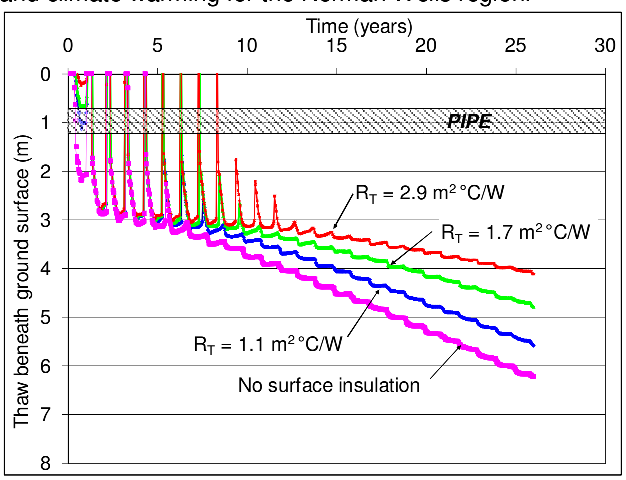


Figure 7. Modeling results of long term geothermal changes in the ground as a result of right-of-way clearing with various surface insulation values in the Norman Wells region. Data includes climate warming.

Table 2 provides a comparison of insulation materials that could be used to control the thaw rate. For the Norman Wells pipeline project, the applied surface insulation applied was locally derived wood chips.

An associated issue with geothermal modeling is that of thaw consolidation and the generation of excess pore water pressures in the thawing soil. When thawing of ice-rich soils occurs at a rapid rate, excess pore water pressures are generated that could weaken the soils and induce instability in slopes, additional buoyancy forces around pipelines, and weakened subgrades under foundations or backfill over pipelines. Thaw consolidation theory was first described by Morgenstern and Nixon (1971) and Nixon and Morgenstern (1973). The excess pore water pressure is primarily a function of two variables: square root of the thaw rate and the coefficient of consolidation, as governed by equation 1:

$$u(z,t)= \frac{z\gamma'}{1+\frac{1}{2R^2}} \qquad [1]$$

where $u(z,t)$ = the pore water pressure as a function of depth (z) and time (t)

γ' = effective unit weight of soil

R = thaw consolidation ratio

The thaw consolidation ratio is a function of thaw depth and the coefficient of consolidation, as follows:

$$R = \frac{\alpha}{2\sqrt{c_v}} \qquad [2]$$

where α is the thaw depth divided by the square root of time

c_v is the coefficient of consolidation

Table 2. Comparison of different insulation materials having the same thermal resistance (R_T).

Material	Thermal conductivity (W/m°C)	Thickness (m)
R_T = 1.1 m² °C/W		
Extruded polystyrene	0.03	0.03
Wood chips	0.265	0.3
Straw bales	0.1	0.11
R_T = 1.7 m² °C/W		
Extruded polystyrene	0.03	0.05
Wood chips	0.265	0.45
Straw bales	0.1	0.17
R_T = 2.9 m² °C/W		
Extruded polystyrene	0.03	0.09
Wood chips	0.265	0.76
Straw bales	0.1	0.29

Figure 8 presents an example of the excess pore water pressure with time as thaw progresses. In the early period where thaw rates are high, the excess pore water pressure can reach values equivalent to the overburden stress. Thus, after construction and into operations, the control of thaw rates and associated pore water generation in ice-rich permafrost is important to the stability of slopes and other features.

3.1.4 Slope stability

The stability of slopes along the pipeline route must be considered from all manner of issues and events. Clearly, there are parallel design considerations for pipelines in more temperate regions, but in permafrost terrain there are added complexities. For example, a slope that may be stable in frozen, thawed or unfrozen terrain may not be stable during the period of thawing. This is because as the frozen soils thaw pore water pressures are generated that may destabilize the slope.

McRoberts and Morgenstern (1974) described the stability of thawing slopes and present a close-form equation based on infinite slope theory. One of the key

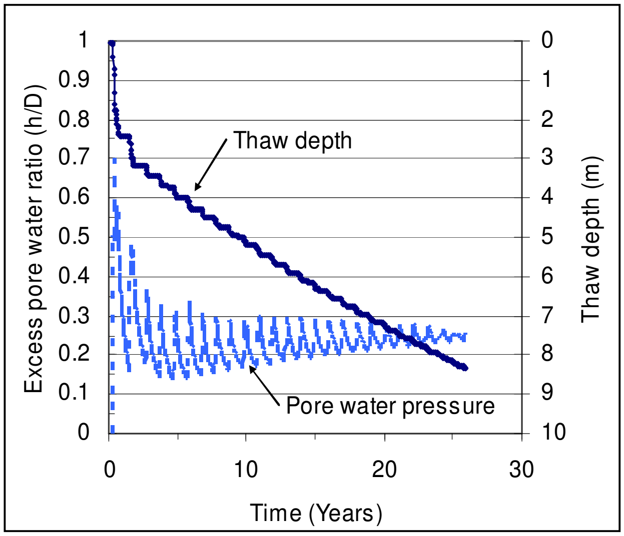


Figure 8. Excess pore water pressure generated as a result of thawing of ice-rich permafrost. h is the pore pressure head above ground surface, and D is the thaw depth.

aspects of the theory is the generation of pore water pressures as a function of thaw rate and depth.

The factor of safety of a thawing infinite slope of a defined width and depth, with excess pore water pressures was reported by Hanna and McRoberts (1988), presented as equation 3:

$$FOS = \frac{c'}{\gamma d}(\sec\theta \ \mathrm{cosec}\,\theta + 2(\frac{0.8\,d}{S})\ \mathrm{cosec}\,\theta) + \frac{\gamma'}{\gamma}(\frac{1}{1+2R^2})\frac{\mathrm{Tan}\,\Phi'}{\mathrm{Tan}\,\theta}\,(1+\frac{0.8K_o\ d}{S}) \qquad [3]$$

Where c' = effective cohesion of the soil

Φ' = effective friction angle of the soil

γ = total unit weight of soil

γ' = effective unit weight of soil

d = depth of thawing

θ = slope angle

S = thaw bulb width

R = thaw consolidation ratio

K_o = earth pressure coefficient

0.8 = thaw bulb shape factor

Equation 3 is conservative in a number of aspects; one important aspect is the fact that for slopes of finite length the factor of safety is actually higher, all else being equal. A modification of the equation to include a passive soil wedge at the toe of the slope can be made to address this conservatism. In addition, the thaw bulb shape factor of 0.8 can be varied to account for the actual shape of the thaw bulb. For assessment of the operational stability of slopes along the Enbridge Pipelines (NW) Inc. Norman Wells pipeline, the factor was varied from about 0.5 to 0.8 depending actual field data that measured the shape of the thaw bulb.

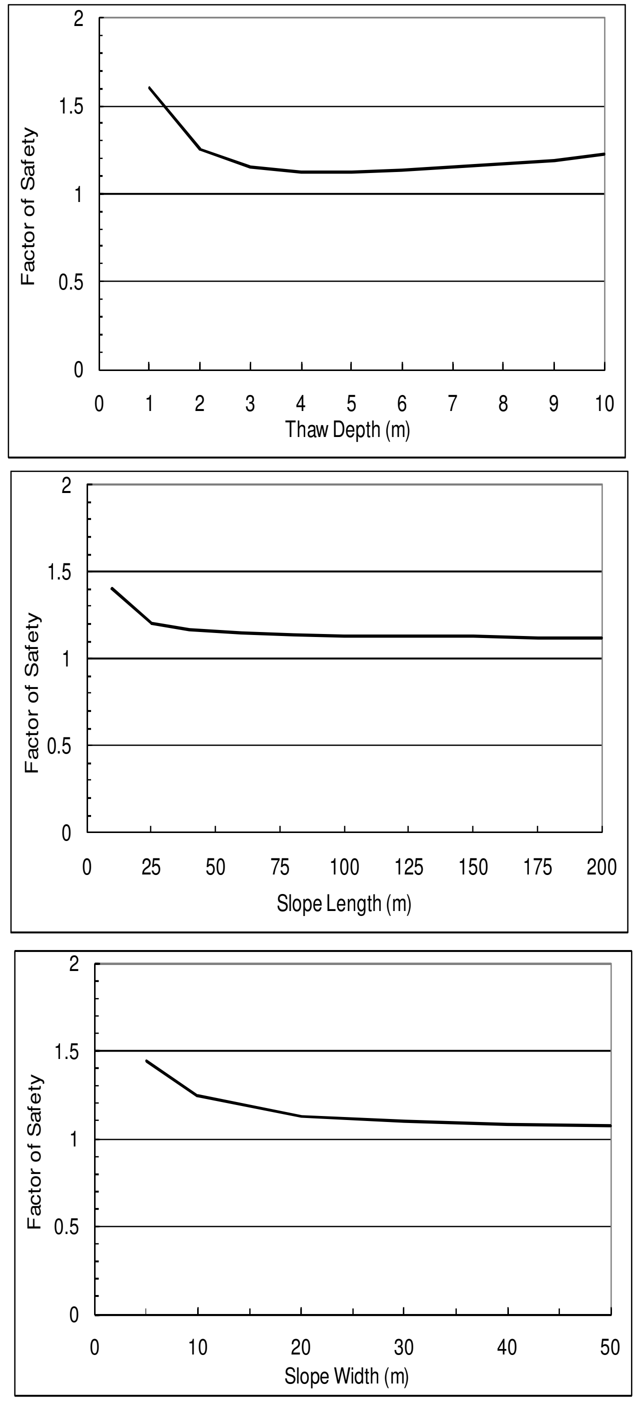


Figure 9. Parametric results for factor of safety of slopes based on equation 3.

Figure 9 presents the effects of a parametric study using a modified version of Equation 3 (to account for slopes of variable finite length). The figures show the effect of thaw depth and slope length on the factor of safety for a fixed set of parameters. It is seen that as the thaw depth increases the factor of safety drops to some minimal value and then starts to increase. This means that the stability of a slope may not be at its most vulnerable at its greatest thaw depth over the life of a project but at some intermediate depth. As noted previously, because of soil restraint at the toe of the slope, shorter slopes are more stable than longer slopes.

Equation 3 or modifications thereof can be used to determine threshold slope angles above which design mitigation may need to be applied to ensure stability of those slopes. Table 3 presents the threshold angles used on the Norman Wells project (Hanna and McRoberts 1988) and for preliminary engineering for the MGP (Colt-KBR, 2006). Differences in the two sets of threshold angles arise from differences in factors such as right-of-way width, depth of thawing and in one case, the specified factor of safety (1.30 versus 1.50 used for most conditions).

Where the calculated factor of safety for a particular slope geometry and soil strength parameters is less than the desired value (for example, 1.5) some form of mitigation is needed. This may take the form of grading to reduce the slope angle or interventions to address the pore water pressure issue. Table 3 presents the design mitigations chosen for the Norman Wells pipeline (Hanna and McRoberts, 1988). Where insulation was needed to ensure stability, the selected material was locally derived wood chips. Potential insulation materials are discussed elsewhere in this paper. One important aspect of slope insulation was the fact that the purpose of the insulation on the Norman Wells project and the MGP was not to entirely prevent thawing but rather slow the thawing to a rate that would not generate destabilizing pore water pressures.

Oswell, Skibinsky and Radmard (2007) examined the actual pore water pressure performance of slopes along the Norman Wells pipelines. The measurements were taken from 16 piezometers in ice-rich permafrost. As shown in Figure 10, the pore water pressures are trending towards a hydrostatic condition. Slopes with apparently high ice contents are draining towards hydrostatic conditions, while slopes with low ice contents may be saturating towards hydrostatic conditions.

The long term thaw behaviour of slopes along the Norman Wells pipelines has also been examined. Oswell and Skibinsky (2006) compared the actual temporal thaw depth behaviour to empirical data gathered during the 1970s and 1980s for disturbed linear corridors in permafrost terrain. Both non-insulated and wood chip insulated slopes were considered. Some key findings from this study were:

- time is likely the most important factor in determining long term thaw depth. The Norman Wells pipeline sites that incorporated previously disturbed terrain had already experienced considerable thaw when the pipeline was constructed.
- the efficiency of the surface wood chip insulation in retarding thaw was apparent by comparison of the various wood chip thicknesses.
- slope orientation (north facing versus south facing) appears to have a relatively small impact on thaw rates.
- initial ground temperature appears to have a strong influence on the thaw rates over time. Sites with “warmer” initial ground temperatures will thaw faster than sites with initial colder temperature.

3.1.5 Thaw settlement

Thaw settlement occurs when the ice content of a soil is sufficiently high that melting of the ice causes the soil grains to physically settle. The total thaw settlement is a function of both the ice content and the depth of thawing. Hanna, Saunders, Lem and Carlson (1983) documented the thaw settlement behaviour of many northern Canadian soils and developed relationships for thaw strain as a function of volumetric ice content. The calculated thaw settlement has been found to be generally conservative. The over-estimation of thaw settlement may arise from several factors. First, the actual depth of thawing may be less than predicted. Second, the thaw strains reported by Hanna et al. (1983) likely assume that the measured water content is the same as the ice content. But it is well known that the unfrozen water content can be appreciable in many soils even at soil temperatures in the order of -5°C. Thus, thawing will not affect the volume of this unfrozen water. Third, there are likely sampling and testing issues that introduce potential errors. For example, a thaw settlement test is conducted on a specimen recovered by coring. Stress relief of the core may cause expansion that could be interpreted as settlement during test as the specimen is thawed. Other factors may also be at play.

A full scale test site was constructed and operated near Inuvik in the early 1970s. This test site provided important design data on the behaviour of pipelines in thawing soils (Watson, Rowley, and Slusarchuk, 1973).

The thaw settlement behaviour of the soil needs to be assessed to determine the strains imposed on the pipeline. The shape of the settling region is one factor, with the length of the thawed span being another. Historically, it was assumed the shape of the thaw settlement zone to be similar to a bathtub: very steep sides and a uniform, flat base. Recent work has suggested alternative representations to this potentially conservative approach. The use of an auto-correlation function to relate the thaw settlement values to the potential thaw span was first proposed by Palmer (1972) but not actually adopted for application to northern pipelines until recently (Nixon and Nixon, 2010).

If the actual pipe strains that arise from the settlement are less than the code allowances, then no intervention is needed. It is only at the transitions between the thaw settling zones and the non settling (thaw stable) zones that need to be considered. There are no adverse strain effects on the pipeline in the middle of a long thaw settled pipe section. Mitigation for thaw settlement may take several forms. For example, over excavation of the ice-rich soils beneath the base of the pipeline may be

Table 3. Summary of threshold slope angles for Mackenzie gas project and Norman Wells oil pipeline. Permafrost slopes with angles greater than the threshold angle were considered to require thermal mitigation to control thawing and pore water pressure development to maintain stability (a specified factor of safety of 1.50).

	Mackenzie Gas Project				Norman Wells
	Gathering Pipelines [1]	Inuvik to Loon River North Compressor Station	Loon River North Compressor Station to Great Bear River Compressor Station	Great Bear River Compressor Station to Alberta	Pipeline Project
Ice-rich clay	7°	11°	8.5°	7.5°	9°
Ice-rich till	7°	12°	11°	9.5°	13°
Ice-poor till	7°	12°	13°	12.5°	18° [2]

Notes: 1. Threshold angles for the gathering system were determined based on slope creep (solufluction) considerations. 2. Based on a target factor of safety of 1.3.

Table 4. Design Slope Guidelines used on Norman Wells Pipeline Project (Hanna and McRoberts, 1988)

Soil Type	Bare Surface	Wood chip Insulation	Gravel Insulation	Backfill with Backhoe Spoil	Backfill with Ditcher Spoil
Ice Rich Clay	< 9° stable	> 18° (1)	> 14° (1)	> 4° (3)	> 7° (4)
Ice Rich Till	< 13° stable	> 20° (1)	> 18° (1)	> 7° (3)	> 10° (4)
Ice Poor Till	< 18° stable	> 18° – 22° (2)	> 18° – 22° (2)	> 10° (3)	> 14° (4)

Notes: 1. Cut and insulate or install thermopiles
2. Cut back depending on height of slope
3. Improve or replace
4. Select backfill

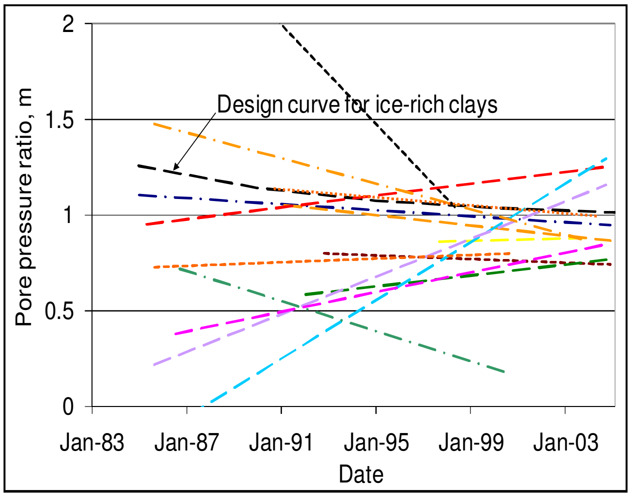


Figure. 10. Long term response of pore water pressure at slopes along the Norman Wells pipeline. The ratio m = h/d where h is the height of water above the thaw depth, d, which is measured from the mineral ground surface (the base of wood chips on insulated slopes). For the case where the groundwater table is coincident with the ground surface, m is equal to unity. When excess pore water pressures are present, m is greater than unity (from Oswell, Skibinsky and Radmard, 2006).

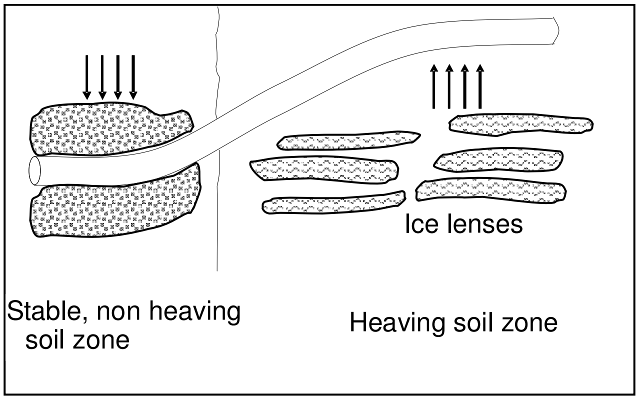


Figure. 11. Schematic of frost heaving under pipeline problem (not to scale)

considered. In this case the pipeline could be buried at a deeper depth, or the excavated soils replaced with thaw stable materials and the pipe placed at the normal design depth. Other mitigation may include increasing the wall thickness of the pipeline or pipeline steel strength that would increase the allowable strains that can be tolerated. Finally, revisions in the operating characteristics of the pipeline may be initiated, such as operating the pipeline a colder temperature with the effect that less thawing will occur or installing cooling systems to counter the heat flux from the pipe.

3.1.6 Frost heave

If the pipeline operates at a mean annual temperature below freezing in unfrozen soils, the formation of ice lenses in the soils could occur. These ice lenses could become sufficiently thick to vertically displace the pipeline upwards. See Figure 11. In addition, if the pipeline is very cold, there could be small amounts of frost heave even in frozen soils where high unfrozen water contents are present and the water freezes in response to the very cold pipe.

Frost heave was a critical topic of inquiry at the 1970s Berger hearings into the proposed Mackenzie Valley gas pipelines. One of the most significant events of the hearing process was the admission by one of the proponents that there had been a systematic error in the frost heave laboratory testing conducted, and that their predictions of the potential frost heave may have been underestimated by a factor of two or more. The inability of the 1970s era Mackenzie Valley gas pipeline proponents to provide convincing engineering mitigation for frost heave lead Berger to state: *"The question of frost heave is basic to the theory and design of the pipeline project. If the pipe is to be buried, the gas must be chilled. If the gas is chilled, the result – frost heave – must be overcome. The pipeline companies are obviously having trouble in designing their proposal to deal with frost heave, and they are making fundamental changes in the methods proposed for heave control. Their methods seem to be getting more complex, and the conditions for success more restrictive"* (Berger, 1977).

Frost heave requires three basic conditions: freezing temperatures in unfrozen soils, a source of water to migrate to the freezing front and frost susceptible soils that permit free water to migrate through the soils. If any of these conditions can be changed or disrupted, then frost heave will be lessened or eliminated.

In the late 1970s and early 1980s research continued into the theory of ice lens formation in freezing soils. Two theories to address frost heave include the "segregation potential" theory (Konrad and Morgenstern, 1981, 1984) or "discrete ice lens" theory (Nixon, 1991, 1992). Both are applicable to two-dimensional pipeline problems; they can be incorporated into numerical models to provide a useful predictive and design tool. Lawrence, Smith and Burgess, (2005) provide a review of frost heave theories and experimental testing related to pipelines

The segregation potential theory of frost uses the following relationships to predict ice lens formation:

$$h = \int \frac{SP_p}{e^{ap}} \,\mathrm{grad}T \, dt \qquad [4a]$$

$$SP_p = \frac{SP_o}{e^{ap}} \qquad [4b]$$

where h = heave

SP_p = segregation potential at pressure (p)

SP_o = segregation potential at zero applied pressure

a = soil specific parameter related to overburden pressure

p = applied pressure

grad T = temperature gradient at the freezing front

t = time

As is seen by Equation 4 the segregation potential is inversely proportional to the applied pressure. As the depth of burial and effective overburden pressure increases, the amount of frost heaving will reduce. Thus, in theory and as suggested in the Berger Hearings, there may be a so-called "cut-off" pressure wherein frost heave can be arrested.

To predict the frost susceptibility of the soils under a pipeline with cold flow, knowledge of the soil characteristics are necessary. Historically the frost susceptibility of soils has been characterized by a simple relationship to grain size. For example, for highway design, many jurisdictions state that frost susceptible soils are those with a fines content (particles smaller than 0.08 mm) greater than about 10% by weight. However, this criterion has been found to have a reliability of only 40% to 80% (Konrad and Lemieux, 2005). A correlation to multiple soil parameters such as grain sizes finer than both 0.02 mm and 0.002 mm, d_{50} particle size, specific surface area, and Atterberg Limits are now being considered (Konrad and Lemieux, 2005, Konrad, 2005; Visson 1988). For example, Konrad 1999 proposed the following correlation relative to segregation potential:

$$SP_oS_s = [116 - 75 \log d_{50}(FF)] \times 10^3 \ (mm^4/(°C \cdot s \cdot g)) \qquad [5]$$

where S_s = the specific surface area (mm^2/g),

d_{50} (FF) is the average diameter (µm)of the fine fraction (that fraction of the soil finer than 0.08 mm)

The above correlation may be practical for predicting frost heave potential in predominately fine grained soils but not applicable to soils with a significant coarse grained fraction, since it is the total grain size distribution that controls frost heave, not just the fine fraction.

The issue of frost heave relative to pipelines is not so much the total displacement as it is the differential movement and the pipe strains that occur at the frost stable – heaving interface. Figure 11 presents a soil-pipe interaction diagram. The ability of the pipe to displace upwards through the stable, non-yielding soils is primarily a function of the strength of the frost stable soil. The weaker that part of the soil the less bending strain the pipeline will experience.

Several large scale frost heave tests have been conducted in North America. The Calgary, Alberta test site was operated from 1974 to 1981 at a site near the present-day University of Calgary. A second test site during approximately the same period was operated off Cheena Hot Spring Road near Fairbanks, Alaska. Other, small sites were also operated in Alaska. Data from the Calgary test site has been published in reports that are now in the public domain (for example: Slusarchuk, Clark, Morgenstern, Nixon, and Gaskin, 1978; Carlson, Ellwood, Nixon and Slusarchuk, 1982; Carlson and Nixon, 1988). Most, if not all data from the initial Fairbanks and other Alaska test remains proprietary. In the late 1990s and early 2000s, the Fairbanks test site was re-commissioned and a new frost heave test section was installed. Huang, Bray, Akagawa, and Fukuda, (2004), Oswell and Tchekovski (2005) and Kim, Zhou and Huang (2008) have published information on the performance of these recent tests.

Nixon and Hazen (1993) examined the uplift restraint issue with small to medium scale laboratory tests. Likewise, Liu, Crooks, Nixon, and Zhou (2004) reported on the results of laboratory based mid-scale pipeline uplift tests. Liu, Moffitt, Nixon and Zhou (2004) report on numerical modeling to simulate the laboratory uplift tests. The results from these various tests suggest that the uplift resistance reaches a maximum value and then reduces (strain softens) to a minimum, residual value at large pipe displacements. Visual examination of the laboratory tests suggest that the initiation of strain softening corresponds to the development of horizontal cracks and/or a vertical crack over the pipe that penetrates the soil cover. For all the reported tests, the depth of cover to pipe diameter ratio was one. It may be postulated that the soil failure mechanism may be change with increasing burial depths. Loading on the pipe to some peak value may be controlled by the strength (and temperature) of the overlying soil, and if strain softening behaviour develops after peak load is achieved then the strain softening behaviour may be controlled by fracture mechanics. Nixon and Oswell (2010) describe analytical solutions for both peak and residual uplift resistances. They show the dependence of pipe diameter and temperature on peak uplift resistance and the dependence of cover depth on residual uplift resistance.

As with thaw settlement, if the predicted pipe strains arising from frost heave are less than the strain capacity of the pipe steel, then no intervention or mitigation is needed. If the stain “demand” exceeds the strain capacity then mitigation is needed. Mitigation can take several forms. For example, the segregation potential theory states that frost heave is a function of overburden or applied pressure. Thus, there should be a theoretical depth of pipe burial that is sufficient to arrest the formation of ice lenses. The application of insulation around or under the pipe may be useful in limiting the advancement of the frost bulb. Sub-drainage to intercept free ground water might also be applicable. Finally, increasing the pipe wall thickness or steel strength to increase the strain capacity of the pipe or altering the pipe temperature operating conditions may also be considered.

3.2 Permafrost issues in pipeline construction and operations

3.2.1 Ditching

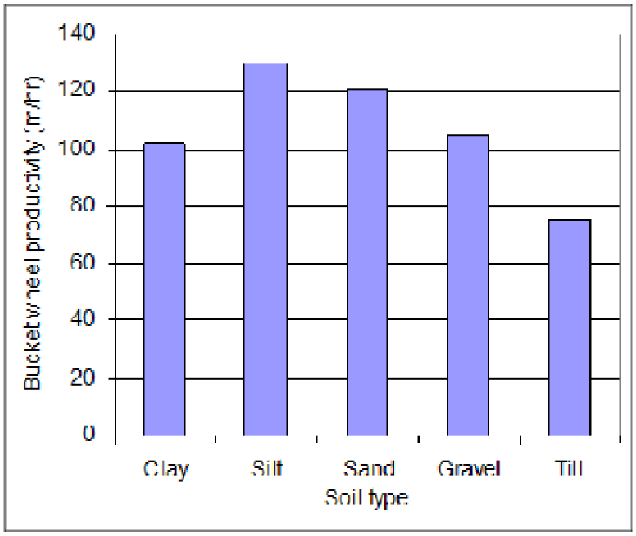
The presence of permafrost, particularly in a till or cobbly soil, can dramatically reduce the productivity of some trenching equipment. Bucket wheel ditchers can experience excessive wear on the bucket teeth where cobbles are embedded within a frozen fine grained matrix. Hayley, Inman and Gowan (1984) reported on permafrost excavation techniques based on field trials for the Arctic Pilot Project. Saunders (1989) examined the relationship between soil parameters and bucket wheel trenching production on the Norman Wells oil pipeline. Blanchet, Lenstra, Skalski, Zhou and Smith (2002) reviewed pipeline trenching methods in permafrost. Table 5 lists some of the trenching methods used or proposed for use in permafrost terrain. All three trenching methods discussed have been used for pipeline projects: backhoes and bucket wheel trenchers were used on the Norman Wells oil pipeline; backhoes and chain trenchers were used on the Ikhil gas pipeline and the Oooguruk offshore

Table 5. Summary of Arctic pipeline trenching methods

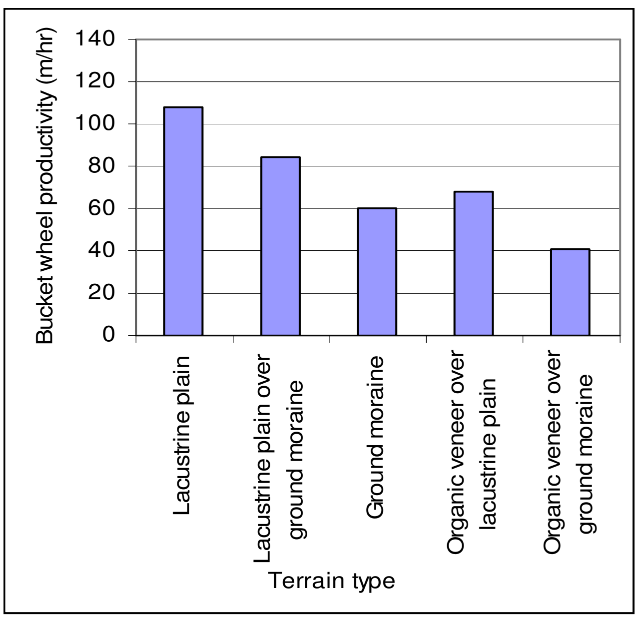
Trenching method	Advantages	Disadvantages
Backhoes	Relatively independent of terrain and soil conditions Can trench around corners and bends	May require pre-treatment of ground (ripping, blasting) May not trench bedrock Rough and irregular trench geometry Spoil needs processing prior to backfilling Moderate depth range (to approximately 5 m)
Bucket wheel trenchers	High productivity in uniform fine grained soils Can trench soft bedrock Very uniform trench geometry Spoil can be used for backfill without processing Productivity increases with ice-content	Low productivity or restricted use in soils with cobbles and boulders, greater than 200 mm diameter Trench only in straight lines Shallow to moderate depth range (approximately 4 m)
Chain trenchers	High productivity in some soils and bedrock Can trench most bedrock Very uniform trench geometry Spoil can be used for backfill without processing Trench depths to 7.5 m Higher forward velocity than bucket wheel machines	Trench only in straight lines May have lower productivity in soft or ductile soils

flow lines; backhoes were used for the Trans Alaska oil pipeline.

Saunders (1989) in his review of the Norman Wells bucket wheel ditcher production developed correlations with soil type and terrain type. Figure 12 presents these data. As expected glacial soils, which typically comprise a non homogeneous mix of fine grained through coarse grained particles and cobbles experienced the lowest productivity. Hayley, Inman and Gowan (1984) found a relationship between ditcher productivity and excess ice content based on trials with a bucket wheel trencher on Melville Island; Figure 13 presents the relationship. Saunders also found that productivity correlated to soil moisture content.



(a) Bucket wheel ditcher productivity based on soil type



(b) Bucket wheel ditcher productivity based on terrain type

Figure 12. Bucket wheel ditcher productivity from the Norman Wells pipeline by soil type and terrain type (from Saunders, 1989).

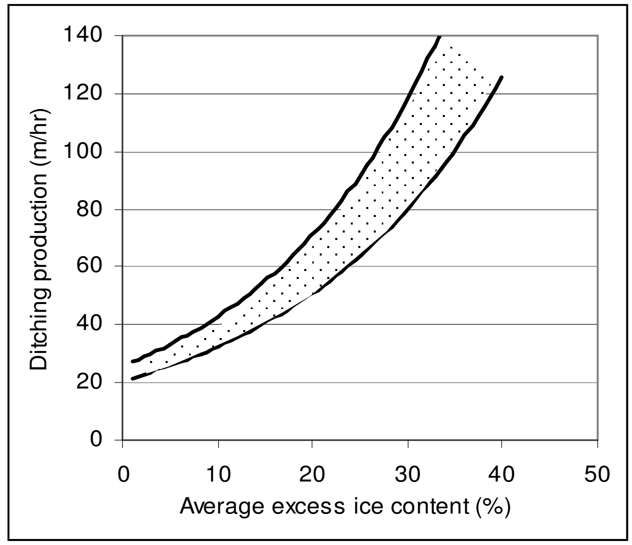


Figure 13. Bucket wheel ditching productivity from trials on Melville Island by excess ice content (adapted from Hayley, Inman and Gowan, 1984).

3.2.2 Thaw Mitigation by Surface Insulation

As noted in the subsection on slope stability the development of rapid thawing can lead to excess pore water pressures, which may destabilize the slope. One mitigation strategy for this event is to control the rate of thawing such that excess pore water pressures do not develop. This can be achieved by the placement of surface insulation. There are a variety of insulation materials, including rigid extruded polystyrene, wood chips, straw bales and others. Another means of reducing the thaw rate is to install thermosyphons along the slope length. For the Norman Wells pipeline project extruded polystyrene under a layer of gravel and woodchips were proposed. For construction, wood chips were used. For the MGP wood chips, straw bales and thermosyphons were considered. Figure 7 shows the effect of insulation materials on the long term thawing of the pipeline right-of-way. By presenting the insulation as a R_T value, a number of different insulating materials can be compared. Table 4 presents the R_T values from Figure 7 converted to equivalent thicknesses for several materials.

As part of the preliminary engineering for the MGP, field insulation trials were conducted at two locations. One site was operated north of Wabasca AB for several years. This site, although cool, was not underlain by permafrost. The second site was located within the municipal boundary of Norman Wells. This site was underlain by warm permafrost. The Wabasca site tested three materials: straw bales, white reflective surfaces and shredded wood. The Norman Wells site tested only white reflective surfaces and straw bales. Monitoring consisted of a multi-bead thermistor cable installed under the center of each test cell. A control cell was also installed against which the temperatures under the test cells could be compared. Oswell and Everts (2008) reported on the performance of the surface insulation materials. Table 6 presents a summary of the performance data in terms of thawing degree-days. It is seen that straw bales were the most effective form of insulation, which is confirm by examination of the thermal conductivity and thermal resistance values for the respective thicknesses.

3.2.3 Buoyancy and uplift of pipelines in thawing permafrost

Buoyancy control of pipelines in permafrost is, for the most part the same as in temperate, unfrozen terrain. The characterization of the route and trench backfill is the same and many of the mitigation methods; select backfill, pipe weights (either concrete bolt-on or "saddle bags"), and screw anchors all have applicability.

One issue that arises in thawing permafrost is the potential for buoyant forces produced in thawing permafrost. Thaw consolidation theory (Morgenstern and Nixon, 1971) predicts that excess pore water pressures can be generated in rapidly thawing ice-rich soil. Applying Equation 1 to the buoyancy forces leads to a prediction of the potential uplift forces for various pipe sizes and water contents. Figure 13 shows the effect of excess pore water pressures in a thawing clayey soil on the buoyant factor of safety. The effect of pipe diameter is clear.

Comparisons of buoyant forces with and without excess pore water pressure reveals that ignoring the excess pore water pressures may underestimate the total buoyant forces by over 10 percent, which may exceed the available factor of safety in some instances.

The legacy of floating pipelines in northern Russia may be partly related to this mechanism. Seligman (1998) prepared one of the most comprehensive reviews of the performance of the Russian northern gas pipeline system. Seligman identified the absence of temperature control of the gas as a key factor that resulted in thawing of ice-rich permafrost around the pipelines, which in-turn created the buoyancy problems.

Upheaval buckling has been identified as a potential uplift issue for pipelines in cold regions. The issue arises primarily because of the potentially large thermal expansion forces that can be generated by the differential temperatures between the burial temperatures and operating temperatures. For example, a pipeline installed in winter and backfilled at a temperature of -35°C and then operated at a temperature of +5 °C will experience thermal expansion equivalent to 40 °C. For steel with a thermal expansion coefficient of 11 x 10^{-6} m/m/°C, the lengthening of a 500 m segment of pipe would be 0.22 m. If there is insufficient restraint by the backfill the pipeline will expand upward through the backfill. For the above example and assuming a very simple triangular shape with the base being 250 m and the hypotenuse being 250.11 m, the vertical component would be 7.4 m; that is, the apex of the arc that the pipeline would form would be 7.4 m above the base of the pipeline trench.

Palmer and Williams (2005) discuss this issue in relation to frost heave as a contributing driver to the mechanism. He and Jin (2010) reported that a small diameter oil pipeline experienced an upheaval event in permafrost terrain on the Qinghai-Tibet plateau; this reported incident is considered isolated. Nixon and Vebo (2005) noted that the Trans-Alaska fuel-gas pipeline has experienced several instances of upheaval buckling, and Oswell, Cavanagh and Skibinsky (2005) reported that several smaller diameter pipelines in northern Alberta have experienced uplifting, but all in summer months. It is considered that frost heaving and upheaval buckling may be tenuously related. The development of a frost bulb around a chilled pipeline would provide additional rigidity to the system that would assist in restraining the pipeline. In no case has an upheaval buckling event of a pipeline in permafrost been reported to result in loss of containment.

3.2.4 Horizontal Directional Drilling

There have been few applications of horizontal directional drill technology to pipelines in permafrost terrain. For hydrocarbon development the Colville River crossing on the Alaska North Slope was perhaps one of the first crossings. This project, constructed in the late 1990s consisted of four separate bores approximately 1300 m long. The four components in each bore included a 355 mm oil pipeline, 300 mm seawater pipeline, 200 mm utility conduit, and a 200 mm corrosion anode. The horizontal drilling was complicated by the presence of a large deep talik under the Colville River. Thus the drill trajectory passed from cold permafrost soils to unfrozen soils back into cold permafrost. (Meyer, 1999). To provide stability of the approaches to the River, the project included the installation of thermosyphons to help maintain cold ground temperatures at depth.

3.2.5 Monitoring

Monitoring the performance of a pipeline in permafrost terrain is more necessary than for pipelines installed in temperate areas. This is because of the potential dynamic nature of the permafrost and its interaction with the pipeline. As noted throughout this paper, permafrost-pipeline interactions may include thaw settlement, frost heave, upheaval buckling, buoyancy, slope instability and others. Many of these issues are temporal, developing many years after construction and only in response to changes in the thermal regime of the right-of-way. In-line-

Table 6. Summary of surface insulation materials from Wabasca test site, presented in terms of annual degree-days.

Test Cell Section	Calculated Annual Thawing (°C-Days)	Percent of Control	Efficiency Compared to Control	Thermal Resistance (m^2°C/W)
Control	2,174	100	1.0	-
Straw bales	1,090	50	2.0	4.0
Reflective surface	1,945	89	1.1	-
Shredded wood	1,711	79	1.3.	2.8

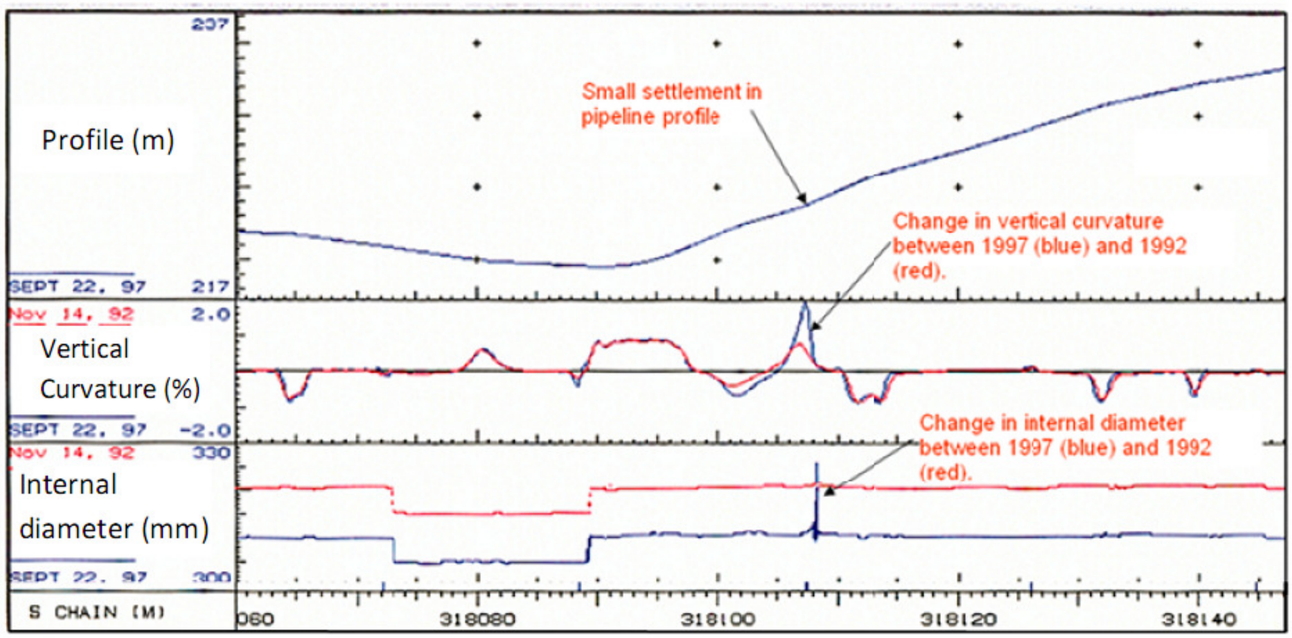


Figure 14. Example of in-line inspection tool output for pipeline experiencing thaw settlement and axial movement.

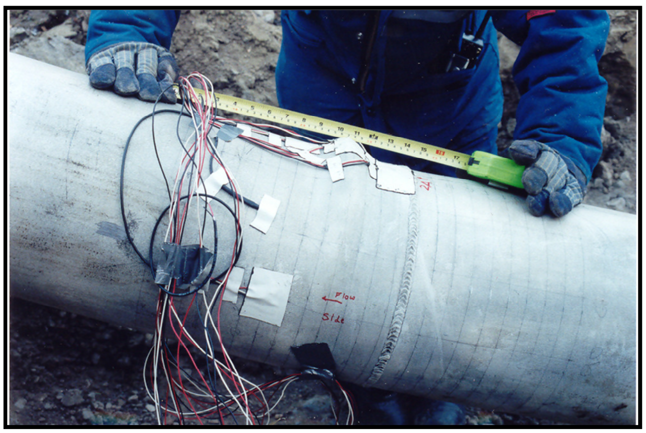


Figure 15. Wrinkle on pipeline that was identified from ILI inspections, and illustrated in Figure 14.

inspection (ILI) tools provide an important tool to monitor pipelines in permafrost or remote regions of the world. They provide metre-by-metre data on the curvature, ovality, vertical and horizontal position of the pipeline, and from these data bending strains can be determined. In fact, the development of ILI technology was in-part precipitated by the Norman Wells oil pipeline, wherein the National Energy Board of Canada imposed a condition on the Operator that develop a procedure for "*…monitoring the radius of curvature of the pipe at sites of soil movement where critical pipe stresses may be exceeded…*" (National Energy Board, 1981). An example of the output from an ILI tool is shown in Figure 14. In this figure, comparing the geometry of the pipeline between 1992 and 1997, there is evidence of a small amount of settlement, but more significantly is the change in both vertical curvature and internal diameter between 1992 and 1997. Figure 15 shows the physical evidence of the change in internal diameter illustrated in Figure 14. The value of the monitoring in this specific example is discussed by Oswell, Hanna, Doblanko, and Wilkie (2000).

Doblanko, Oswell, and Hanna (2002) discuss other monitoring activities as they apply to the Norman Wells pipeline. This pipeline is unique in many respects, least of which is, first the amount of monitoring that the pipeline is subject to by order of the National Energy Board, and second, the amount of collaborative monitoring and research of the pipeline right-of-way between the pipeline operator and government departments and agencies. The level of geotechnical monitoring undertaken on the Norman Wells pipeline includes:

- routine monitoring of ground temperatures and pore water pressures at selected wood chip insulated slopes
- monitoring of slope inclinometers at specific slopes
- annual ILI tool runs over the first 336 km of the pipeline
- thaw probing of insulated slopes on a two year cycle
- aerial line patrols several times each month
- an annual geotechnical inspection of the pipeline right-of-way.

It is not the scope of this paper to defend or critique the amount of monitoring of this pipeline, particularly after over 25 years of operation. But the overall successful geotechnical performance of the pipeline and right-of-way suggests that monitoring programs should be considered in light of performance, risks, and available technology.

4 CONCLUSIONS

This paper has demonstrated that there are fundamental differences in some of the geotechnical issues that should be addressed by designers when considering a pipeline in permafrost terrain. Several of the important factors that need to be considered include the impact of excess pore water pressures on slopes and pipeline buoyancy when ice-rich permafrost soils thaw, the settlement of warm pipelines that span thaw sensitive permafrost terrain, the upward heaving of pipelines because the freezing of frost susceptible soil, the strength of soils at interfaces between stable and non stable (either thawing or heaving) ground, installation of horizontal directional drilled pipelines in permafrost, and ditching productivity in frozen ground.

The development of geotechnical engineering as it has been applied to pipelines in permafrost terrain has made significant advances in the past four decades. The degree of sophistication and complexities of the analyses to address problems has increased dramatically, with the anticipated result of more cost effective systems, but will the same or better level of safety of the early pipeline systems.

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