Environment Canada Environnement Canada

National Hydrology Research Institute

NHRI PAPER NO. 8
IWD TECHNICAL BULLETIN NO. 114

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Cat. No. En 36-503/114

ISBN 0-662-10757-8

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Abstract

In a northern environment various interactions between pipelines and the terrain which they cross may produce adverse effects on pipeline integrity; adverse effects on the environment may also result, either directly or as a consequence of the increased maintenance or repairs required. In any particular situation the interactions and the severity of their effects will depend on the pipeline construction mode (e.g. buried or above-ground) and operation mode (e.g. chilled or warm); on the distribution of frozen and nonfrozen ground; and on the relative sensitivity of the ground during freezing and/or thawing. Most of the interactions are related to the occurrence and movement of surface water and subsurface water or to the occurrence or formation of ice. A tabulation of possible interactions and effects is presented as a guide to the potential problems that may occur during the construction and operation, as well as after abandonment, of a pipeline. When recognized early enough, development of such problems can often be avoided by rerouting or prevented by special design measures. Early recognition can in most cases only be achieved through special studies on groundwater levels, flow rates and temperatures; on the occurrence of icings; and on the distribution and character of ground ice.

Résumé

Dans l'environnement du Nord, plusieurs genres d'interactions entre un pipeline et le terrain qu'il traverse peuvent produire des effets défavorables affectant l'intégrité du pipeline; en outre, elles peuvent engendrer des répercussions environnementales, soit directement, soit en conséquence des travaux d'entretien ou de réparation requis. Dans toute situation donnée, les interactions et l'importance de leurs effets seront fonction des modes de construction (enfoui ou surélevé, par exemple) et d'opération (réfrigéré ou chauffé, par exemple); de la répartition et de la nature du pergélisol; et de la vulnérabilité du sol au gel ou au dégel. En général, les interactions envisagées surgiront à cause de la présence et du mouvement des eaux de surface et souterraines et de la présence ou de la génération de glace. Une table d'interactions et de leurs effets probables est présentée en tant que guide aux problèmes qui peuvent se poser lors de la construction et de l'opération, autant qu'après l'abandon du pipeline. Si les problèmes sont discernés à l'avance, il est possible de les éviter en modifiant le tracé ou en prenant des mesures spéciales de conception ou de construction. Dans la majorité des cas, il faut réaliser à cet effet, des études détaillées sur le niveau, le débit et la température des eaux souterraines, sur la provenance des naleds, aussi bien que sur la répartition et la nature du pergélisol riche en glace.

Potential Interactions between Pipelines and Terrain in a Northern Environment

R.O. van Everdingen

INTRODUCTION

Proponents of recent proposals for the construction of high-capacity pipelines to transport oil and natural gas from the Alaska North Slope, the Mackenzie Delta and the Arctic Islands to southern markets in Canada and the United States are all faced with the need to develop novel designs that will, at reasonable cost, assure the integrity of such pipelines in the northern environment, with a minimum of adverse environmental impact. In particular, the special problems related to the widespread occurrence of perennially frozen ground (permafrost) in both Alaska and northern Canada (Ferrians *et al.*, 1969) necessitate modifications in the engineering design and the construction procedures commonly used by the pipeline industry. Experience in this field is limited because, until a few years ago, no large-diameter buried pipelines had been constructed and operated in areas with permafrost anywhere in the world.

The Alyeska oil pipeline, carrying hot oil from the Alaska North Slope to Valdez, is elevated above the ground on vertical supports for about half its length to avoid problems that might result from the thawing of permafrost in potentially thaw-sensitive soil materials along the route. The recently reported discovery of small fractures associated with "wrinkling" of the pipe at two buried locations has raised the question whether it is possible to determine accurately all areas along a pipeline alignment where thaw-stable permafrost is present, and therefore, where a warm pipeline can be buried safely.

Proposals for the construction of the Mackenzie Valley gas pipeline and, more recently, the Alaska Highway gas pipeline have generally been based on the buried mode of construction; chilling of the gas would be used along at least part of these routes to prevent detrimental thawing of permafrost. During the Mackenzie Valley Pipeline Inquiry, differential heaving associated with the freezing of frost-sensitive nonfrozen ground along the route was identified as a potentially damaging side effect of the chilling of the gas. Designs to limit frost heave by deep burial and surcharge loading (using a berm), based on the shutoff pressure concept, were found to be impractical. The effectiveness of other measures, such as insulating the pipe, localized heating or rapid freezing, replacing sensitive materials by stable backfill, and using slip joints, has so far not been demonstrated.

In addition to the potential problems of frost heave and thaw settlement, Berger (1977) identified several other geotechnical terrain characteristics that could lead to problems affecting the integrity of the pipeline as well as the extent of environmental impact of the pipeline project. These included slope stability (including creep), surface drainage and erosion, subsurface drainage, and icings.

The more recent Alaska Highway gas pipeline proposal suggested that an above-ground construction mode, with the pipeline installed in a granular embankment, could be used to avoid adverse effects in places where use of the buried construction mode might lead to unacceptable frost heave (along the chilled portion of the route) or thaw settlement (along the warm portion). The proceedings of the technical hearings held in Whitehorse by the Alaska Highway Gas Pipeline Environmental Assessment Panel indicated that the "berm" mode, while conceivably alleviating some of the frost-heave and thaw-settlement problems, could also give rise to additional geotechnical and environmental problems.

When recognized early enough, some of the terrain-related problems could possibly be avoided by rerouting, while the development of many others might be prevented by appropriate modifications in either the pipeline design or the methods used during construction. The tabulation of possible pipeline-terrain interactions and their effects, presented in the next section, may assist in the early recognition of many of these problems. Terminology used in the text and in Table 1 is that of van Everdingen (1976).

PIPELINE MODES

Pipeline Construction Mode (Table 1, column 1)

Two construction modes are under active consideration for gas pipelines in northern Canada: the buried mode and the above-ground/berm mode. In the buried mode, which is apparently preferred at present by the pipeline industry for large-diameter high-pressure gas pipelines, the pipe would be installed in a trench backfilled with excavated material, with select (stable) backfill or with some combination of these. In the above-ground/berm mode, suggested as a local alternative for troublesome locations on the Alaska Highway gas pipeline, the pipe would be installed inside an embankment or berm of granular material (e.g. gravel).

The elevated mode, used extensively for the Alaska oil pipeline, is not shown in Table 1 because its interactions with the terrain are likely to be minor. In this mode the insulated pipe is supported some distance above the ground on vertical support members; when required, automatic heat exchangers can be installed in the vertical support members to prevent thawing of permafrost. The elevated mode is apparently not considered suitable for large-diameter high-pressure gas pipelines by the pipeline industry.

Pipeline Operation Mode (Table 1, column 2)

The two potential operation modes for pipelines are the warm mode and the chilled mode. Oil pipelines are generally operated in the warm mode; gas pipelines may be operated either chilled or warm. Chilling of the gas, to a temperature below the freezing point of the surrounding ground, has been suggested as a means to prevent the thawing of permafrost. The Alaska Highway gas pipeline in the Yukon would receive chilled gas at the Alaska-Yukon border. Chilling of the gas would be discontinued at either the first or the third compressor station in the Yukon; beyond that point the pipeline would operate at temperatures above $0^\circ C$.

TERRAIN FACTORS

Initial Condition of the Ground (Table 1, column 3)

The initial condition of the ground in which a pipeline is to be installed can be specified as either frozen or nonfrozen. Some fine-grained soils may be only partially frozen, containing some proportion of liquid water at temperatures below $0^\circ C$. For the purpose of Table 1, such soils should be regarded as frozen for those situations and periods in which they will be subjected to thawing as a result of pipeline construction or operation; they should be regarded as nonfrozen for situations and periods in which they will be subjected to further freezing.

In Table 1 special attention is directed to the *transitions,* between frozen and nonfrozen ground, where thaw settlement and/or frost heave have their greatest potential for causing damage to the pipeline by differential movements of the pipe.

"Character" of the Ground (Table 1, column 4)

The character of the ground is specified as either sensitive or stable in Table 1. The term "sensitive" is meant to indicate thaw-sensitive frozen ground and frost-sensitive nonfrozen ground; the term "stable" is meant to indicate thaw-stable frozen ground and frost-stable nonfrozen ground.

It should be stressed here that the actual stability or sensitivity of the ground depends not only on the grain-size distribution and the composition of the soil materials but also on the subsurface water conditions and on the temperature regime. A soil material classified as frost-stable (on the basis of conventional laboratory analysis) may be part of a frost-sensitive system; similarly, the system can be frost-stable even if it contains soil material classified as frost-sensitive, provided that the temperature regime or the water conditions preclude the formation of excess ice. Thaw-sensitive soil could behave in a stable manner if thawing proceeded slowly enough to allow drainage without buildup of "excess" pore pressures.

Although this is not emphasized in Table 1, transitions between areas of sensitive ground and areas of stable ground form a second group of points at which there is a significant potential for pipeline damage by differential movements of the pipe.

POTENTIAL INTERACTIONS AND EFFECTS

Before Operation (Table 1, columns 5 and 6)

Major activities during the pre-operation stage include clearing and grading of the right-of-way; construction of access roads; trenching, followed by pipelaying and backfilling, or construction of an embankment, followed by pipelaying and covering; and hydrostatic testing. In some cases as long as two years may elapse between installation of the pipe and the start of operation.

The initial effects of clearing of the right-of-way may include increased frost penetration in nonfrozen ground and increased thaw penetration in perennially frozen ground, possibly with some frost heave or thaw settlement, respectively. Locally, thawing of ice-rich permafrost may affect the stability of slopes.

Natural slopes crossed by a pipeline, as well as a number of cut slopes, may require dewatering as a means of improving their stability. Designing adequate dewatering systems for such slopes could be challenging, because drains may freeze during the winter when drainage rates are low and disposal of the drainage water can lead to ponding or icing problems. Slope stability problems can also be caused by the seasonal freezing and thawing of apparently stable cut slopes that produce little or no visible seepage of water. Such slopes can be prone to repeated failure during successive spring thaws as a consequence of slow pressure buildup behind the frozen face of the cut during the winter. The deceptive character of such slopes is not always recognized in time to prevent failure.

During trenching operations in areas with a high groundwater table, the trench may fill with water, the

TABLE 1. POTENTIAL PIPELINE-TERRAIN INTERACTIONS AND THEIR EFFECTS IN A NORTHERN ENVIRONMENT

PIPELINE		TERRAIN		INTERACTIONS AND EFFECTS							
				BEFORE OPERATION		DURING OPERATION				AFTER ABANDONMENT	
CONSTRUCTION MODE	OPERATION MODE	INITIAL CONDITION of GROUND	CHARACTER of GROUND	GROUND	WATER	GROUND	PIPELINE	SURFACE WATER	GROUNDWATER	GROUND	WATER
BURIED (may be insulated)	COLD $T<0°C$	FROZEN	STABLE	THAWING	CHANNELING of SURFACE WATER on RIGHT-of-WAY, and of GROUNDWATER in TRENCH FILL; PONDING, EROSION, ICINGS; possibly SLOPE FAILURES	FREEZING	—	—	—	—	—
			SENSITIVE	THAWING, CONSOLIDATION, INSTABILITY of SLOPES		FREEZING, HEAVING	LIFTING	PONDING of SURFACE WATER, ICINGS, EROSION of RIGHT-of-WAY	—	THAWING, CONSOLIDATION, INSTABILITY of SLOPES	PONDING, ICINGS, EROSION of RIGHT-of-WAY
		TRANSITION ZONE	N.A.	INCREASE in STRESSES on PIPE (possibly FAILURE)		MAXIMUM DIFFERENTIAL in HEAVE	MAXIMUM INCREASE in PIPE STRESSES; PIPE FAILURES		N.A.	N.A.	
		NONFROZEN	SENSITIVE	FREEZING, HEAVING	same as above, plus DROWNING of TRENCH, seasonal FAILURE of CUTS	FREEZING, HEAVING	LIFTING		RESTRICTION of FLOW: NEW DISCHARGES, ICINGS, FROST BLISTERS	THAWING, CONSOLIDATION, INSTABILITY of SLOPES	same as above, plus CHANNELING in TRENCH FILL, EROSION by 'PIPING'
			STABLE	FREEZING		FREEZING	—			THAWING	
	WARM $T>0°C$	FROZEN	STABLE	THAWING	CHANNELING of SURFACE WATER on RIGHT-of-WAY, and of GROUNDWATER in TRENCH FILL; PONDING, EROSION, ICINGS; possibly SLOPE FAILURES	THAWING	—		CHANNELING in TRENCH FILL: 'PIPING', ICINGS, NEW DISCHARGES	FREEZING	—
			SENSITIVE	THAWING, CONSOLIDATION, INSTABILITY of SLOPES		THAWING, CONSOLIDATION, INSTABILITY of SLOPES	SETTLEMENT			FREEZING, HEAVING	PONDING, ICINGS, EROSION of RIGHT-of-WAY
		TRANSITION ZONE	N.A.	INCREASE in STRESSES on PIPE (possibly FAILURE)		MAXIMUM DIFFERENTIAL in CONSOLIDATION	MAXIMUM INCREASE in PIPE STRESSES; PIPE FAILURES		N.A.	N.A.	
		NONFROZEN	SENSITIVE	FREEZING, HEAVING	same as above, plus DROWNING of TRENCH, seasonal FAILURE of CUTS	WARMING	—		CHANNELING in TRENCH FILL: 'PIPING', ICINGS, NEW DISCHARGES	—	same as above, plus CHANNELING in TRENCH FILL, EROSION by 'PIPING'
			STABLE	FREEZING		WARMING	—			—	
ABOVE GROUND/ BURIED in a BERM (may be insulated)	COLD $T<0°C$	FROZEN	STABLE	COMPACTION (active layer)	PONDING of SURFACE WATER, SEEPAGE through BERM, EROSION, ICINGS; RESTRICTION of GROUNDWATER FLOW, NEW DISCHARGES, FROST BLISTERS; possibly DAMAGE to or FAILURE of BERM at CULVERTS	COMPACTION (active layer)	SETTLEMENT	PONDING of SURFACE WATER, SEEPAGE through BERM, ICINGS, possibly DAMAGE to or FAILURE of BERM at CULVERTS	RESTRICTION of FLOW: NEW DISCHARGES, ICINGS and FROST BLISTERS	—	PONDING of SURFACE WATER, EROSION, SEEPAGE through BERM, GROUNDWATER DISCHARGE, FROST BLISTERS, ICINGS, possibly DAMAGE to or FAILURE of BERM
			SENSITIVE	THAW SETTLEMENT						—	
		TRANSITION ZONE	N.A.	DIFFERENTIAL COMPACTION		DIFFERENTIAL COMPACTION	INCREASE in STRESSES on PIPE			N.A.	
		NONFROZEN	SENSITIVE	FROST HEAVE		COMPACTION; HEAVING	SETTLEMENT; LIFTING			THAWING, CONSOLIDATION	
			STABLE	COMPACTION		COMPACTION, FREEZING	SETTLEMENT			THAWING	
	WARM $T>0°C$	FROZEN	STABLE	COMPACTION (active layer)		COMPACTION (active layer)	SETTLEMENT			FREEZING	
			SENSITIVE	THAW SETTLEMENT		COMPACTION; THAWING, CONSOLIDATION	SIGNIFICANT SETTLEMENT			FREEZING, HEAVING	
		TRANSITION ZONE	N.A.	DIFFERENTIAL COMPACTION		DIFFERENTIAL COMPACTION	INCREASE in STRESSES on PIPE			N.A.	
		NONFROZEN	SENSITIVE	FROST HEAVE		COMPACTION	SETTLEMENT			—	
			STABLE	COMPACTION						—	

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June 1979

trench walls may become unstable, and the trench may in some instances act as a drainage channel, with the possibility of significant erosion. In such areas, weighting of the pipe or some method of dewatering would be required to allow installation of the pipe; weighting or deep burial would be required to counteract buoyancy of the pipe after installation; and progressive settlement of backfill placed in a water-filled trench would likely necessitate more frequent maintenance for drainage and erosion control. Where dewatering is to be used as a means to facilitate pipelaying, the disposal of the water could lead to erosion, to siltation of water bodies and, in winter, to icing problems.

Potential problems related to the occurrence of a high water table may not always become obvious before or during construction; they will, however, show up later in the form of unexpected buoyancy of the pipe and possibly in excessive settlement of the trench fill. This is most likely to be encountered in areas with competent soil materials of low permeability or in areas that experience large seasonal fluctuations of the water table if construction takes place during a period when the water table is low.

Artificial drainage and erosion controls are normally required to prevent surface erosion along the right-of-way. The trench fill, however, which in general will be more permeable than the surrounding ground, can act as a subsurface drainage conduit, diverting both surface and subsurface water. This in turn can lead to erosion of the trench fill and the creation of new discharge points, with attendant icing problems in winter. Channeling of water in the trench fill might be of particular concern where a pipeline route crosses one or more alluvial fans because of the nature of the fan deposits and the hydraulics of the high-energy streams that built them. Impermeable plugs might be placed in the trench fill at some distance on either side of existing stream beds to stop channeling of infiltrated water in the permeable trench fill. Streams on alluvial fans, however, are prone to avulsions (course changes) as a result of accumulation of debris in their original channels. When an avulsion occurs, water from such a stream might infiltrate the alluvial materials at a point where trench plugs would not prevent it from flowing along the trench fill.

Construction of embankments, for the above-ground/berm mode and for access roads, will lead to disruption of surface-water drainage patterns unless adequately sized and properly placed culverts are provided. Inadequate drainage may lead to ponding and to seepage of water through the base of the embankment, which may result in erosion and eventual failure of the embankment. Icings can block culverts during the winter; significant icing buildup may thus lead to erosion and possibly failure of an embankment during the spring thaw. The above-ground/berm mode would be considerably more vulnerable to erosion damage from avulsions of streams on alluvial fans than the buried mode.

Construction of an embankment will often lead to compaction of underlying ground and, in areas with permafrost, to a gradual upward displacement of the permafrost table below the embankment. Where the movement of groundwater is impeded by the occurrence of either of these phenomena, discharge of groundwater is likely to occur on the uphill side of the embankment, with associated problems of ponding and icing. In some situations the restriction of groundwater movement can result in the formation of frost blisters, as described by Eager and Pryor (1945) for a location on the Alaska Highway and by van Everdingen (1978) for a location near Fort McPherson.

During hydrostatic testing of completed sections of a pipeline, large quantities of water would be withdrawn from and subsequently released back into conveniently located bodies of water. Withdrawal and release points can be selected, and withdrawal and release rates controlled, to minimize the impact of such operations on the water environment. It is to be expected, however, that an accidental, uncontrolled release of hydrostatic testing fluid could result in severe erosion along the right-of-way and subsequent siltation of nearby water bodies.

Most of the problems associated with pipeline activities during the pre-operation period can be expected to become noticeable well within the first year after construction. The integrity of the pipeline is only likely to be affected during this period in cases of slope failure, embankment failure, or erosion of the right-of-way or the trench fill.

During Operation (Table 1, columns 7 to 10)

The major cause of pipeline-terrain interactions during the operation of a *buried* pipeline in a northern environment will be the exchange of thermal energy between the pipeline and the surrounding ground. Operation in the chilled mode will cause freezing of initially nonfrozen ground, whereas operation in the warm mode will cause thawing of initially frozen ground. Insulating the pipe will reduce the rate of thermal energy exchange and the magnitude of its effects on the surrounding ground, but it will not eliminate them. Use of the above-ground/berm mode of construction might reduce these effects somewhat further; use of the elevated mode would practically eliminate them.

The freezing resulting from the operation of a *chilled* buried pipeline will have little effect on initially frozen and initially nonfrozen frost-stable ground; it may cause formation of some excess ice in already frozen frost-sensitive ground (Mackay *et al.,* 1979); and it can cause significant heave by formation of excess ice in initially nonfrozen frost-sensitive ground. Along a chilled pipeline, the maximum potential for differential frost heaving will be found at the boundaries between initially nonfrozen frost-sensitive ground and already frozen frost-stable ground. At such transitions the buried pipe and its insulation would be subjected to the severest stresses, with the highest chance of failure. In any particular case, the actual movements and deformation of the pipe would be dependent on such factors as uplift resistance, bulb stiffness and sharpness of the transition.

Occurrence of frost heave on the right-of-way will disrupt surface-water drainage patterns, which may result in ponding of water, formation of icings and, possibly, erosion along the right-of-way.

The formation of a frost bulb (zone of frozen ground) around a chilled buried pipeline may restrict the movement of groundwater. This can lead to discharge of groundwater to the surface uphill from the pipeline, necessitating additional drainage measures to prevent ponding and erosion during the frost-free season and to prevent formation of icings during the winter. Extra drainage measures might not be required at stream crossings, but the induced icings could deprive fish-overwintering areas of their water supply and they could also lead to an increase in the rate of lateral erosion and in the depth of scour in small streams.

In some situations, restriction of groundwater flow by a frost bulb could also lead to the formation of seasonal frost blisters on the uphill side of the right-of-way, similar to those described by Eager and Pryor (1945) and van Everdingen (1978). Such frost blisters might not have any direct effect on the pipeline, but rupturing of the frost blisters would lead to formation of icings, and the presence of the frost blisters during the spring melt could disrupt local surface drainage patterns.

The thawing resulting from the operation of a *warm* buried pipeline will have little effect on initially nonfrozen ground or on initially frozen thaw-stable ground. It will cause melting of excess ice, resulting in thaw consolidation and possibly instability in initially frozen thaw-sensitive ground. Along a warm buried pipeline the maximum potential for differential thaw settlement will thus most likely be found at the transitions between areas of initially frozen thaw-sensitive ground and areas of stable frozen or nonfrozen ground. The probability of failure of the pipe at any of these transitions will be highest where the thickness of excess ice in the thaw-sensitive ground is largest.

The occurrence of thaw settlement on the right-of-way will lead to ponding of water and possibly erosion.

In a few instances, the thawing of initially frozen ground may open up new discharge paths for groundwater. Wherever the fill in the pipeline trench is more permeable than the surrounding ground, thawing will allow the trench to act as a groundwater conduit. This could also give rise to new groundwater discharge points with potential drainage problems and possibly winter icings; it could also lead to gradual erosion of the trench fill by "piping."

In the case of an *above-ground* pipeline buried in a berm, compaction of underlying ground would likely continue during the operation phase, but its effects would be modified by freezing or thawing of the ground. Although the rate of exchange of thermal energy between the pipe and the ground could be lower for the above-ground/berm mode than for the buried mode, it would still be significant. Freezing of the ground caused by a chilled pipeline would tend to slow down compaction of the near-surface layers; formation of excess ice could in some cases lead to a reversal of the actual movement. The compaction process could be somewhat enhanced by thawing of initially frozen ground by a warm pipeline; the effect of thawing could be considerable where a large thickness of excess ice is available to produce significant thaw settlement.

Many of the effects of the thermal energy exchange between a pipeline and the surrounding ground may become apparent only after a number of years of operation.

The integrity of the pipeline may be affected during the operation period by intolerable stresses on the pipe induced by frost heave or thaw settlement, particularly at the transitions defined earlier; by slope or embankment failures; by erosion of the trench fill; or by excessive lateral erosion or scour at stream crossings.

After Abandonment (Table 1, columns 11 and 12)

Once the operation of a pipeline is discontinued, one can expect a reversal of some of the effects caused by the operation phase. Actual removal of the pipe may either speed up or delay the eventual establishment of new equilibrium conditions.

In the case of a chilled buried pipeline, areas that were affected by frost heaving will be subjected to gradual thawing of excess ice. They will experience thaw settlement and possibly reduced stability of slopes, and unrestricted movement of groundwater will resume as the frost bulb thaws. In the case of a warm buried pipeline, areas that were affected by thaw settlement may be subjected to gradual aggradation of permafrost and possibly some frost heaving. In the case of an above-ground pipeline buried in a berm, compaction resulting from construction of the berm may continue, at a gradually decreasing rate, for some time after abandonment.

The effects on and interactions with surface water and groundwater will generally be similar to those described for the pre-operation period. They include ponding of water and associated erosion of the right-of-way; channeling of groundwater in the trench fill, possibly accompanied by erosion of the fill; seepage of water through pipeline and road embankments; and seasonal formation of frost blisters and of icings that may block culverts, possibly leading to embankment failures during spring thaw.

The terrain effects resulting from abandonment of a pipeline are likely to become noticeable as soon as maintenance of the right-of-way is discontinued.

DATA REQUIRED FOR EARLY RECOGNITION OF PROBLEMS

The listing of potential problems in the foregoing sections clearly indicates that most pipeline-terrain interactions are related in one way or another to the occurrence and movement of water or to the occurrence or formation of ice. Early recognition of many of the potential problems will require information on groundwater levels, flow rates and temperatures; on the location and regime of groundwater-related natural icings; and on the distribution of frost-sensitive and thaw-sensitive (ice-rich) deposits.

Some of the information required (e.g. instantaneous groundwater levels, water temperatures, ground-ice distribution) can be gathered during the course of geotechnical drilling programs; moisture contents and hydraulic and thermal conductivities can be determined on soil samples and cores in the laboratory. Reliable information on maximum water-table levels can only be obtained through regular (at least weekly) measurements or recording of water levels over a period of at least one year. Simple slotted standpipes installed in geotechnical test holes might serve as observation wells for this purpose. Determination of flow rates will only be possible if representative data on permeabilities and gradients can be obtained. The location and regime of natural icings will have to be determined through repeated observations during several winters.

ACKNOWLEDGMENTS

Discussions on pipeline-terrain interactions, with J.A. Banner, Hydrology Research Division, Environment Canada; J.R. Ellwood, Foothills Pipe Lines (S. Yukon) Ltd.; O.L. Hughes, Terrain Sciences Division, Geological Survey of Canada; and P.J. Williams, Department of Geography, Carleton University, all contributed to the present perception of the problems outlined in this report. Critical comments on the manuscript were provided by R.J.E. Brown, Division of Building Research, National Research Council of Canada, and by O.J. Ferrians, Jr., U.S. Geological Survey.

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