GEOTECHNICAL ASPECTS OF NORTHERN GAS PIPELINE DESIGN

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Abstract

This paper reviews some of the geotechnical issues associated with freezing and thawing of soils beneath a pipeline, and describes some of the analytical tools that are available to predict the effects on the pipeline.

Preliminary predictions for continuing or "secondary" heave beneath a cold pipe in warm permafrost are made, and movements of up to 25 cm could be expected under reasonable worst-case conditions. Climatic warming over a 25-year period appears to have little effect on this result.

Frost heave in initially unfrozen ground has been predicted for silts and silty clays using the Segregation Potential frost heave method, incorporated in a 2-D geothermal model. Comparison with two well-documented case histories shows that the method holds good promise for predicting frost heave to a reasonable engineering level of accuracy. Climatic warming was incorporated in a simple way into the geothermal model used for frost heave, and a beneficial effect in reducing frost depth and frost heave is predicted.

Thawing beneath a warm pipeline is also considered, and a 10C pipeline could be expected to thaw up to 10 m of permafrost beneath the pipe. The effects of climatic warming appear to be minimal for this case. Published results from a typical structural analysis indicate that tolerable amounts of settlement resulting from thaw are relatively large, before overstraining of the pipe becomes a concern.

Recent developments in the area of monitoring pipe curvatures and displacements are briefly outlined, and these show considerable promise in the early detection of areas of pipe movements.

Résumé

Cet article traite de certaines questions géotechniques associées au gel et au dégel des sols sous un pipeline, et décrit quelques outils analytiques de prévision des effets sur le pipeline. Des prévisions préliminaires sont établies pour le soulèvement continu ou «secondaire» sous un tuyau froid dans un pergélisol chaud, et des mouvements atteignant 25 cm sont prévisibles dans les pires conditions raisonnables. Un réchauffement du climat pendant une période de 25 ans semble avoir peu d'effet sur ce résultat. Un soulèvement dû au gel a été prévu dans un sol initialement non gelé constitué de limons ou d'argiles limoneuses par la méthode du potentiel de ségrégation dans un modèle géothermique 2D. La comparaison avec deux cas bien documentés révèle que la méthode semble prometteuse pour prévoir le soulèvement dû au gel avec une précision raisonnable sur le plan technique. Le réchauffement du climat a été incorporé de façon simple dans le modèle géothermique utilisé pour la prévision du soulèvement dû au gel, ce qui permet d'anticiper une réduction souhaitable de la profondeur du gel et du soulèvement dû au gel. Le dégel sous un tuyau chaud est aussi examiné, et il est raisonnable de s'attendre à ce que le sol soit dégelé jusqu'à une profondeur de 10 m sous un tuyau à 10 °C. Les effets du réchauffement du climat semblent minimes dans ce cas. Les résultats publiés d'une analyse structurale type indiquent que les niveaux tolérables de tassement dû au dégel sont relativement importants avant que la déformation du tuyau ne devienne critique. Les progrès récents en matière de contrôle de la courbure et du déplacement de tuyaux sont décrits brièvement, faisant ressortir les avantages considérables de la détection précoce des zones touchées par des mouvements de tuyaux.

Introduction

Design of a natural gas pipeline from the Arctic to a southern location requires consideration of several geothermal and geotechnical aspects. Firstly, for the gas flow rate, pipe size and compressor station spacings of interest, there is a 10 to 15C decrease in gas temperature between compressor stations. The primary factor causing the cooling is the Joule-Thompson effect. Therefore, depending on the upstream compressor station discharge temperature, the pipeline segment between stations may induce thawing of frozen soils over the upstream part of the line, and also result in freezing of unfrozen soil beneath the downstream part of the same line.

The amount of frozen ground varies from north to south in response to regional climatic changes, and to a lesser extent to local factors such as elevation, vegetation and

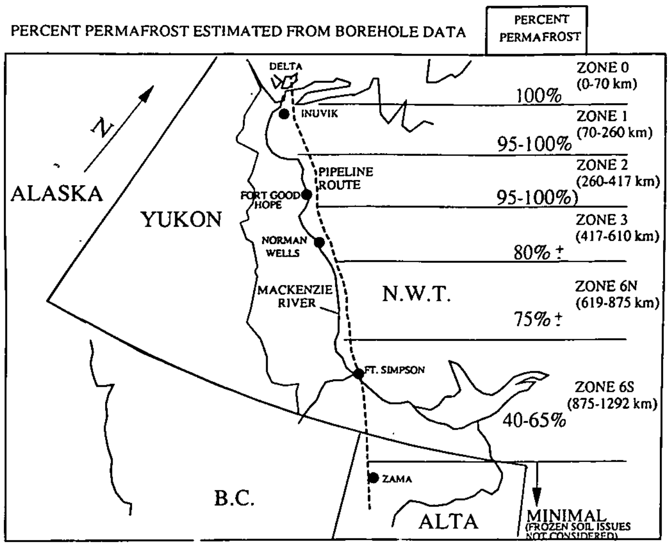


Figure 1. Percent permafrost along Mackenzie routing.

micro-climate. If the permafrost/non-permafrost boundary were a discrete line, it would be a relatively easy matter to operate the pipeline below freezing north of this line, and above freezing to the south. As shown on Figure 1, however, a gradual transition from frozen to unfrozen occurs over a lengthy part of the proposed pipeline route.

There are a number of alternative pipeline routes to transport gas from the Mackenzie Delta to existing pipeline connections in southern Alberta. This paper refers to one such route, i.e. the Mackenzie Valley route.

The route within the Mackenzie Valley has been subdivided for present purposes into 6 physiographic/climatic zones, based on published work by Zoltai, Tarnocai and others (e.g. Tarnocai, 1973). This has been done for convenience of grouping terrain, borehole and climatic data. A computer-based borehole data base is maintained by Esso Resources which contains about 11 000 borehole records. This data base can be used to assess the presence of frozen ground, cobbles or boulders, till, and data on soil classification and water content with depth. In the northern part of the route between the Mackenzie Delta and somewhere around Fort Good Hope, borehole data indicate that over 95 % of the terrain is frozen. There is a rather marked decrease in the percentage of frozen terrain as evidenced by borehole logs to the south of this point. The next two zones, 3 and 6N exhibit 75-80 % frozen terrain. To the south of these 2 zones (Willowlake River to the 60th parallel), the borehole data base indicates about 65 % of the terrain is frozen. However, some areas of this zone, 6S, have not been investigated fully, and a lower percentage of permafrost may be present based on other geophysical records, and experience from the Norman Wells pipeline.

It is reasonable to suggest that the pipeline should be operated continuously below 0 °C to some point close to Fort Good Hope, in view of the very high percentage of frozen ground to the north of this point. In this way, the extent of pipeline likely to experience thaw settlement problems would be minimized. However, the extent of pipe chilling could be continued to the south of this point, depending on the relative severity of the geotechnical problems posed by frost heave and thaw settlement. This paper reviews some of these geotechnical issues, and offers some initial thoughts on the relative complexity of the frost heave and thaw settlement problems.

Gas pipeline temperatures.

A gas pipeline along the Mackenzie corridor will undoubtedly involve a number of gas compressor stations, in order to maintain flow and pressure in the pipeline. Of the various pipelines currently proposed, some pipe diameter in the range of 910mm (36 inch) appears to be most favoured. At each compressor station, the gas would be taken through a compression cycle, which elevates the temperature considerably. Depending on the time of year and the desired discharge temperature, the gas may be cooled by air coolers and/or refrigeration units, and then discharged into the pipeline. In order to minimize thaw settlement effects, and also limit the length of pipe over which seasonal or continuous chilling takes place, a discharge temperature in the range of +10 °C would seem to provide a balance between freezing and thawing effects. Cooler discharge temperatures are certainly possible, but do not greatly reduce the thaw depth, and allow a greater potential for frost heave. Hotter discharge temperatures are also possible, but again do not greatly reduce the length of pipe beneath which heave might occur, as the gas temperatures appear to cool towards the ambient temperature over much the same distance.

Figure 2 shows a typical simplified spreadsheet-based prediction for a gas line temperature having a diameter and cover depth of 910mm. The prediction uses an equation from King(1981). Typical ground heat flow and ambient ground temperatures have been assumed for the discontinuous permafrost zone. Due to the Joule-Thompson effect, the total temperature drop is a strong function of the total pressure drop along the length of pipeline between any 2 stations. If the distance between the 2 stations on Figure 2 is reduced,

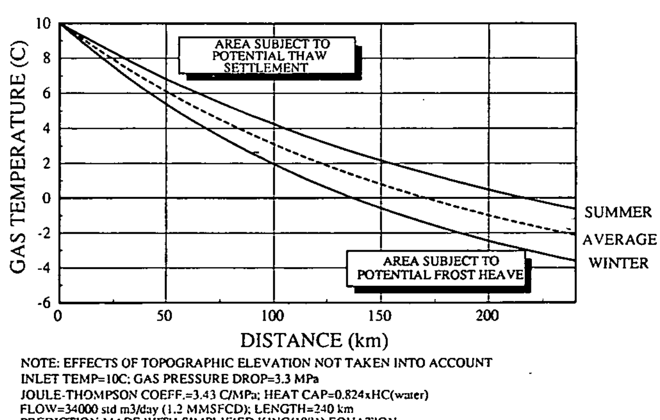


Figure 2. Predicted flowing gas line temperatures for typical conditions.

but the pressure difference is kept the same, then the outlet temperature at the end of the pipe section will be much the same. In order to eliminate the section of sub-zero gas temperatures, it is necessary to bring the stations closer together, and to reduce the total pressure drop between stations. Alternatively, the discharge temperature can be increased, or an intermediate heater station can be provided. However, the final choice of station-to-station spacing and gas operating pressures will be based to a large extent on economics, combined with the relative severity of the problems posed by frost heave and thaw settlement.

The temperature profile on Figure 2 suggests that for these assumed conditions, about 2/3 of a 250 km long pipe section would experience thaw settlement, and about 1/3 would be subject to frost heave. It is of interest to note that because of the difference in ground heat flow conditions between summer and winter, the extent of the zone over which frost heave might be expected will vary throughout the year. That is, some of the downstream sections of the pipeline will be subject to seasonal frost heave, whereas it is possible that another section of pipe would experience continuing freezing and potential frost heave.

Several more sophisticated computer programs are available to more accurately predict the pipeline temperature profiles, incorporating the effects of variable gas properties, variable topographic changes, different combinations of compressor and heater stations, changes in line size and operating conditions. However, the spreadsheet-based equation used to generate Figure 2 allows the effects of several ground thermal and operating characteristics to be quickly established.

Geotechnical issues.

(a) Frost Heave

Based on the foregoing discussion of pipeline operating temperatures and ground thermal regime, any unfrozen area of the route north of a point where the pipe is operated below 0 °C will be subject to freezing and potential frost heave. The converse is also true for thaw and possible settlement south of the last point of cold gas flow. Depending on the station configuration and gas pressure profile, frost heave may also occur over some parts of the route to the south of the last point where gas temperatures are controlled below 0 °C.

In the northern part of the route, unfrozen ground is very limited in extent, and is likely confined to riverbeds, beneath large lakes and highly disturbed terrain. Most of this can be avoided, except for the northern rivers, which must be crossed by the pipeline. Special measures involving insulation, heat tracing or line heaters may be considered in such areas where the unfrozen soil is considered frost susceptible.

Further south, if more widely spaced stations and larger gas pressure drops are considered, then pipeline design studies could be carried out to determine the tolerable frost heave for the buried line. These allowable frost heave amounts could be compared with the frost heave predicted in that soil type, for the appropriate pipe operating and ground temperature conditions. This is discussed in more detail later.

(b) Heave in frozen ground

North of the last point of cold gas flow, there may be areas of warmer, fine-grained soils where a concern for heave in initially *frozen* ground exists. The phenomenon of frost heave in initially frozen soil has been documented in the lab, and for a small range of negative temperatures in the field (Smith,1985). Water flows in clay soils at temperatures below 0 °C under the influence of temperature gradients. The temperature gradient gives rise to a suction gradient in the frozen soil, and this gradient in conjunction with the hydraulic conductivity of the soil results in a small flux of water from the warmer to the colder temperature. Because of the 2-D flow patterns established around a buried chilled pipe, Nixon (1987) showed that a steady, but slow rate of frost heave was possible beneath the centre-line of a pipe. Provided the hydraulic conductivity is sufficiently large (i.e. usually greater than 10^{-10} cm/sec or so), water could move through the frozen soil around the pipe towards the colder soil beneath the pipe, where the ice content of the soil would gradually increase with time.

Smith(1985) has back-calculated the hydraulic conductivity of a clay near Inuvik, and these data appear to form a reasonable upper bound for the available published data reviewed on Figure 3. More data are needed to quantify the range of hydraulic conductivities that might be encountered in the northern part of the Mackenzie Valley. Nixon (1987) has shown that for a typical range of soil conditions and pipe operating conditions, the rates of heave in frozen ground beneath a buried pipe are reasonably small. This work has been extended for a 910 mm buried line, using the hydraulic conductivity data from Smith (1985), as shown on Figure 4. A frost heave of about 24 cm was predicted after 25 years of pipe operation at -5 °C, in a permafrost area where the initial ground temperature was -1 °C. Once the initial transient temperature disturbance has dissipated, the rate of heave becomes relatively constant thereafter.

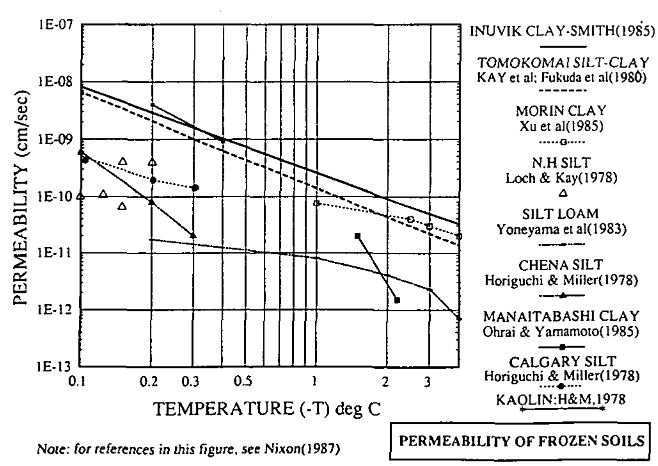
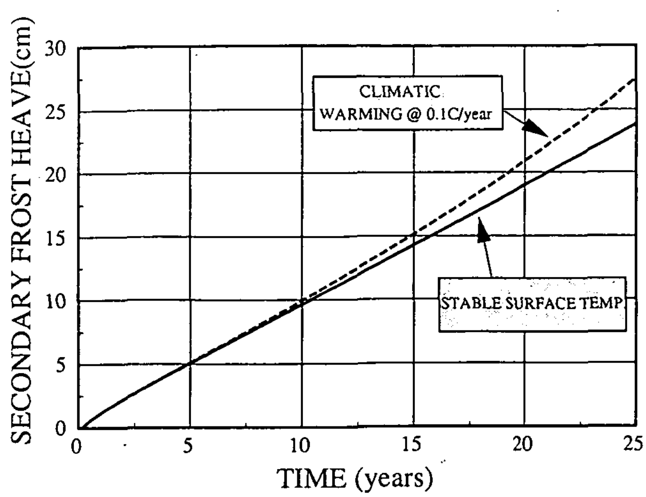


Figure 3. Permeability of frozen soils.



INITIAL GROUND TEMPERATURE = -1C,
PIPE TEMP. = -5 C (CONSTANT), SURFACE TEMP VARIABLE
FROZEN CLAY PERMEABILITY=2.66E-10 (-T)^-1.5(cm/sec)

Figure 4. Prediction of heave of chilled pipe in warm frozen clay.

The phenomenon of heave in initially frozen soil does not appear to pose a significant threat to a chilled pipe, because (a) the magnitude of frost heave experienced over the operating life of the pipe is relatively small, and falls within the normal range of frost heave that would be considered tolerable for pipelines of typical diameters and wall thicknesses; (b) the heave occurring differentially from place to place would be damped to a large extent because of the large body of frozen ground present around the pipe. That is, if differential heave in frozen soil were anticipated because of changes in soil type, the mass of frozen soil initially present around the pipe would tend to mechanically dissipate any sudden changes in heave.

This issue will undoubtedly be studied further, but should not prove to be a major design concern for a northern gas pipeline project.

(c) Thaw Settlement

Where the pipeline would operate warm, it would thaw the frozen ground initially present beneath the pipe. As discussed earlier, as much as 60-80% of the terrain is frozen north of the 60th parallel. Some of this terrain has excess ice, and would settle to some extent on thawing. Gravity loads from the backfill on top of the pipeline would exert downward loads on the pipeline, attempting to make the pipe conform to the curvature of the settling terrain. The pipe is a very stiff structural member, and bends to a curvature that depends on the stiffnesses of the pipe and the soil supports resisting downward movement of the pipe. These curvatures induce strains in the pipe, and it is necessary to design the pipe to accommodate these strains, in addition to the strains arising from other sources such as internal pressures and temperature expansion. This will be discussed in more detail later.

(d) Slopes

The pipeline will have to traverse many slopes of varying length and slope angle. Where the pipe is operated cold, there is little concern for pipe integrity, as the pipe will maintain a bulb of frozen soil along the length of the slope. However, the right-of-way (ROW) slope outside the immediate thermal influence of the pipe will still require consideration, due to the environmental consequences of surficial slope instability. In the northern part of the route, such ROW slopes may require protection in the form of surficial insulating layers. In areas of warm gas flow, the pipe may also require insulation and/or heat removal on steeper slopes in fine-grained soils. Fine-grained permafrost soils tend to have lower strengths when thawed, and may also maintain excess pore pressures if thawed too quickly (Morgenstern and Nixon, 1971). Much valuable experience has been gained in the area of slope design and mitigation during the construction and initial years of operation of the Norman Wells pipeline (McRoberts *et al*, 1985; McRoberts *et al*, 1986). Wood chips were used as an organic insulator on steeper permafrost slopes, and have functioned reasonably well for the most part (e.g. Hanna & McRoberts, 1988). The Norman Wells pipeline was essentially an ambient temperature pipeline, in which the pipe temperatures were generally within a few degrees of the prevailing ground temperature.

The operation of a larger diameter, warm gas pipeline poses some new issues that must be addressed. On steeper slopes underlain by fine-grained permafrost soils, it will not be sufficient to simply protect the ROW with a surface insulation blanket, as this would not remove the heat generated by the buried pipeline. If the pipeline is to remain buried, it will likely be necessary to contemplate some pipe insulation, coupled with some form of heat removal. In this way, the heat that slowly passes through the pipe insulation can be transferred to the surface, without inducing significant thaw or settlement beneath the pipe. A possible design to achieve this is given on Figure 5. The method of heat removal shown employs heat convection ducts buried adjacent to the insulated pipe, although some commercially available thermal siphon could be considered just as easily.

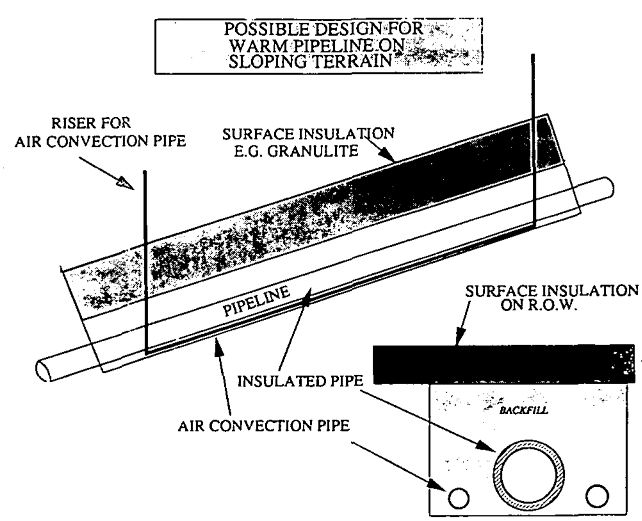


Figure 5. Possible design for warm pipeline on sloping permafrost terrain.

Heat convection ducts have been used on a trial basis on the Norman Wells pipe, for a slightly different purpose, as well as for road stabilization in Alaska (Zarling *et al*, 1983).

The other major development that is likely to influence slope design in permafrost is the use of some surface insulation material, other than wood chips. Some other materials considered include harvested peat, and baked clay/shale materials such as "Granulite", a lightweight granular fill marketed by an Alberta concrete company. This latter material shows particular promise, as it retains stable long-term insulating properties provided it remains reasonably well-drained. It is not, therefore, subject to the same problems of deterioration with time, that other organic insulators may suffer.

The alternative to some of these mitigative techniques on sloping terrain is to elevate the pipeline on pile supports for short lengths, and using surface insulating layers to protect the ROW surface as before.

(e) Buoyancy

In areas of warm gas flow, a large diameter pipeline will be subject to buoyant uplift forces for its operating lifetime. Furthermore, in more northerly areas of cold gas flow, the pipe may also be subject to such forces during its inactive period between construction burial, and start-up. The concern in these more northerly areas is not as serious, however, as it is unlikely that the ground will thaw to a depth beneath the pipe base before the start of operation. A calculation of the weight of pipe and contents, as compared with the weight of water displaced by the pipeline will quickly reveal that a net buoyant uplift force must be resisted by any large diameter gas line. This is not generally as much of a concern for an oil pipeline, as the weight of contents are sufficiently high to prevent flotation in water.

This net buoyant force must be resisted by the weight of backfill soil over the pipe, possibly with some allowance for side-shear between the backfill and surrounding soil. For some areas where the surficial soils have a low density or high water(ice) content, consideration may have to be given to the use of select backfill material, conventional concrete pipeline weights, or possibly some method of contained backfill over the pipe using geotextiles. This last method shows particular promise, and has been described by Couperthwaite and Marshall (1987), with application to pipelining in muskeg.

(f) Ditching/Construction

There are many other construction-related issues, where geotechnical input is required. These include river crossings, revegetation, ditching methods, delineation of borrow materials, winter workpad considerations, design of construction facilities, compressor stations and permanent airstrips and roads if necessary.

Of particular interest is the relationship between soil properties and the ability to use certain ditching methods during construction. There are major economic and engineering advantages to the use of wheeled ditchers for excavating the pipeline trench. The width of the disturbed area can be better controlled, and a backfill of more uniform size can be replaced over the pipe during backfilling. The production rates for wheeled ditchers appear to correlate strongly with soil type, ice content and the geological origin of the soil deposit (Saunders, 1989). Glacial tills with large cobbles and boulders caused the most dramatic reduction in ditching production rates. Experience from the Norman Wells pipeline indicate that some of these variables can be used to better estimate anticipated ditching performance, and therefore better optimize the size of construction spreads and equipment utilization.

FROST HEAVE DESIGN

The frost heave issue for buried pipelines centres around the fact that a chilled pipe will cause a "bulb" of frozen soil to form around the pipe, and that ice lenses may form due to water attracted to the freezing front. Frost heave in itself is not of great consequence to the pipe, but rather it is differential frost heave that poses a concern, and forms the basis for pipeline design in such areas. Differential frost heave could result from a change in soil types (*textural transition*) , or may result from a change from frozen to unfrozen ground (*thermal transition*). Because the frozen ground on the frozen, or stable, side of a thermal transition may offer a stiffer restraint to upward pipe movement, the thermal transition would appear to form a more extreme design case.

A typical design approach to the frost heave problem is illustrated on Figure 6. The pipe structural problem may be analysed by one of several commercially programs, which are capable of handling the non-linear, elastic-plastic behavior of the steel pipe. The minimum wall thickness of the pipe is established using well-defined methods that use the internal pressure in the pipe, steel grade and the temperature difference between tie-in and operating temperatures. Under these conditions, the stress in the pipe is maintained at some level below the elastic limit. Pipe structural analysis for frost heave or settlement is then carried out incorporating the additional deformations resulting from heave or

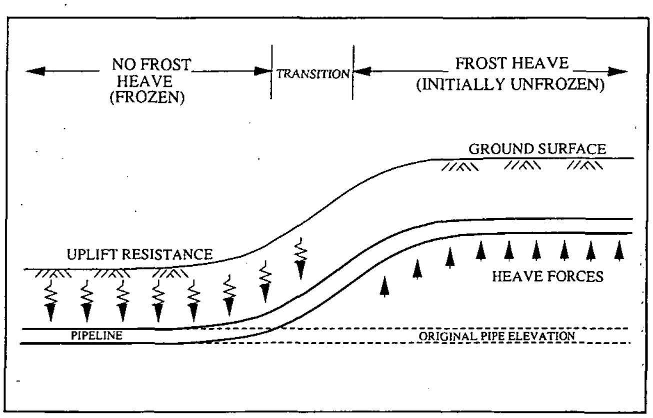


Figure 6. Differential frost heave of buried pipeline.

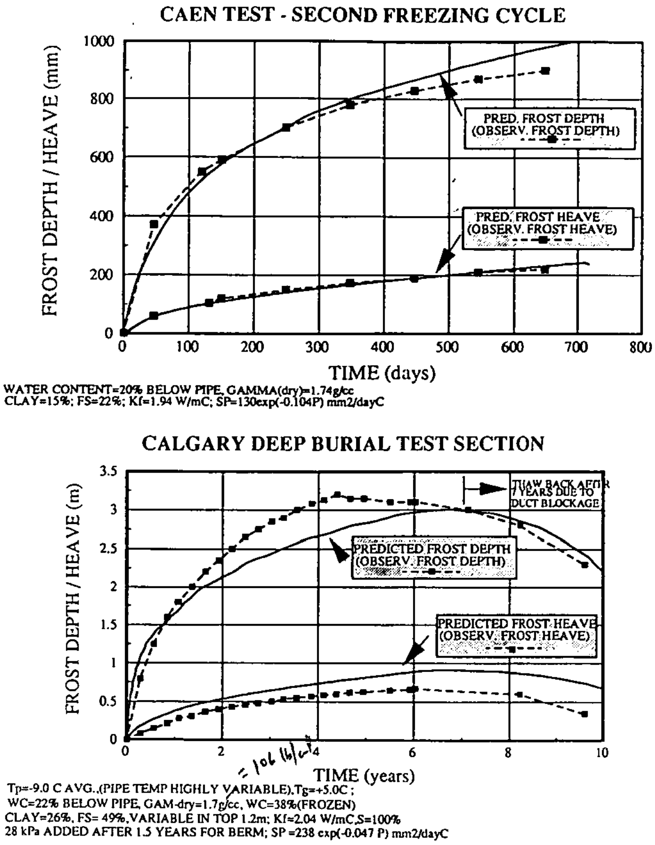


Figure 7. Comparison of predicted frost heave with results from 2 test sites.

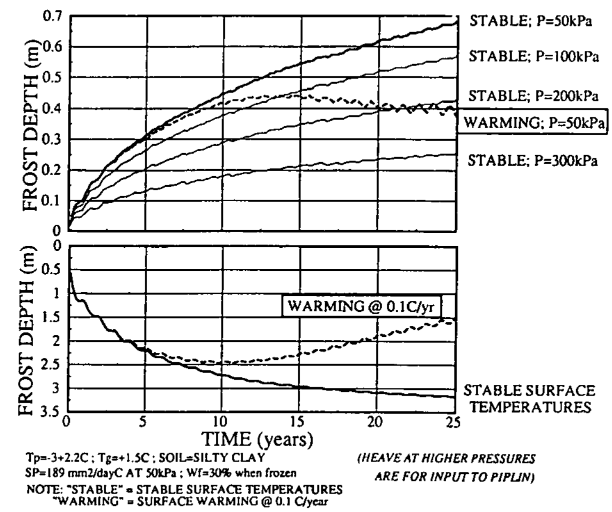


Figure 8. Predicted frost depth and heave for typical soil and pipe conditions.

settlement. The structural program models the inelastic properties of the steel. Some allowable strain limit greater than the elastic limit is selected to maintain an adequate margin of safety against overstraining the pipe. The allowable frost heave for a given set of soil and pipe conditions is established by increasing the frost heave until the strain in the pipe wall equals the previously established strain limit.

The primary inputs to the frost heave structural analysis are the predicted amount of frost heave with time, and its dependency on pressure, and the uplift resistance exerted by the frozen backfill to upward pipe movement (see Figure 6). The amount of frost heave has been the subject of considerable study in the past, and a summary of the available methods of estimating frost heave is given in Nixon (1987). The Segregation Potential method of Konrad & Morgenstern (1982) appears to be capable under simulated field conditions of providing predictions of frost heave to a satisfactory level of engineering accuracy. The Segregation Potential and its dependency on pressure can be correlated with soil properties such as grain size and water content. The method has been used to compare predictions with published test site observations in Calgary and Caen by Nixon (1984), and can be calibrated in the future against other proprietary test site results, when available. Agreement with observation is good, as shown on Figure 7, and the method holds promise for predicting unrestrained frost heave in a wider variety of soil types.

To illustrate predicted results for a typical practical pipeline situation, the geothermal model of Nixon(1986) was used to carry out a set of frost heave predictions using the SP method, and SP input parameters for a highly frost susceptible silty clay such as the Calgary test site soil, as shown on Figure 8. The pipe temperature has a mean value of -3 °C, but varies seasonally with an amplitude of 2.2 °C. This results in seasonal thawback and advance of the frost front for the conditions assumed. Heave rates can be calculated for different soil pressures on the base of the frost bulb, and can then be fitted to a function of pressure and time for input to the structural pipeline analysis.

The uplift resistance required for input to the analysis can be estimated based on various mechanisms including creep of the pipe through frozen soil, or by cracking of the frozen soil adjacent to the pipe, followed by flexural creep in the frozen soil on either side of the pipe (Nixon *et al*, 1984). It may be important to model the seasonal reductions in uplift resistance that occur due to surface warming or thaw in the backfill over the pipe in summer. In this way, the resistance to upward pipe movement is reduced each year, allowing some relief of the strains and curvatures built up in the pipe. Current computer programs also have the capability to model the viscous creep response of a loaded pipe buried in frozen soil, and this may also be important in reducing the uplift resistance as frost heaving develops gradually over long time periods.

A frost heave design may result from a series of computer simulations using a structural analysis such as PIPLIN, in the form of a relationship between allowable frost heave and pipe wall thickness, for example. Pipe wall thickness is a very effective method of accommodating for soil loads such as frost heave or thaw settlement. The potential for frost heave within each of the major geological terrain units must then be assessed, depending on the soil and pipe operating conditions. The wall thickness of the pipe can then be selected to resist the likely differential frost heave that may occur within a geologically similar terrain unit. Differential frost heave is normally taken conservatively equal to the total frost heave within the unit, due to possible presence of a sudden change in soil type or the existence of a thermal transition from frozen to thawed soil. It is generally accepted that it is not possible to know the location of each and every thermal transition or soil type boundary in advance of construction, so the pipeline in any unit must be capable of withstanding loads resulting from frost heave at any location within the geological unit, or units under consideration.

Thaw settlement design

Much of the pipeline may be operated at temperatures well above freezing. Where the ground is initially frozen, a thaw bulb will develop around the warm pipe, and some settlement may result if the ground contains ice in excess of its normal water content.

Using the existing 11 000 borehole records in the Mackenzie Valley, it is possible to build up an extensive data base for the likely terrain properties and expected thaw settlement within each terrain unit. These predicted thaw settlement values can be compared with observed settlements beneath the Norman Wells pipeline, and also against settlements along old clearings and cut lines, where thaw has taken place many years ago. An important study by Collins and Morgenstern (1989) showed qualitatively how the extreme high and low values of one-dimensional thaw settlement within the ground would tend to be averaged out, resulting in a smoothed or damped surface expression of thaw settlement. Further study of this nature may be required in order to evaluate the beneficial of arching within the thawing ground itself.

Again, as in the case of frost heave, thaw settlement only becomes a concern to the pipe where differential settlement occurs over relatively short distances of less than 30m or so. The pipe must then span between the stable areas, carrying the downward gravity load of the soil over the pipe in the intervening settling areas. The geotechnical input to the pipe structural analysis involves calculating a load to represent the downward weight of settling backfill over the pipe, together with an allowance for side-shear between the backfill and the surrounding settling soil. In addition, the load-displacement functions describing the response of the stable soil support in the non-settling section are of particular importance. These are calculated using conventional soil mechanics methods of bearing capacity and deformation in soils. Some of the various forces acting on the pipe can be idealized and represented as shown on Figure 9.

A pipe structural analysis is carried out using the same computer program as used for frost heave analysis, by increasing the thaw settlement until some tolerable pipe strain limit is achieved. The resulting thaw settlement is then the allowable settlement for that set of conditions. The results of a series of such structural analyses can be incorporated into a thaw settlement design summary, that relates allowable thaw settlement to pipe wall thickness, for example. As in the case of the design of the Norman Wells pipeline, it is often found that relatively modest increases in wall thickness can result in significant increases in allowable thaw settlement (Nixon *et al*, 1984). The pipe design then revolves around selecting a wall thickness that will withstand the thaw settlement that is anticipated for a terrain unit, or group of terrain units through which the pipeline will pass.

A review of published analyses for allowable frost heave and thaw settlement (Kaustinen, 1986; Workman,1985) indicates that allowable frost heave appears to be typically about one-half of the allowable thaw settlement, all other factors being equal. Therefore, it would appear that pipeline design from a pipe integrity viewpoint should favour thaw settlement over frost heave, as the geotechnical loadings generated during thaw settlement are generally lower and more compliant than those generated during frost heave. However, limited frost heave over a small proportion of the route may prove quite tolerable and economically attractive for some operating conditions.

Climatic warming

It is beyond the scope of this paper to discuss the potential for climatic warming, and the rate at which it might occur. Etkin (1989) has reviewed the evidence and predictions for climatic warming for the next century, and although the recent historical observed rates of warming may not support this, a warming rate of 0.1 °C/year appears to provide an upper bound to the near future ambient air warming rates (Nixon, 1990). The rate of surface temperature increase is more difficult to predict, as the surface temperature is also a function of changing snow and vegetative cover that could also accompany climatic change. However, for present illustrative purposes, the surface temperature might be assumed to increase 1 °C per decade, in order to assess the effects on a gas pipeline in a preliminary way.

Surface warming was incorporated in the geothermal model described earlier by the simple addition of a time-dependent term to the surface temperature input. The effects of surface temperature warming on "secondary" or

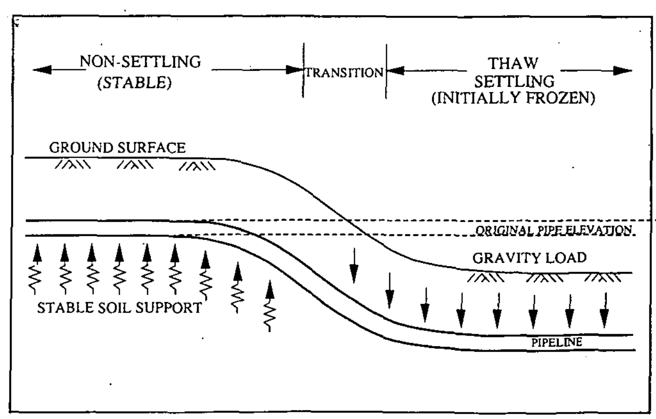
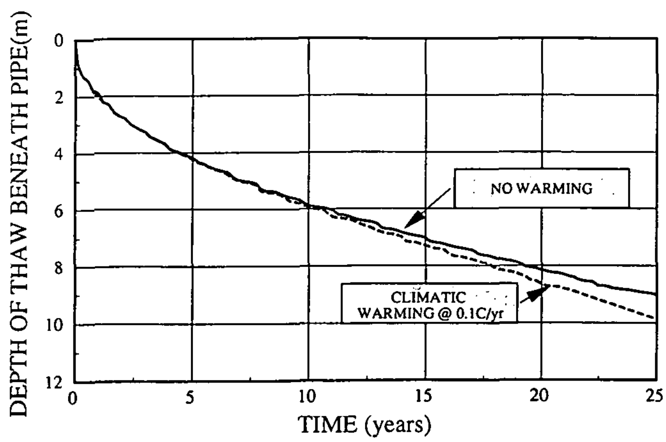
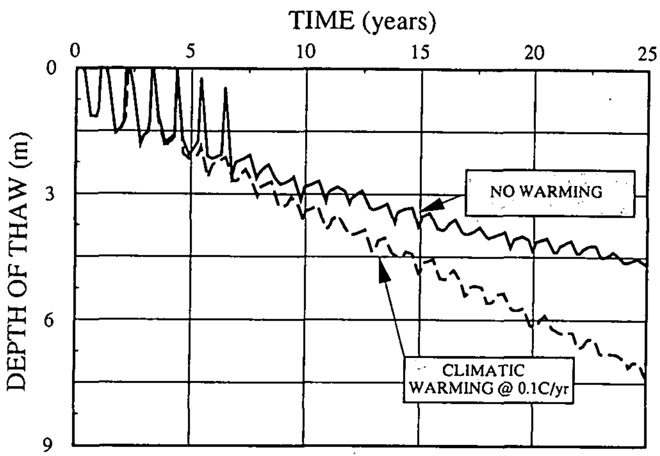


Figure 9. Differential thaw settlement of buried pipe in permafrost.



Tg = -1 C; SOIL = SILTY CLAY AT 25% W.C.
PIPE BASE AT 1.8m; PIPE TEMP=+10C; PIPE DIAM=0.91m

Figure 10. Predicted centre-line thaw depth beneath 10C pipe in warm permafrost.



Tg = -1C ; SOIL = SILTY CLAY, W.C.=25%
0.3 m OF SURFACE PEAT

Figure 11. Effect of climatic warming on cleared R.O.W in warm permafrost.

continuing frost heave has been included on Figure 4, and the simulation indicates a modest increase in the rate of continuing heave over a 25-year period. The effects on the predicted frost heave are more interesting, and are included with the pipe frost heave predictions on Figure 8. The depth of frost approaches equilibrium after 10 years for the pipe temperature considered, and in fact starts to retreat gradually from that time onwards under the influence of surface warming. The corresponding frost heave rises to a peak after about 10 years, and then remains at a constant or slightly diminishing level thereafter.

Figure 10 indicates that only minor effects would be noticed beneath a warm pipeline, where the thermal effects of the pipe tend to overpower the effects of surface warming generated at the ground surface. The effects of warming beneath a disturbed ROW are more pronounced, however. Figure 11 shows a one-dimensional prediction for long-term thaw beneath a cleared or disturbed area in discontinuous permafrost. Because the heat flux causing thaw is quite small in the first place, the increased heat flow that could occur from climatic warming may be significant in hastening thaw of the underlying soil, and possibly the related slope stability issues.

In summary, surface warming due to changing climate may be important in cases where the permafrost is sensitive to small changes in heat flux entering the ground, but does not appear to be significant where the effects of the pipe are dominant in the ground thermal regime.

Monitoring

The ability to monitor the response of a buried pipeline to geotechnical processes such as frost heave and thaw settlement is an important part of pipeline design. Recent developments in pipeline pigging (Adams *et al*, 1989) have provided important new capabilities for detecting anomalies in buried pipelines. Currently, an inertial pig has the capability of acquiring data for up to 7 days travel time in a 300mm or larger operating pipeline, and has an internal power supply, sonar caliper system, an inertial guidance system and a digital recording system. The collected data, when combined with statistical and structural analysis, can provide the pipeline operator with an estimate of changes to the pipeline geometry for predictive and corrective maintenance planning. A developed system has been run successfully through the IPL Norman Wells pipeline, with apparently good results. The inertial pig provides local profile, displacement, curvature and ovality of the operating pipeline.

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