DIFFERENTIAL FROST HEAVE AT PIPELINE-ROAD CROSSINGS

Gerry Ferris

BGC Engineering Inc, 200 – 1121 Centre Street NW,
Calgary, Alberta, Canada, T2E 7K6,
Tel. (403) 250-5185, Fax. (403) 250-5330, gferris@bgcengineering.ca

ABSTRACT

Essentially all areas of Canada are affected by significant seasonal frost penetration. The effect of the frost penetration on roads and highways, especially the amount of total frost heave and the effect of the subsequent thaw, varies with soil type. Road design and construction must consider the effects of frost heave and subsequent spring thaw. The location and amounts of differential frost heave are especially important to pavement performance.

Frost heave behaviour can be manifest at pipeline crossings as “reverse frost heave”, where the ground above the pipeline does not heave as much as the adjacent ground. If the amount of differential heave within pipeline crossing is large, it can lead to rough, and potentially unsafe, driving conditions. In the case of pipeline crossings, if rough road surface conditions occur in the right of way, highway agencies typically request compensation for additional maintenance costs from the pipeline company.

A case study that shows the effects of differential frost heave at a pipeline road crossing is presented.

INTRODUCTION

Road design in Canada typically requires some consideration of the effects of frost action on the pavement performance. This most typically takes the form of ensuring that the pavement structure is appropriately designed to handle the loading during freeze-thaw cycles, or through the application of spring road bans which limit traffic loading during the spring melt period when the subgrade soil is weaker. Another aspect to be considered as part of the road design is avoidance of differential frost heave, which leads to rough pavement surfaces. One of the potential causes of differential frost heave are utility crossing, this paper concentrates on pipeline road crossings and discusses the problem in general and presents case study results.

BACKGROUND

Almost all areas of Canada are affected by frost penetration to a lesser or greater degree. The major control on the amount of frost penetration is temperature. Figure 1 shows a map of the normal Freezing Index (degree day Fahrenheit) for Canada. The Freezing Index is calculated as the additive number of days below freezing (32ºF) by how many degrees below freezing on that day.

The normal Freezing Index varies from less than 100 degree days Fahrenheit (55 degree days °C) in southwestern British Columbia to 7,500 degree days °F (4,150 degree days °C) in northern Manitoba and Northern Quebec. The majority of Canada's population and the majority of the road and pipeline networks are located south of the 4,000 degree days °F limit.

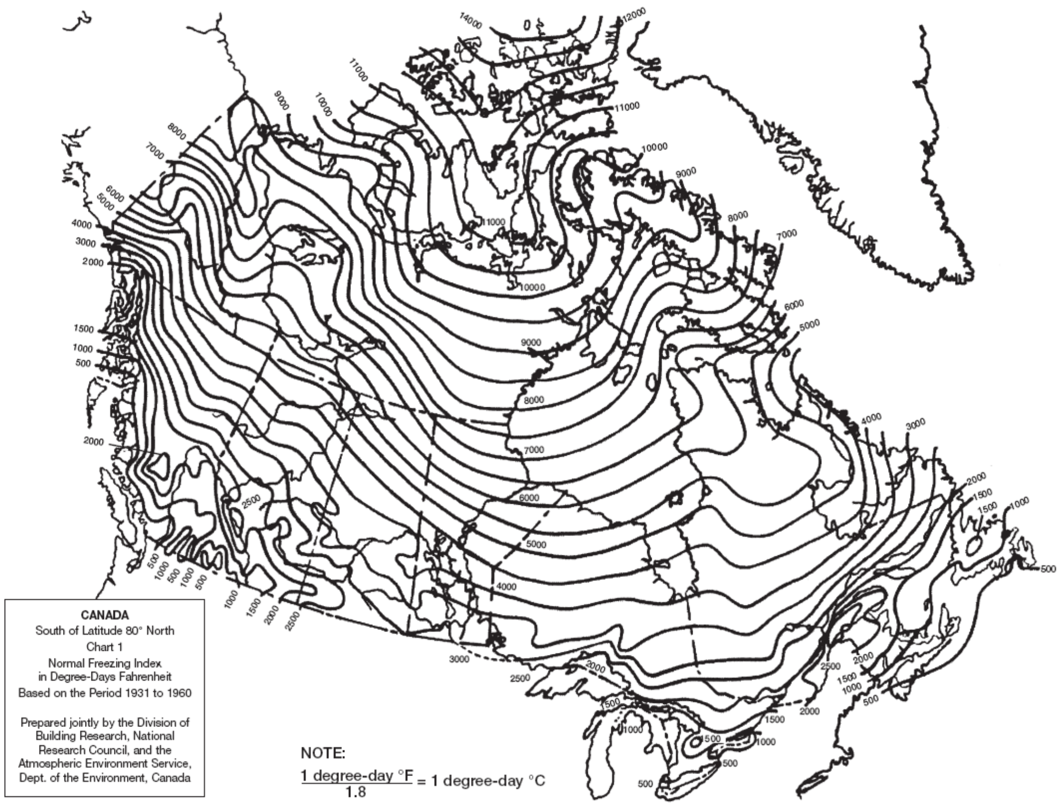

Figure 1 Normal Freezing Index for Canada in degree days Fahrenheit based on the period 1931 to 1960 (CBD 182)

If only a bare ground condition is considered, a correlation between Freezing Index and frost penetration can be demonstrated, Figure 2. Based on this correlation and the Freezing Index from Figure 1, frost penetration throughout the most populated areas of Canada can be expected to vary from about 0.25 m to 3.0 m.

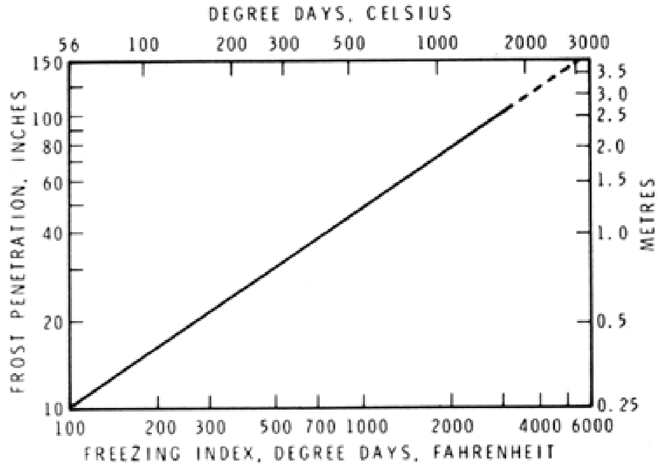

Figure 2 Relation between Freezing Index and depth of frost penetration (CBD 182).

The depth of frost penetration is largely determined by the rate of heat loss from the soil surface. Air temperature has the largest influence on frost penetration (as shown in Figure 2), however other climatic factors such as solar radiation, snow cover, and wind also have an influence. Additionally, the physical and thermal properties of the soil affect the depth of frost penetration. These factors combined can significantly affect the frost penetration and correlations such as the one show in Figure 2 should be used for general guidance only.

For frost heave to occur, three basic conditions must be satisfied: the soil must be frost-susceptible; water must be available in sufficient quantities; and temperature conditions must cause soil and water to freeze.

Frost-susceptibility of soil is related to the size distribution of soil particles and specific surface area of the fines (<0.075 mm) fraction (Konrad 2000). In general, coarse-grained soils such as coarse sands and gravels do not heave, whereas clays, silts and very fine sands will support the growth of ice lenses even when present in small proportions in coarse soils.

Water must be available in the unfrozen soil for movement to the freezing plane where the growth of ice lenses occurs. A high groundwater table with respect to the location of the ice lenses will therefore favour frost heave.

ROAD DESIGN IN SEASONAL FROST AREAS

The design of roadways in Canada and the United States for areas of seasonal frost is typically based on empirical design methods, such as AASHTO (C-SHRP 2002). Consideration of the effects of frost penetration and thaw weakening is typically based on empirical correlations of the Department of Transportation and the judgment of the design engineer (C-SHRP 2002 and Smith 2006).

If frost-susceptible soils are present in the subgrade of the road section, frost heave, thaw weakening and freeze-thaw cycling can cause substantial damage to roads (Andersland and Ladanyi 2004). In addition to distress on the pavement structure differential icing and differential heave can cause considerable problems for winter driving.

CULVERT ANALOGY

Culverts placed under pavements in frost susceptible subgrades frequently experience differential frost heaving (St. Pierre 2006).

Differential heave at the pavement surface occurs in two ways, as shown in Figure 3. Water flow in a culvert will provide a heat source to the soil, thereby preventing soil freezing below the culvert. This will reduce the surface heave (which could result in a depression) directly above the culvert. A dry culvert will allow greater frost penetration due to the cold air blowing through the culvert during the winter season, resulting in a larger differential frost heave at the surface (bump). It is more usual that a depression will occur above the culvert (St. Pierre 2006). The effect of a warm culvert is thought to be a good analogy for a pipeline crossing.

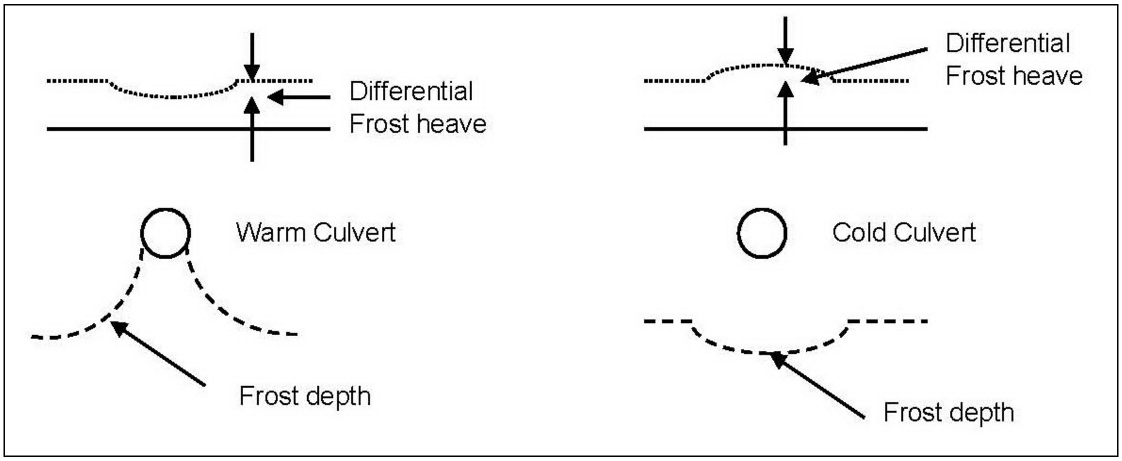

Figure 3 Differential frost heave caused by culverts
(after Andersland and Landayi 2004)

PIPELINE CROSSINGS

Canadian code (CSA Z622) for the installation of pipeline crossings require that a pipeline be installed a minimum depth of 0.75 m below the base of a ditch and 1.2 m below the traveled surface.

Additionally the code requires:

- The backfill of any open-cut crossing shall be performed in such a manner that neither the pipe or the pipe coating is damaged by the backfill material or subsequent surface activities.
- Backfill procedures shall not cause distortion of the pipe cross-section that would be detrimental to the operation of the pipe or passage of cleaning or internal inspection devices.
- Backfilling shall be performed in such a manner as to prevent excessive subsidence or erosion of the backfill and support material.
- Backfill shall be compacted adequately to prevent settlement detrimental to the facility being crossed.

The code does not specifically address the effects of frost heaving and the literature on the effects of pipelines on pavement structure is very limited, the literature on the effects of culvert crossings on pavement structure is similarly limited. The effect of a warm pipeline on the road surface during the winter can be very similar to that of a warm culvert. As shown in Figure 4, this can result in a crack in the pavement directly above the pipeline. If the differential heave is significant enough it will lead to rough, then unsafe, driving conditions.

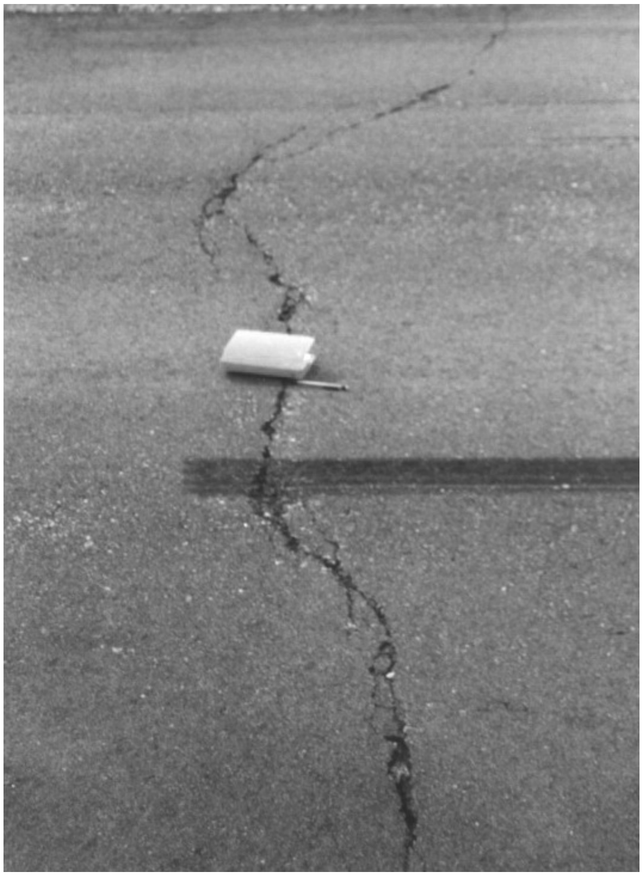

Figure 4 Surface Cracking at a Pipeline Crossing

Historically, most pipeline road crossings were constructed via open cut. The current trend in Canada is to install pipelines at highways and other road crossings locations via horizontal boring, augering and jacking (trenchless technology). This change has been largely driven by environmental and permitting issues. This change is also thought to reduce the effects of differential frost heave at the crossing.

FROST HEAVE AND HIGHWAYS

Frost heaving occurs in locations where ice lenses form during the freezing process. The heave is caused by the formation of ice lenses parallel to the freezing plane with the direction of the frost heave perpendicular to this plane (Konrad 1994). The condition of seasonal frost penetration occurs in nearly all parts of Canada; therefore the potential for frost heave is typically related to the presence of a water supply and having frost susceptible soils. It should be noted that in areas where frost susceptible soils are present the soils can supply water to the freezing front through the process of capillarity even if the depth to the water table is considerable.

The amount of frost heave varies considerably with climate effects and pavement design. The typical methods employed by highway agencies to mitigate the effects of frost heaving on roads consist of;

- partial replacement of the frost susceptible soils with non frost susceptible soils within the depth of frost penetration,
- complete replacement of frost susceptible soils with non frost susceptible soils within the depth of frost penetration,
- placement of insulation to reduce the depth of frost penetration, which in turn limits the amount of heave, and
- provision for drainage.

The amount of frost heave under similar climate and moisture conditions is related to soil properties. The United States Army Corps of Engineers published a 1985 version of a correlation between soil type, percentage of soil weight smaller than 0.02 mm and frost heave rate (Andersland and Ladanyi 2004). This rating system only provides a rough guide for initial frost heave, and generally requires that the soil in question be tested in a frost heave test to determine heave rates for the particular soil.

An alternative approach is to determine the Segregation Potential (SP) of the soil. SP is defined as the ratio of frost heave rate to the temperature gradient in the frozen soil. The SP (Konrad and Morgenstern 1981) varies with the soil type and overburden pressure, but when it is combined with the rate of freezing (from thermal modeling) it can be used to determine total heave. The SP concept has been used successfully to predict the frost-heaving effect related to chilled pipelines and artificial ground freezing (Konrad 1994).

Typical ranges of SP for silty sand, sandy silts and tills are 0 to 60 mm^2/day ºC. For clays and clayey silts the SP ranges from 43 to 175 mm^2/day ºC. Recently Konrad has provided methods to estimate the SP of soils based on other more standard soil classifications and index testing for various soils (Konrad 1999) and specifically for fine grained soil (Konrad 2005). With the estimated (or measured) SP value and frost penetration modeling predictions of total frost heave can be made. To make accurate predictions of frost heave amounts many factors need to be considered; such as rate of frost penetration, amount of non-frost susceptible soils within the profile, overburden pressure, suction pressures within the capillary fringe and a determination if the saturation is less than 70% to fully model the heave expected (Konrad and Roy 2000). Some measured total heave at different highways in Quebec has been presented in the literature (Konrad 1994, Konrad and Roy 2000), as shown in Table 1.

Table 1 Measured Heave at Various Highways in Quebec.

Location	Total Heave (mm)	Segregation Potential (mm^2/ºC-day)
Highway 122	50	43
Desrocher Street	40	80, 53, 33
Road 161	50 to 100	20, 10, 30

A correlation between SP and the expected frost heave, for typical Quebec highways, was developed (Konrad 2000) for screening of potential heave determinations and is shown in Table 2.

Table 2 Anticipated Heave with Respect to Segregation Potential

Segregation Potential (mm^2/ºC-day)	Anticipated Heave (mm)
Less than 100	Low (less than 30)
Between 100 and 200	Medium (less than 60)
Greater than 200	High (greater than 60)

These measured and typically predicted frost heave amounts need to be compared to the allowable differential heave for highways. Typically, the maximum allowable differential heave is based on if a driver would "feel" the variations when driving at the speed limit (C-SHRP 1999). For a newly constructed asphalt pavement the maximum differential elevation within a "bump" on the pavement surface is between 8 to 13 mm (C-SHRP 1999). Based on this, for this paper the maximum allowable differential elevation within a pipeline crossing is estimated to be somewhere between 13 and 25 mm, which is twice the allowable range for newly constructed highways. From these guidelines it is apparent that differential frost heave at a pipeline crossing could be an issue if:

- No heaving occurs above a pipeline and the heave of the surrounding soil is more than about 13 to 25 mm.
- The heat induced in to the ground by the pipeline is enough to reduce the heave above the pipeline such that the differential heave is in the 13 to 25 mm range.

CASE STUDY

A study was undertaken at five separate pipeline road crossings that showed evidence of differential frost heave occurring within the pipeline right of way. A typical photograph showing the differential heave in one of the crossings is shown in Figure 5. All of the sites were located adjacent to wet ground such as sloughs or peat, so the sites had both cold conditions and access to water. Four of the sites were gravel pavement and one site had asphalt pavement.

The study included the following elements; visual inspection of the crossing, collection of soil samples, laboratory testing of samples, determining pipeline temperatures, review of past repairs at the crossings and a detailed survey program of the surface of the road through the crossing. The surface of the road was surveyed using a total station on three separate occasions throughout the winter. At each crossing three different road surface profiles were measured; the centre of the right lane, the centerline of the road and the centre of the left lane. The survey of each of these profiles was done at a 0.3 m spacing, the location was marked during the first survey event and were re-measured in the two follow-up monitoring events. Figure 6 shows the data obtained from one of the sites, on the road centre line, right lane and left lane. The differential heave shown at this particular location is about 130 mm.

Note that in Figure 6 the pipeline is located at distance 17.5 m. For the centerline profile road surface is at elevation 273.884 m.

Figure 5 Differential Heaving of a road within a pipeline ROW

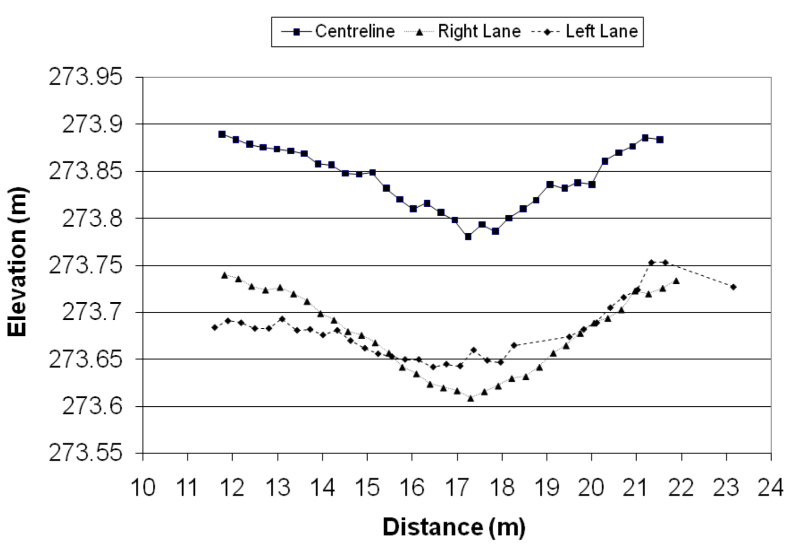

Figure 6 Crossing profiles showing differential heave

Similar surveys were undertaken at each of the five sites. The results of the survey are shown in Table 3, which indicates the average differential heave that was measured at each site (the maximum differential from each of the three different profiles).

Table 3 Differential Heave at the Study Sites

Site	Differential Heave (mm)
Gravel Pavement	140, 96, 86, 66
Asphalt Pavement	50

All the sites in this study were within the same geological area and had subgrade soil that varied between:

- SILT, some clay, trace sand, trace gravel, having a natural water content of 17.1% with a plastic limit of 18 and the liquid limit 24
- Silty CLAY, some sand, trace gravel, having a natural water content of 53.5% with a plastic limit of 20 and a liquid limit 42.

At two of the five sites it was confirmed (based on notes made by an inspector during construction) that the pipeline installation was performed using open cut methods. As part of this installation the pipeline trench was backfilled with a course sand and gravel. It is suspected that this was the installation method at all five of the crossings, since they were constructed in sequence in one construction season.

Based on the literature of measured total heave at different highways, it appears that the backfill material used for these pipeline installations was non-frost susceptible and that the differential heave measured actually represents the total heave at these locations, with no heave occurring directly above the pipeline. This meant that the pipeline temperature would have little influence on the amount of differential heave, but that the main issue was the total heave of the soil not replaced by the pipeline trench.

Using the methodology for estimating SP for fine grained soil (Konrad 2005) the estimated SP for these sites are (the necessary data was available for only three of the five sites): 250, 305 and 400 mm^2/ºC-day. From examination of Table 2, the predicted total heave for these sites should be greater than 60 mm. It must be noted that Table 2 was developed for the climate conditions encountered in Quebec and is thought to be valid for similar climate conditions. Figure 7 plots the estimated SP and the measured total (and differential) heave at the three study sites with the general categories predicted by Konrad, from Table 2, relating anticipated heave to SP. Also shown on this plot are results relating SP to total heave as measured by Konrad (from Table 2) for the Quebec sites.

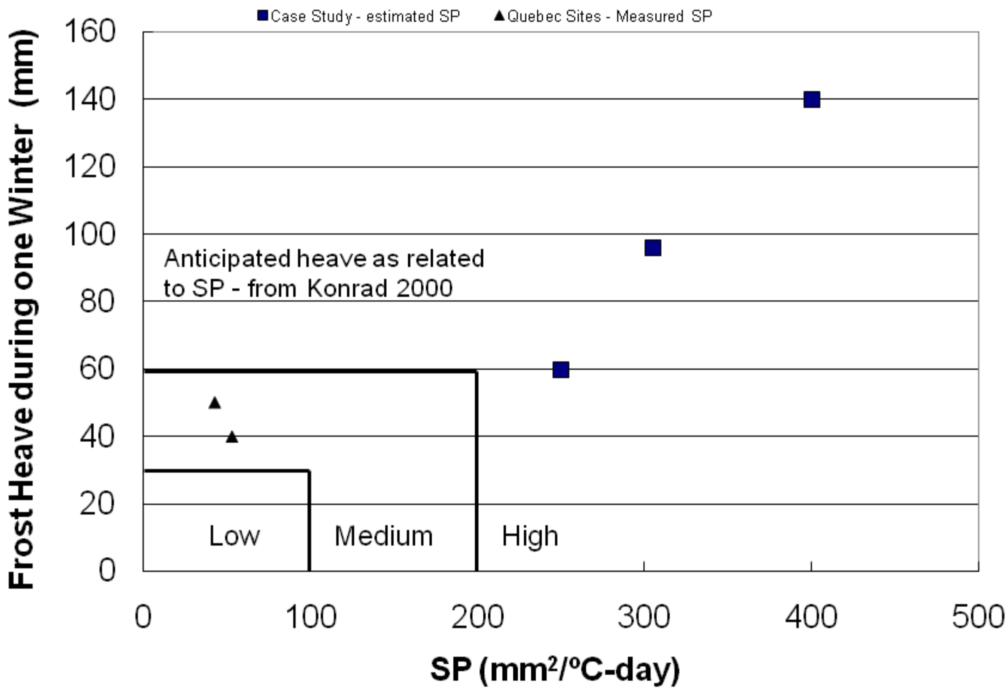

Figure 7 Case study results relating estimated SP versus measured heave

The amount of differential heave occurring at these crossings is between double to four times the expected allowable maximum by highway authorities. Thus, it is expected that in order to produce an acceptable pavement during the winter period the highway department will have to complete repairs at these crossings. Based on the information it appears that the cause of measured differential heave is twofold: the presence of highly frost susceptible soils and an installation procedure that replaced the frost susceptible soil with a non-frost susceptible soil. This has created a situation where differential frost heave occurs during the winter period.

SUMMARY

This paper presents a case study of differential frost heave occurring at five different pipeline road crossings. The differential heave measured at these crossings ranged from 50 to 140 mm. This amount of heave is significantly greater than the range of local elevation variance thought to be allowable by highway authorities, of between 13 and 25 mm.

The pipelines were generally installed by the open cut method and the backfill used appears to have been completed using non frost susceptible soils. The differential heave measured at these crossings is thought to be the total frost heave of highly frost susceptible material as compared to no heave occurring directly above the pipeline.

REFERENCES

Andersland, O.B. and Ladanyi, B. 2004 Frozen Ground Engineering, 2nd Edition, John Wiley & Sons, Inc. New Jersey

Canadian Standard Association Z662 Oil and Base Pipeline systems

Canadian Building Digest (CBD) CBD-182 Frost Action and Foundations http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd182_e.html

Canadian Strategic Highway Research Program (C-SHRP) 2002 Pavement Structural Design Practices Across Canada C-SHRP Technical Brief #23

Canadian Strategic Highway Research Program (C-SHRP) 1999 Summary of Pavement Smoothness Specifications in Canada and Around the World. C-SHRP Technical Brief #16

Konrad, J.M. and Morgenstern, N.R. 1981 The segregation potential of a freezing soil. Canadian Geotechnical Journal; 18, pp. 482-491

Konrad, J.M. 1994 Sixteenth Canadian Geotechnical Colloquium: Frost Heave in Soils: Concepts and Engineering. Canadian Geotechnical Journal; 31, pp. 223-245

Konrad, J.M. 1999 Frost susceptibility related to soil index properties. Canadian Geotechnical Journal; 36: 403-417

Konrad, J.M. and Roy, M. 2000 Flexible Pavements in cold regions: a geotechnical perspective. Canadian Geotechnical Journal; 37: 689-699

Konrad, J.M 2000 Assessment of Subgrade Frost Susceptibility from Soil Index Properties. In Ground Freezing 2000: Proceedings of the International Symposium on Ground Freezing and Frost Action in Soils, Universite-Catholica de Louvain, Belgium, 2000, pp.89-94

Konrad, J.M. 2005 Estimation of the segregation potential of fine-grained soils using the frost heave response of two reference soils. Canadian Geotechnical Journal; 42, pp. 38-50

Smith, B.S. 2006 Design and Construction of Pavements in Cold Regions: State of the Practice. Unpublished M.Sc. thesis submitted to Brigham Young University

St. Pierre, M.A. 2006 Performance of Insulated Shallow Cross Pipes in a Cold Region. Unpublished M.Sc. thesis submitted to University of Maine