Highway embankments on degrading and degraded permafrost

Remblai routier sur permagélisol dégradé ou en dégradation

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ABSTRACT

Global warming is affecting transportation systems in northern Canada. Thawing permafrost and expanding infrastructure systems require improved designs, construction and maintenance. The paper provides information about sampling, testing, instrumentation, and numerical modelling on two instrumented sections of provincial roads in Northern Manitoba.

RÉSUMÉ

Le réchauffement global affecte les systèmes de transport dans le nord du Canada. La fonte du permagélisol ainsi que les demandes croissantes requiert l'amélioration des conceptions, de la construction et de l'entretient. Cet article donne de l'information sur l'échantillonnage, les tests, l'instrumentation et l'analyse numérique sur deux sections instrumentées de routes provinciales dans le nord du Manitoba.

Keywords: permafrost, degrading, highways, instrumentation, temperatures, settlements, modelling.

1 INTRODUCTION

Global warming affects civil engineering infrastructure substantially, especially in cold climates with regions of permafrost. This is particularly true where the permafrost is locally discontinuous, usually in areas with mean annual temperatures close to 0ºC. In these locations, thawing may produce large and irregular settlements.

About one-fifth of the land area of the earth is underlain by permafrost. Its characteristics are controlled by climatic, topographic, geographic, hydrologic and geological factors. Its thickness depends on conditions in the active layer where temperatures change seasonally, the insulating cover of vegetation and snow, drainage, thermal properties of soil and rock, and the complex boundary layer between soil and air (Osterkamp and Lachenbruch 1990). Changes in meteorological conditions, rain and snow precipitation, solar radiation, wind speed and other factors induce changes in temperatures at the ground surface and at greater depths.

Frozen soil is stronger and less compressible than unfrozen soil. Frozen silty sands, silts, and silty clays frequently also contain layers of ice that form as a result of water migration to negative water potentials at the freezing front (Konrad 2008). If thawing occurs, either as a result of warming climate or engineering activity, ice lenses melt and water moves towards the ground surface. The resulting decreases in effective stress cause weakening and deformations in foundations for buildings and pipelines, airport runways, rail beds, and highway sub-bases, cuts and fills. Out-migration of water often produces irregular settlements that lead to serviceability issues. Roads and runways remove vegetation cover, affect snow cover, increase heat transfer, and affect drainage patterns. They therefore contribute significantly to disturbance of discontinuous permafrost.

Northern Canada is home to First Nations people and rich in mineral, petrocarbon and hydroelectric resources. In Manitoba (MB), discontinuous permafrost is encountered (Figure 1) north of an isotherm that corresponds approximately to a mean annual air temperature of 0ºC (about 2500 ºC-days of frost). It becomes continuous further north, near the Hudson Bay coast. Road, rail and air communications are essential in the North and are becoming increasingly important with further resource development. Thawing of summer ice in the Arctic Ocean may lead to increased shipping into Churchill. Additional roads and railways will have to be constructed over already poor soils with engineering properties that may degrade further with climate and land-use changes.

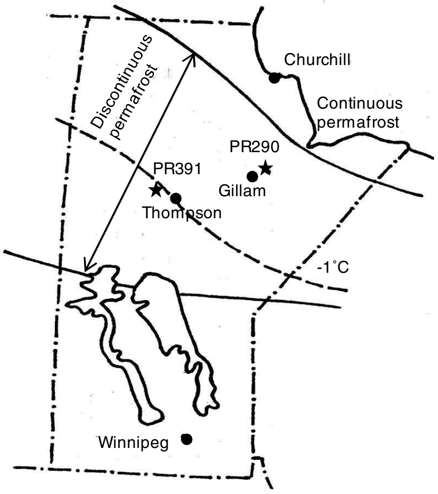

Figure 1. Locations of test sites and extent of permafrost in Manitoba, Canada.

Construction of highway fills in Northern Manitoba follows the same practices as those in warmer regions. The fills generally have high thermal conductivity, leading to heat transfer into underlying layers and thawing of previously frozen foundation soil. Asphalt surfacing absorbs heat from the sun and transfers it to the embankment. Generally, degradation of permafrost begins at the toe of embankments. Melting reduces strength and increases pore-water pressures when the hydraulic conductivity of the foundation soil is low. This leads to differential settlements, lateral spreading, and instability.

In order to produce improved design and maintenance procedures, Manitoba Infrastructure and Transportation (MIT) have undertaken an extensive research program that involves field instrumentation, laboratory testing and numerical

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modelling. This paper reports work on two sites in a region of discontinuous permafrost near Thompson, Manitoba, about 800 km north of Winnipeg (Figure 1).

2 PROVINCIAL ROAD PR290

2.1 *Location and stratigraphy*

The first study site is on PR290, north-east of Gillam, MB. Instrumentation consisted of thermistor strings to track temperature changes at various depths. Soil properties were determined from samples taken from the site, supplemented by additional information from the region. The site exhibits characteristics typical of road embankments constructed over degrading permafrost. These include poor drainage, settlements, longitudinal splitting, and loss of shoulder support.

The site conditions consist of 1.5 – 4m of coarse-grained embankment fill over 0 – 1m of peat above 6 – 8m of highly plastic clay. Drilling was ended at depths of 6 - 12m before reaching bedrock. Frozen soil was found intermittently in some, but not all, boreholes. Original construction records showed higher prevalence of frozen soil. The ground water table was almost at the ground surface. Classification information, including water contents, Atterberg limits, visual descriptions, etc. are available but are not reported here. The temperature range in the area (Figure 2) is considerable, with extreme values reaching +25ºC in summer and -40ºC in winter.

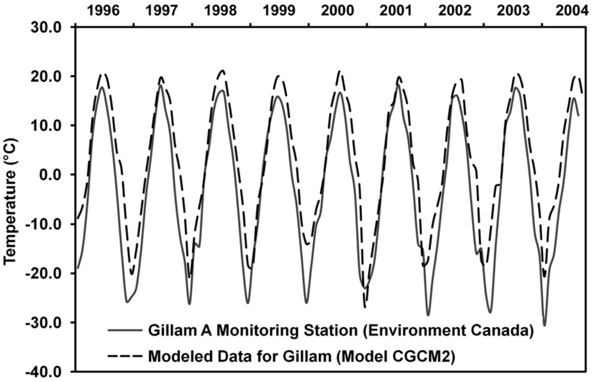

Figure 2. Measured and simulated (averaged) air temperatures, Gillam A Station, Model CGCM2, A2

2.2 *Temperature modelling*

Numerical modelling can provide information for developing innovative design and construction techniques for road embankments on discontinuous permafrost. The modelling in this project used TEMP/W (from GeoSlope International Inc). This finite element (FE) code can simulate thermal changes caused by climatic changes or by new construction that alters the thermal regime. Boundary conditions for 2-D modelling were as follows. The bottom of the cross-section was a constant temperature boundary at 0.5ºC at 9m depth below ground surface. The sides were assumed to be no-flux boundaries, with the FE mesh extended far enough to make heat flow essentially vertical. An empirical approach was used for the upper boundary at the ground-air interface (Andersland and Ladanyi 2004). Simulating the observed ground surface temperatures used separate *n-factor* boundary modifiers for freezing and thawing, as well as records of surface freezing and surface thawing indices (in degree-days) at nearby Gillam. Figure 2 shows measured and simulated air temperatures. The agreement is good.

2.3 *Thermal conductivities*

Thermal conductivity is a measure of the quantity of heat that flows through a unit area in unit time under a unit time gradient. It increases as soil freezes and decreases as it thaws (Farouki 1985). Table 1 shows values of the frozen and unfrozen thermal conductivities used in the modelling. More details are given in Ciro and Alfaro (2005).

Table 1. Frozen and unfrozen thermal conductivities

Material	Frozen thermal conductivity*	Thawed thermal conductivity*
Coarse-grained fill	346	242
Peat	91	36
Clay	173	138

* kJoules/(day.m.ºC)

2.4 *Calibration*

Strings of thermistors were installed at depths down to 9m at 26 locations along PR290. Results were sufficiently consistent to allow temperature modelling using average conditions. The strings were installed at the north and south toes of the embankments and at the centreline. Ground temperatures were simulated for four times of year when the largest seasonal variations were expected. Figure 3 shows measured and simulated ground temperatures at the embankment toe in a) February, when air temperatures are coldest, and b) July, when air temperatures are hottest. The modelling provides good agreement with measured results, supporting the selections made for the surface flux boundary and material properties.

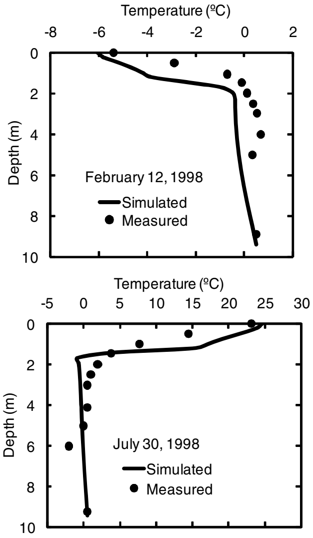

Figure 3. Calibrations for simulations at toe of the embankment

2.5 *Modelling ground temperatures*

A first set of modelling simulated seasonal temperature changes in the cross section under current climatic conditions. Figures 4a,b show distributions of frozen and unfrozen soil in February and November 1998 respectively. After several months of cold weather, the February simulation shows the upper part of the profile, including the embankment, peat, and upper foundation soil to be frozen. Only the soil beneath the active layer is unfrozen. After warming during the summer months, cooler weather in October/November promotes a freezing front to advance downward in the embankment and surrounding ground. There is still, however, a substantial region of unfrozen soil, particularly beneath the toe.

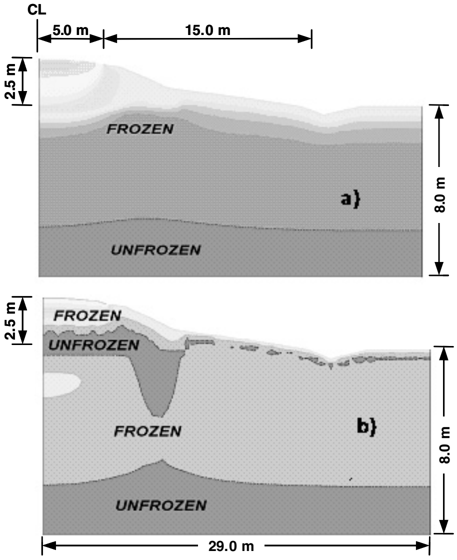

Figure 4. Temperature simulations for a) Feb 1998; b) Nov 1998.

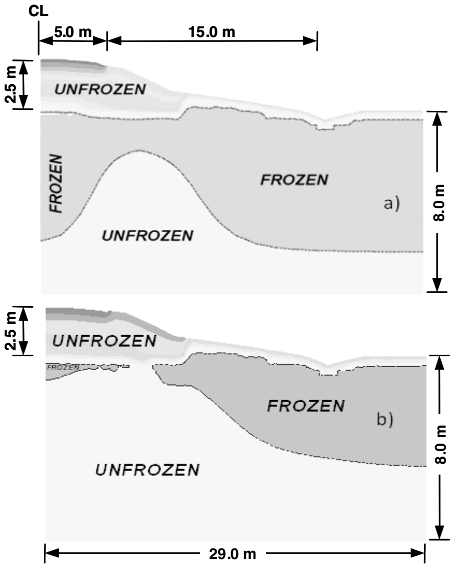

Figure 5. Simulated degradation for a) Jul 2010; b) Jul 2040.

2.6 *Modelling future trends*

Climate-change scenarios can be used to simulate how highway infrastructure may be impacted by global warming. It is important to remember that modelling along these lines represents possible events and not formal predictions. The Canadian Centre for Climate Modelling and Analysis has several models that permit climate prediction, climate change, and variability. This project used the Second Generation Coupled Global Climate Model (CGCM2) because it couples the atmospheric component (AGCM2) with the ocean component and includes the effect of greenhouse gases. The model displays different scenarios (Control, GHG+A, A2 and B1) for different combinations of greenhouse and aerosol gases and initial conditions.

To help select the forcing scenario that would best represent future trends at PR290, previously recorded temperatures were checked against simulations. Scenario A2 produced the best agreement and was used to run simulations of future temperatures, starting from the measured temperatures in 1998. Figures 5 a) and 5 b) show distributions of frozen and unfrozen soil in July 2010 and July 2040, respectively. There are clear decreases (degradation) of the frozen soil throughout the embankment and the foundation soil.

While there may be uncertainty about the rates and magnitudes of climate warming, the trends in Figure 5 seem clear. Warming will continue to thaw permafrost, particularly under the mid-slopes and toes of embankments. This will produce settlements and lateral movements that will require ongoing maintenance if serviceability is to be assured.

3 PROVINCIAL ROAD PR391

3.1 *Location and stratigraphy*

The second site is on PR391 about 18 km north of Thompson (Figure 1). It is the only road connecting Thompson to northern mining towns, hydroelectric generating stations, and First Nations communities in North-western Manitoba. New research at this site involves field instrumentation, laboratory testing, and numerical modelling. Drilling, sampling, and installation of instrumentation were completed in October 2008. The embankment was initially constructed on discontinuous permafrost. Frozen soil was encountered in drilling programs in 1990-91 and 2005. No frozen soil was encountered in the recent drilling in 2008. Changes in heat transfer in the embankment and foundation soils since construction led to thawing and large settlements that caused dangerous trafficability issues.

Responses by MIT included stabilizing berms on both sides of the embankment, high levels of maintenance that added several metres of gravel fill in the past 20 years, and now a research program to provide a better understanding of natural processes operating at the site. The berms settled into the original soil until their tops were close to the neighbouring ground level. They currently provide no additional support to the embankment. The asphalt pavement has not been replaced.

Two sections, about 25m apart, have been instrumented. One 'stable' section, has not settled much, while the second 'unstable' section has settled considerably. ('Stable' and 'unstable' are here used in the sense of a serviceability limit state and not an ultimate limit state.) Soil conditions vary considerably between the two sections. The stable section consisted of over 4m of clayey-silt to silty-clay with peat intrusions varying from thin stratifications to pockets. The unstable section consisted of 1.5m of clayey peat-silt, 1.5m of fine gravel, followed by approximately 14m of soft to very-soft plastic clay. Both sections are underlain by gneissic bedrock. The surrounding area is relatively poorly drained, with free-standing water close to the embankment during most of the year. Attention will be given to upwards or downwards hydraulic gradients.

3.2 *Instrumentation*

Instrument clusters have been installed at the shoulder, mid-slope and toe of both the stable and unstable sections. Figure 6 shows the layout of instruments at the unstable section. The instrumentation includes thermistors at 1 m intervals, vibrating wire piezometers in the clay and standpipes in the till, surface settlement plates, slope inclinometers, and lateral displacement extensometers at the toe of the embankment. Readings are taken bi-weekly on a data acquisition system (DAS) and downloaded manually at the same time as slope indicator readings are taken. Of possible interest is our concern that the DAS will be damaged by snow mobiles or local hunters with rifles.

At the time of writing, data are just beginning to come in. Figure 7 shows temperatures beneath the toe of the embankment on 5 November and 28 November 2008. These early results show that temperatures down to about 4m depth were already beginning to change with the onset of cold winter weather.

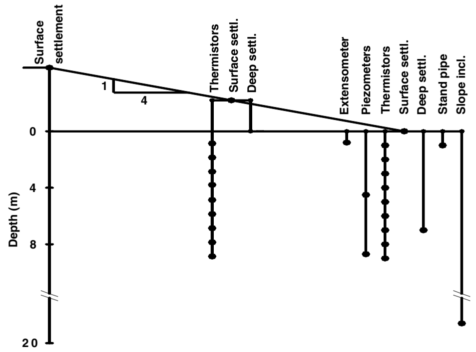

Figure 6. Instrumentation at the unstable section.

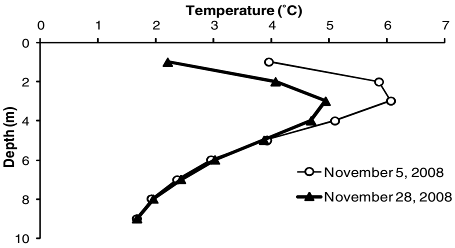

Figure 7. Temperature distribution after installation.

3.3 *Laboratory testing*

Samples collected in October 2008 are still being tested at the time of writing. Of particular interest is the very soft plastic clay found between about 10m and 20m below the unstable embankment. This suggests the presence of high water contents and possibly high water pressures from the formerly frozen soil seen in earlier drilling programs in 1991 and 2005. Alternatively, there may be upwards gradients from the till layer above the bedrock. This will be clarified when pore water pressure readings become available. The laboratory program includes classification tests and stress-deformation testing in oedometer and triaxial equipment.

The emphasis on stress-deformation behaviour is the principal difference between this program at PR391 and the earlier program at PR290, which concentrated on temperature distributions. In particular, we are interested in the effects of different temperatures on stress-deformation behaviour (Graham et al. 2001). The clay is known to be smectitic and to exhibit time-dependent (creep) behaviour that will probably also depend on temperature. Oedometer tests are currently being run at temperatures of 3ºC, 10ºC, and 25ºC to examine the variation of the creep parameter C_α with temperature.

3.4 *Modelling*

Numerical analysis will be done in two phases. In the first, as in PR290, TEMP/W will simulate measured temperature distributions and how they change with time. It is hoped to obtain temperature data over a three-year period, so calibration will be possible over several heating-cooling cycles. Attention will again simulate temperature changes resulting from future climate warming. The foundation soil at PR391 has already thawed so there is little concern about phase changes.

We are also interested in other mechanisms. There is a thin peat layer below the unstable embankment, followed by a thick layer of soft, plastic clay. Both layers will exhibit viscous behaviour that will likely vary with temperature.

Recent years have seen increased attention to what was formerly known as 'secondary compression'. It is now appreciated that viscous behaviour is present at all stages of loading, including primary consolidation, and particularly shear deformations (for example Kim and Leroueil 2001, Yin et al. 2002, Hinchberger and Rowe 2005). Modelling that includes viscosity, for example in the form of an elastic viscoplastic model, produces much better simulations of embankment deformations than time-independent modelling such as Modified Cam Clay (Kelln et al. 2009).

Of particular interest is the approach adopted by Yin, Kelln and their co-workers, in which C_α is treated as a material constant like C_c or C_r. The mathematics are arranged to incorporate the influence of overconsolidation ratio (OCR) on creep rate. The research will incorporate temperature-dependency of C_α into Kelln's model, which is available as an 'add-in' to SIGMA/W (GeoSlope International, Calgary AB).

4 CONCLUSIONS

Field measurements under embankments in Northern Manitoba show significant seasonal changes in soil temperature and also longer-term thawing in originally frozen foundation soil. That is, the foundation soils are 'degrading'. Numerical simulations of temperatures and deformations associated with assumed climatic changes provide information about long-term serviceability of northern highways and the maintenance schedules that will be required. Ongoing projects are examining how warming is affecting stress-strain behaviour of foundation clays and the resulting deformations of embankments.

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