Observed Deformations of an Existing Highway Embankment on Degrading Permafrost

David Flynn
KGS Group, Winnipeg, Manitoba Canada
Marolo Alfaro and Jim Graham
University of Manitoba, Winnipeg, Manitoba, Canada
Lukas U. Arenson
BGC Engineering Inc, Vancouver, British Columbia, Canada

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ABSTRACT
The integrity of infrastructure in northern regions is negatively impacted by thawing and degradation of the underlying permafrost foundation initiated by changes in both air and ground temperatures. Subsequent deformations due to settlement and lateral spreading can lead to potentially hazardous driving conditions for linear infrastructure, such as highways. This paper discusses deformations observed since September 2012 of an instrumented highway embankment sitting on degrading permafrost. The site is located 18 km north-west of Thompson, Manitoba on Provincial Road (PR) 391. Earlier papers on this site reported results from three years of data, but with incomplete instrumentation. Newly-added instrumentation installed in September 2012 has identified a frost bulb in the centre of the embankment. We assessed the effect of the frost bulb, which had not been known and therefore was not included in previous studies, on deformations of the embankment. Lateral and vertical embankment deformations were measured using ShapeAccelArrays installed vertically below the shoulder of the embankment and horizontally at its toe. New instrumentation also included vibrating wire piezometers and thermistors to monitor groundwater and temperatures. Readings from the new instruments provide an improved understanding of the pore pressures and the thermal regime at the site.

RÉSUMÉ
Dans les régions nordiques, l'intégrité des infrastructures est affectée par la fonte et la dégradation du pergélisol sous-jacent causées par les changements de température de l'air et du sol. Les déformations encourues, causées par des tassements et des déplacements latéraux, peuvent induire des conditions de conduite dangereuses dans le cas d'infrastructures de transport linéaires, telles que des routes. Le présent article discute de la déformation affectant un remblai de route construite sur du pergélisol se dégradant instrumenté depuis septembre 2012. Le site est situé à 18 km au nord de Thompson, au Manitoba sur le chemin Provincial (RPS) 391. Les précédents articles documentant ce site ont fourni des résultats basés sur trois années de données, mais issus d'une instrumentation incomplète. L'instrumentation nouvellement installée en septembre 2012 a permis d'identifier un bulbe de gel au centre du remblai. L'effet de ce bulbe de gel sur la déformation du remblai a été évalué, contrairement aux études antérieures qui ignoraient son existence. Les déformations latérales et verticales du remblai ont été mesurées en utilisant des ShapeAccelArrays installés verticalement sous l'accotement et horizontalement au pied du remblai. La nouvelle instrumentation incluait aussi des piézomètres à corde vibrante et des thermistors. Les données enregistrées par les nouveaux instruments permettent une meilleure compréhension des pressions interstitielles et du régime thermique au site d'étude.

1 INTRODUCTION

Development in northern Canada is important for the socio-economic well-being and protection of national sovereignty of the region. This part of Canada is sparsely populated and communities are often remotely connected. Transportation infrastructure is crucial to providing links for promoting development in these communities and the nearby natural resources such as petrocarbons, minerals, and hydro electrical power.

Nearly half of the land surface in Canada is underlain by permafrost (Brown, 1967). Permafrost is ground that remains at or below 0°C for a period of two or more years. Permafrost thickness can vary from several hundred metres in the continuous permafrost regions in the Arctic to thin and sporadic thicknesses found in the southern discontinuous permafrost regions. Figure 1 shows the extent of permafrost in Manitoba and indicates that the project site examined in this study is located in a discontinuous permafrost region. Permafrost becomes continuous to the north near Churchill, Manitoba.

Highway construction in northern Manitoba follows similar practices to those used in the south. Thermal conductivities of fill materials and asphalt pavement are typically higher than the native soils they displace. Construction and maintenance practices involve vegetation removal, and changes to both the drainage patterns and snow removal. These factors contribute to disturbances to the existing thermal regime by increasing heat transfer into previously frozen ground which can lead to thawing and degradation of the embankment (MacGregor et al., 2010).

Transport Canada (TC), Manitoba Infrastructure and Transportation (MIT), and the University of Manitoba (UM) are working together to find improvements to the design, construction, and maintenance of highways in regions of permafrost. This collaborative effort includes providing support to projects that involve field instrumentation, monitoring, laboratory testing, and numerical modelling.

This paper presents observations of lateral and vertical displacements of a highway embankment on Provincial Road (PR) 391. The project site is located 18 km north-west of Thompson, Manitoba on Provincial Road 391 as shown in Figure 1. The highway is located in discontinuous permafrost and is the only road that connects other remote northern communities, hydro generating stations and mines in north-western Manitoba.

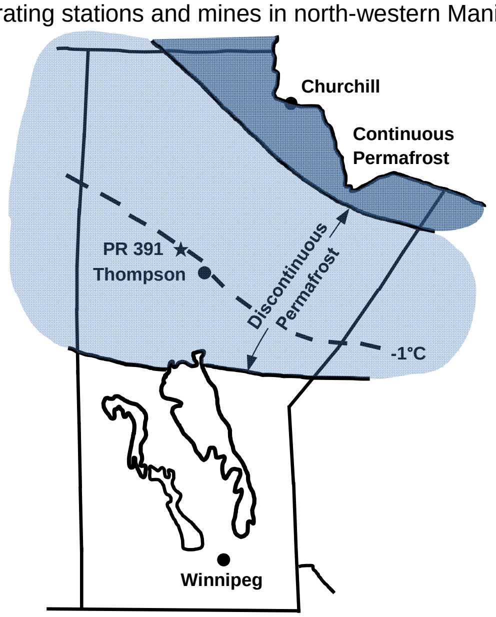

Figure 1: Location of Test Site and Permafrost in Manitoba (Flynn, 2013)

2 SITE BACKGROUND

2.1 Site Investigations

PR 391 was initially constructed as a compacted earth road in the 1960s. Upgrades to gravel and asphalt surfaces were made in the 1970s and 1980s, respectively. However, the road continued to experience irregular deformations, especially in areas that were suspected to be permafrost during the initial construction of the road. In the 1990s, a stabilizing berm was placed along the toe of the embankment in an effort to mitigate the lateral spreading. The berm has settled, essentially disappearing into the natural ground surface, and provides no additional support.

Drilling in 2008 and 2012 revealed 6 m of gravel fill beneath the road surface underlain by approximately 14 m of silty clay before reaching gneissic bedrock at a depth of 18 m. The stabilizing berm was 1 m thick at the project site and consisted of clayey peat silt.

In 1991, drilling encountered frozen soil 1.9 to 10.5 m below the toe of the embankment. Additional drilling in 2005 revealed frozen soil between 4.6 and 10.7 m depth below the toe. In 2008, drilling was carried out at the toe and mid-slope to install instrumentation. No frozen soil was encountered or reported at that time. Frozen and ice-rich soil was found at both the centreline and shoulder of the embankment in 2012 when additional instruments were installed.

Soil samples were collected from the drilling in both research campaigns in 2008 and 2012. The laboratory testing component of the research consisted of oedometer tests, triaxial shear tests, determination of the Atterberg limits, hydrometers analysis, and moisture content tests. Results can be found in Flynn (2015) and are not reported in this paper.

2.2 Field Instrumentation

Figure 2 shows the instrumentation installed in the embankment during two phases of research. The first phase of research installed instrumentation in October 2008 (shown as blue in the figure) and only monitored the toe and mid-slope. In the second phase, additional instrumentation (shown as green) was installed in September 2012 under the shoulder and the centreline after MIT gave permission to drill under the road surface.

The first phase of instrumentation included slope inclinometers to measure lateral displacements at the toe, 9-noded thermistor strings at the toe and mid-slope to monitor the ground thermal regime to a depth of 9 m, and two vibrating wire (VW) piezometers at 4 m intervals under the toe to measure groundwater conditions. Other instrumentation included surface settlement plates, deep settlement gauges, and standpipes. Data were recorded until the termination of phase one in April 2011. Previous publications, such as Batenipour et al. (2011 and 2014), have provided analysis and synthesis of the data collected from this period.

Additional instruments were installed in September 2012 and included two ShapeAccelArrays (SAAs), two 13-noded thermistor strings, and four VW piezometers. The thermistors were installed to a depth of 17 m under the shoulder and centreline to provide a more comprehensive ground thermal regime under the embankment. The piezometers were installed in 4 m intervals under the centreline. Flynn et al (2013) previously described the installation of the field instrumentation in phase two.

A 16 m long SAA was installed horizontally under the embankment to measure vertical displacements between the toe and the centreline. A 20 m long SAA was installed vertically at the shoulder to measure lateral displacements. SAAs consist of a series of rigid 0.5 m long segments with triaxial micro-electronic-mechanical system gravity sensors that measure tilt along three axes. An SAA must be anchored at one end to serve as a reference point for the displacement readings. The vertical SAA was anchored into the bedrock with grout. The horizontal SAA was initially secured at the toe with rebar before upgrading to an 8-foot (2.4 m) long ground anchor.

Phase one required manual data collection. The thermistors and piezometers were the only instruments from phase one that could be incorporated in the remote data collection in phase two. Data have been remotely collected every five days since the initiation of phase two in September 2012. The data acquisition (DA) system is accessed by a satellite system, which allows communication to the site for data collection at any time.

Solar panels were installed to power the DA system because the project location is too remote to connect to the electrical power grid.

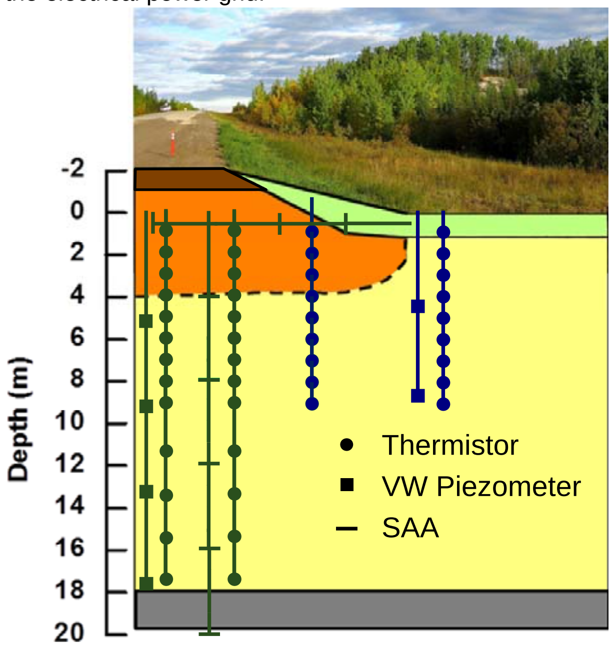

Figure 2: Instrumentation installed. (Note: Blue indicates instrumentation installed in 2008. Green indicates instrumentation installed in 2012). (Flynn, 2013).

3 DATA FROM FIELD INSTRUMENTATION

The following section presents the results and analysis of the vertical and lateral movements collected at the project site. The authors also comment on the groundwater conditions in respect to the displacement measurements. Data include lateral displacements from the slope inclinometer installed at the toe during the first phase as well as the two SAAs installed during the second phase. The first SAA displacement reading is zero and all subsequent displacements are relative to the first reading.

Sub-zero temperatures under the embankment were recorded by the thermistor strings at the same depths ice-rich or frozen ground was encountered during the drilling. The region of sub-zero temperatures is referred to as the “frost bulb” and was found 6 to 10 m and 4.5 to 11 m under the shoulder and centreline, respectively. Marginally sub-zero temperatures were consistently observed in the frost bulb for over two years and confirmed the presence of permafrost. The lowest recorded ground temperature was only -0.25°C. Ground temperatures experience seasonal changes over a yearly freeze-thaw cycle with warmest temperatures observed in the spring and the coldest temperatures observed in the fall. In the fall of 2014, above-zero temperatures were briefly observed in the frost bulb for the first time to indicate degrading permafrost. Flynn et al. (2013) provides further discussion of the synthesis of the thermal and groundwater data collected in phase two of research at the PR 391 site.

3.1 Lateral Displacement

Figure 3 shows quarterly cumulative measured lateral displacements measured by the SAA installed vertically at the shoulder and anchored in the bedrock at a depth of 20 m. The dashed blue region approximates the location of the frost bulb. Positive displacement values indicate deformations away from the centre of the embankment.

Inward lateral displacements towards the centre of the embankment were observed in the 6 m thick gravel fill layer and had a maximum value of 95 mm. The transition to outward displacement away from the centreline of the embankment is noted at depths of 3.5 to 4 m relative to the toe. The transition occurred at approximately the same depth as the boundary between the gravel fill and the silty clay. A maximum outward deformation of 178 mm was measured by the SAA at a depth of 6.5 m which is inside the frost bulb in the silty clay. No significant lateral deformations were observed below the base of the frost bulb at a depth of 8.5 m. This is likely the result of the stiffer mechanical properties of frozen ground compared to unfrozen or thawed ground. The change in displacement as measured between the summer and fall was greater than the change in displacement between any other two consecutive quarters. In other words, a sudden increase in the rate of displacement occurs in the fall, whereas cumulative deformations otherwise increase steadily over the rest of the year. As stated earlier, ground temperatures reach a yearly maximum in the fall after air temperatures gradually penetrated deeper in the ground over the summer. At this time, the soils would be considered at their weakest state because of the loss in strength from warming and thawing, and would be more susceptible to increased rates in displacements.

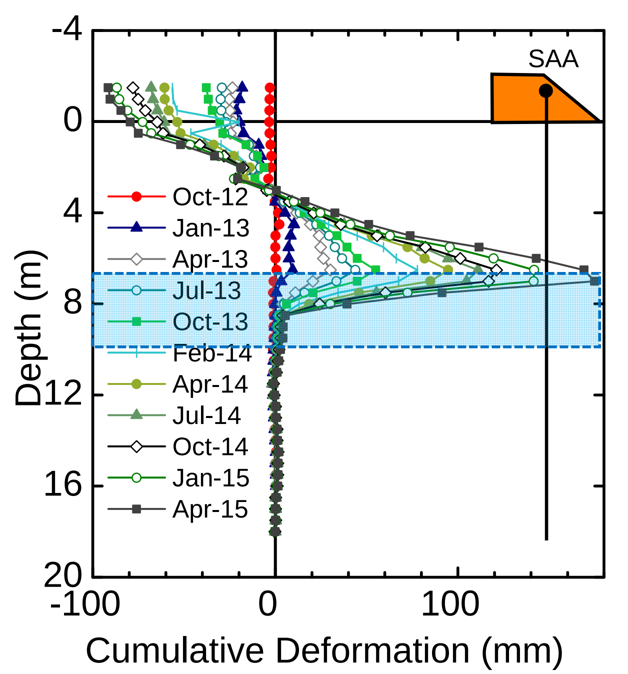

Figure 3: Lateral Displacements at the shoulder measured by a vertically installed SAA

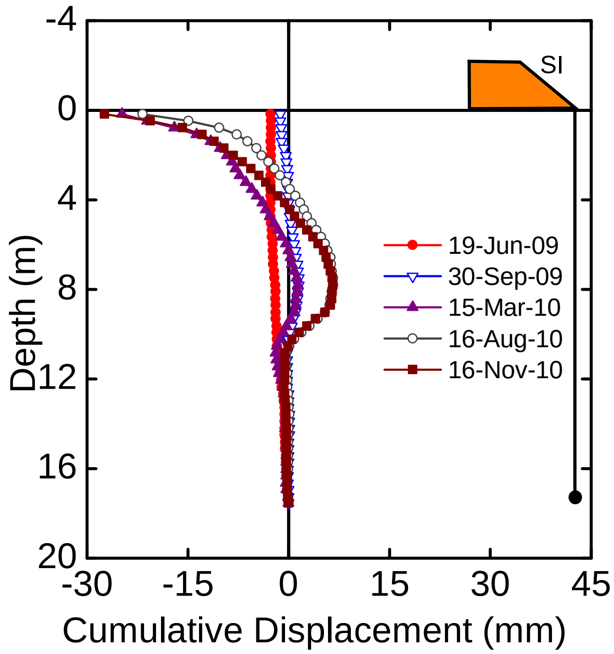

Figure 4: Lateral displacement measurements at the toe by a slope inclinometer (SI) (Batenipour et al., 2011)

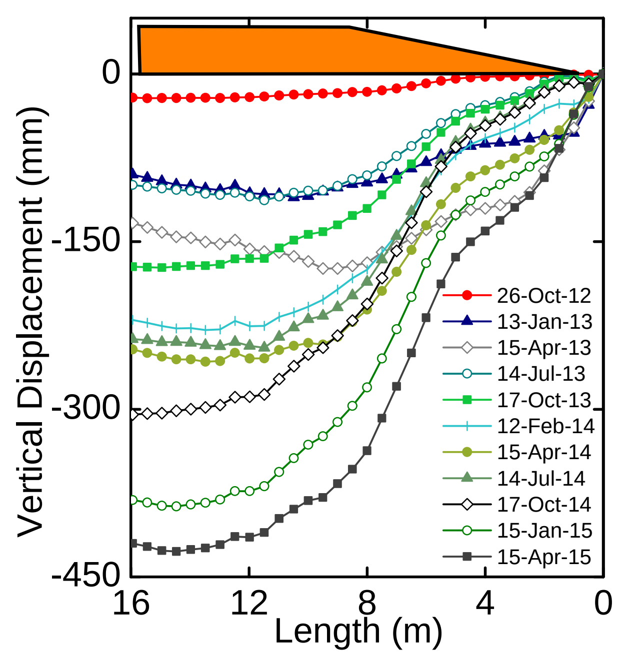

Figure 5: Vertical displacements measured by a horizontally installed SAA.

Lateral displacements at the shoulder (Figure 3) were consistent with those observed at the toe by the slope inclinometer during the initial monitoring period shown in Figure 4 (Batenipour et al., 2011). The displacements at the shoulder shared the same general shape as the toe, but the magnitude was greater. Inward displacement was observed to a depth of 4 m by the slope inclinometer. The maximum outward deformation of 7 mm occurred at a depth of 8 m, while only negligible lateral deformation was observed below 11 m.

Ongoing maintenance places gravel fill on the road surface. Lateral movements were larger and more pronounced at the shoulder compared to the toe because the shoulder was in closer proximity to the maintenance of the road surface. Alfaro et al. (2009) proposed that thaw consolidation is initiated at the toe of embankment. Consequently, larger displacements may have occurred earlier at the toe.

3.2 Vertical Displacement

Figure 5 shows vertical deformations plotted against time as recorded by the SAA installed horizontally 16 m into the embankment. Generally, the embankment has experienced increasing settlements since September 2012. The largest displacements occurred closest to the centreline. Similarly, surface settlement plates positioned closer to the centreline observed the largest deformations during the initial monitoring period (Batenipour et al., 2014). A maximum deformation of 424 mm was recorded on April 15, 2015. Maintenance for PR 391 includes the application and re-grading of fresh gravel on the road surface every year. Comparison between maintenance and the measured settlements could not be made because no exact maintenance records about the quantity of gravel placed on the road were available.

Figure 6a shows settlements at the toe, mid-slope, shoulder, and centreline plotted against time. Frost heave is common in embankments due to ice lens growth in the fall and beginning of winter as the freezing front migrates deeper into the ground. Frost heave is often followed by downward and lateral movements due to reduced shear strength and higher compressibility in the foundation soil caused by thawing in the spring. However, the vertical displacements recorded by the SAAs at the PR 391 project site are atypical for frost heave behaviour. The SAA was installed 2 m below the top of the embankment and therefore does not record movements of the road surface. Figure 6a shows ongoing settlements over most of the nearly three years of monitoring. There are, however, relatively sharp upward movements, a 'spike', in each spring beginning around mid-April and lasting 4 to 8 weeks. Similar to the lateral displacements shown in Figure 3, the rate of change in vertical displacements increased in the fall months compared to the summer because the ground temperatures reached their warmest values (Flynn, 2015). In the summer, there was negligible movement at toe and mid-slope before settling resumed in the fall at rates similar to those at the shoulder and centreline. Consequently, the net yearly displacement at the toe is close to zero. The mid-slope has experienced net zero movement since June 2013 after initially settling approximately 50 mm.

After the spring of 2013, there was concern that the upward spike of displacements was related to an improperly secured anchor point. An 8-foot (2.4 m) ground anchor was installed in November 2013 to replace the rebar that had previously secured the SAA. There were no noticeable differences in displacement readings before and after the new anchor was installed, therefore the authors concluded the anchor point had been adequately secured previously. The upward spike occurred again in

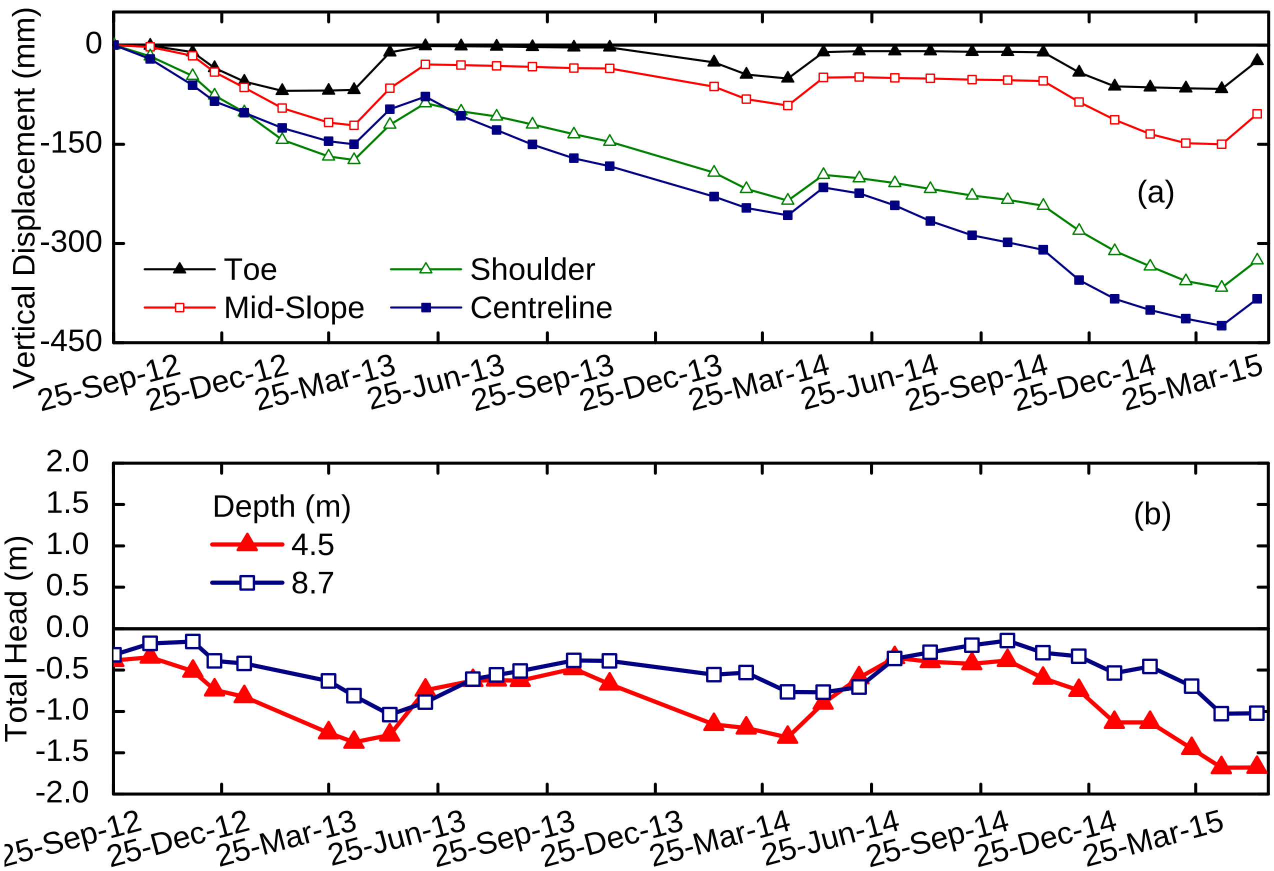

Figure 6: (a) Vertical displacement recorded by the horizontal SAA at the toe plotted on the same time scale as (b) total heads measured by the vibrating wire piezometer at the toe.

the spring of 2014 and 2015. Between April 15, 2013 and June 14, 2013, 53 to 56 mm of heave was observed while 38 to 42 mm was observed between April 15, 2014 and May 15, 2014, and 40 to 46 mm was observed between April 15, 2015 and May 15, 2015

Figure 6b shows the total head at the toe measured by the vibrating wire piezometers against time using the same time scale as for the vertical displacement plot in Figure 6a. Pore water pressure conditions appear to be largely hydrostatic over the summer. In the winter, upward gradients develop which possibly indicates suction pressure (negative potential) caused by the freezing front penetrating deeper into the ground. In the spring, the upward spike in movement occurred at the same time that upward gradient changed back to hydrostatic conditions. There was essentially no movement at the toe or mid-slope during the hydrostatic groundwater conditions measured in the summer. In the fall, settlements at the toe and mid-slope resumed at the same time that the upward hydraulic gradients re-developed. The upward hydraulic gradient reduced the effective stresses in the soil. The lower effective stress also caused decreased lateral confining pressures, a higher effective stress ratio, and increased shear strains. The net effect was an increased rate of settlements and lateral deformations.

4 DISCUSSION

The authors propose that the clay layer expanded under the embankment and caused the upward spike observed each spring. During the spring melt, unfrozen water that originates in the thawed region developing around the frost bulb can accumulate in the clay layer. Konrad and Roy (2000) noted that water cannot easily drain through the impervious still-frozen soil. Consequently, based on observations they made on subgrades in Quebec, the frozen soil swelled in response to the increased water availability from ground ice thawing. The swelling depends on the quantity of meltwater, the swelling index of the subgrade, and the volume of the subgrade (Konrad and Roy, 2000). Clay is commonly used in dikes because of its low hydraulic conductivity. The low hydraulic conductivity of the clay found at PR 391 is likely to behave similarly and the accumulated water under the embankment dissipates very slowly. The clay would begin to expand because the combination of available meltwater and the upward hydraulic gradient would exceed the horizontal drainage capacity in the clay layer. Impeded drainage lasted 3 to 6 weeks in the case of highway subgrade swelling in Quebec documented by Konrad and Roy (2000). At PR 391, the expanding clay pushed the embankment upwards for about 4 to 8 weeks until hydrostatic groundwater conditions were regained, at which time horizontal drainage was believed to be sufficient since there was no longer an upward hydraulic gradient.

Snow accumulation at the toe can accelerate permafrost degradation by acting as a thermal insulator and trapping heat during the winter to initiate thawing. We suggest that additional studies be carried out to determine whether the accumulating net settlements can be reduced by a change in maintenance or improved drainage of the embankment and its surroundings. Controlling water at the toe of the slope can prevent it from pooling and contributing to further thawing.

5 SUMMARY

Our research observed the geotechnical behaviour and performance of a highway embankment built on degrading permafrost. The project site is located 18 km northwest of Thompson, Manitoba on PR 391. This paper discusses lateral and vertical deformations observed over approximately five years. The first phase of the research included instrument installation and monitoring between October 2008 and April 2011. Installation of additional instruments initiated a second phase during which more data have been collected regularly since September 2012. Instrumentation included slope inclinometers, SAAs, thermistor strings, and VW piezometers.

The new thermistors identified a region of sub-zero temperatures, a “frost bulb” which was also encountered during geotechnical drilling. The frost bulb was found at depths between 6 and 10 m under the shoulder of the embankment and between a depth of 4.5 and 11 m under the centreline. In the fall of 2014, above-zero temperatures were briefly observed in the original frost bulb for the first time to indicate degrading permafrost.

At the shoulder, inward lateral movements have been recorded in the gravel layer, and outward movements in the underlying clay before it was restricted by the frost bulb. The shape of lateral deformations from the SAA was consistent with the slope inclinometer data at the toe from the initial monitoring program. The movement was more pronounced at the shoulder than the toe, which suggests that permafrost degradation was progressing from the toe.

Ongoing accumulating settlements have been recorded under the embankment. Thawed soils are more compressible than frozen ground and the greatest vertical deformations were observed in the fall when ground temperatures were warmest. A temporary upward spike of vertical movement was observed in three consecutive springs. At the same time, upward hydraulic gradients of groundwater that had developed over winter transitioned to hydrostatic conditions in summer. The authors proposed that the upward hydraulic gradient and the presence of recently thawed water at the bottom of the frost bulb allowed the clay to expand and push the embankment up for several weeks similar to observations made by Konrad and Roy (2000).

ACKNOWLEDGEMENTS

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