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Challenges from North to South
Des défis du Nord au Sud

High-resolution monitoring of thaw subsidence affecting the access road to Umiujaq Airport in Nunavik (Quebec)

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ABSTRACT
The thaw subsidence along a 300 m long segment of the access road to Umiujaq Airport in Nunavik (Quebec) has been annually monitored since 2006. This subsidence is due to thaw consolidation taking place in a layer of ice-rich silt underneath the road embankment. The increase in air temperature over the last two decades and the thermal insulation of snow cover on the embankment shoulders and toes explain the permafrost degradation. Thaw subsidence as much as 1.50 m has been recorded since the road completion in 1991. Rates of thaw subsidence from 0.056 to 0.138 m/year were observed. According to numerical modeling, the thawing rate is 0.317 m/year. The coefficient of consolidation varies between 1.37 and 2.44 m^2/year for corresponding thaw consolidation ratio from 1.021 to 0.765. The thaw consolidation of the silt layer is almost completed and only little thaw subsidence is expected along the monitored road.

RÉSUMÉ
Un suivi annuel des tassements au dégel le long de la route d'accès à l'aéroport d'Umiujaq au Nunavik (Québec) a été effectué depuis 2006. Ces tassements sont causés par la consolidation au dégel d'une couche de silts riche en glace sous le remblai. L'augmentation de la température de l'air lors des deux dernières décennies et l'isolation thermique de la neige sur les épaulements et au pied du remblai sont à l'origine de la dégradation du pergélisol. Des tassements au dégel aussi élevés que 1.50 m ont été observés depuis la construction de la route d'accès en 1991. Des taux de tassement de 0.056 à 0.138 m/an ont été mesurés. Selon des simulations numériques, le taux de dégel estimé est de 0.317 m/an. Les coefficients de consolidation obtenus varient de 1.37 à 2.44 m^2/an pour des rapports de consolidation au dégel correspondants de 1.021 à 0.765. La consolidation au dégel de la couche de silt est presque complétée et de faibles tassements au dégel sont seulement attendus le long du segment de route étudié.

1 INTRODUCTION

Among the geohazards associated with the permafrost degradation due to climate warming, the vulnerability to thaw subsidence is widespread in the North (Nelson et al. 2001). This geohazard can have major impacts on the performance of man-made infrastructures increasing their maintenance cost, decreasing their useful life span and reducing the safety of users. Investigation of the origin and causes of thaw subsidence is needed to develop mitigation approaches and adaptation strategies. Moreover, there is currently no available case study on the extent and rate of thaw subsidence according to permafrost conditions, thaw consolidation properties and climate warming.

Climate warming is already occurring at high latitudes in Nunavik (Quebec) according to the meteorological records of Environment Canada (Figure 1). The impacts of this climate warming on man-made infrastructures built on ice-rich permafrost are observed all over Nunavik. For instance, the access road to Umiujaq Airport shows major structural problems due to thaw subsidence (Figures 2 and 3). The results of an annual monitoring of thaw subsidence undertaken along this road since 2006 and the assessment of thaw consolidation properties are presented herein to document this geohazard.

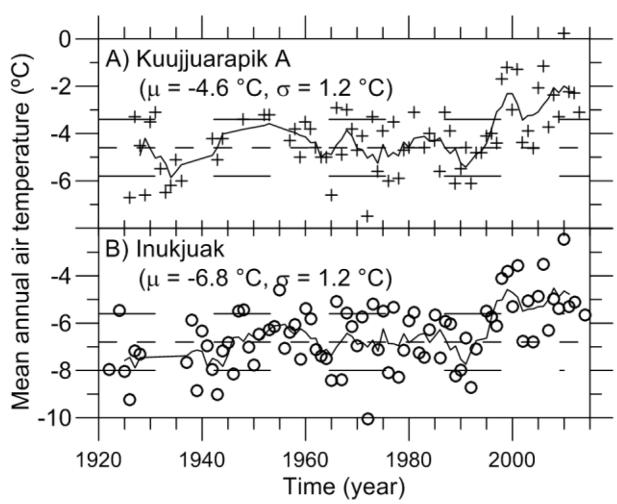

Figure 1. Mean annual air temperature at A) Kuujjuarapik (Whapmagoostui-Kuujjuarapik or WK) and B) Inukjuak in Nunavik (see Figure 2 for the location). Meteorological data from Environment Canada. The full line corresponds to a 5-year running average and the dashed lines are, respectively, the mean μ and ±standard deviation σ over the reference period 1961-1990.

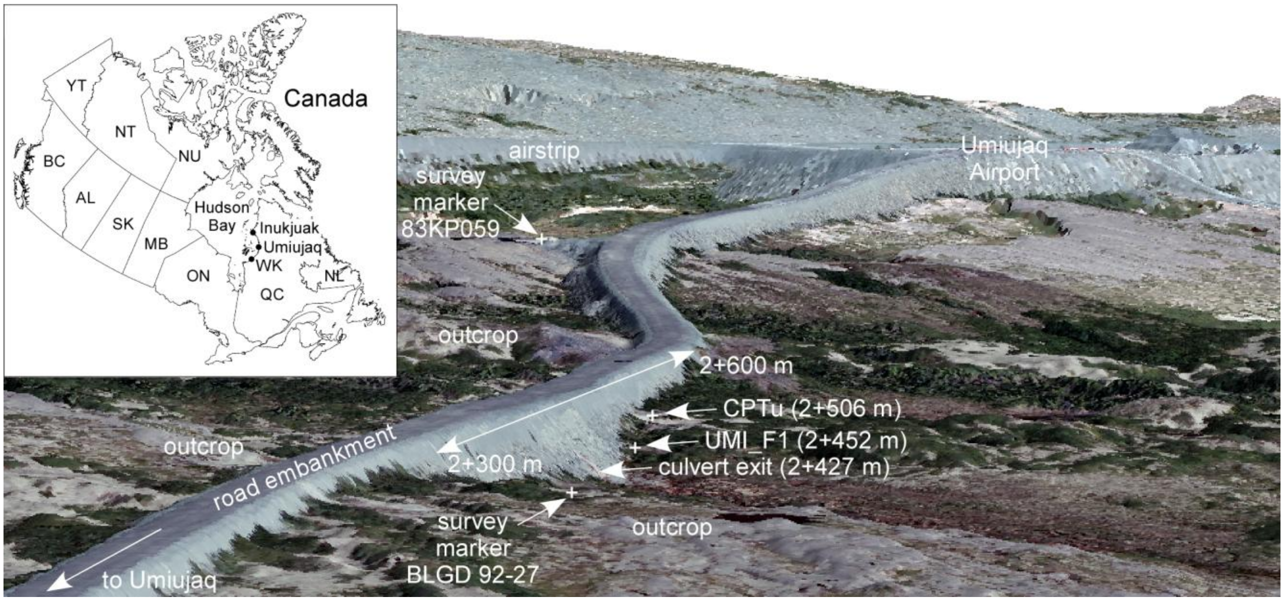

Figure 2. Access road to Umiujaq Airport in Nunavik (Quebec), Canada. The 300 m long road segment from the distance 2+300 to 2+600 m affected by major structural problems due to thaw subsidence is identified. The airfield is visible in the background. The aerial photographs no. Q10801_071_15CM_F09 and Q10801_073_15CM_F09 are draped on a digital elevation model from an airborne LiDAR survey carried out on August 22nd 2010 (all rights reserved to the Ministère des ressources naturelles du Québec). South oblique view with artificial illumination from the west. Note the vertical exaggeration of 2:1. Inset: map of Canada with the location of Umiujaq along the east coast of Hudson Bay (projected coordinate system: NAD 1927 Quebec Lambert). The survey markers 83KP059 and BLGD 92-27 used as references for the leveling surveys are identified. A piezocone penetration test CPTu (Fortier et al. 2011) and soil sampling down to the bedrock UMI_FI (L'Hérault et al. 2009) were carried out near the embankment toe in 2008 and 2009, respectively.

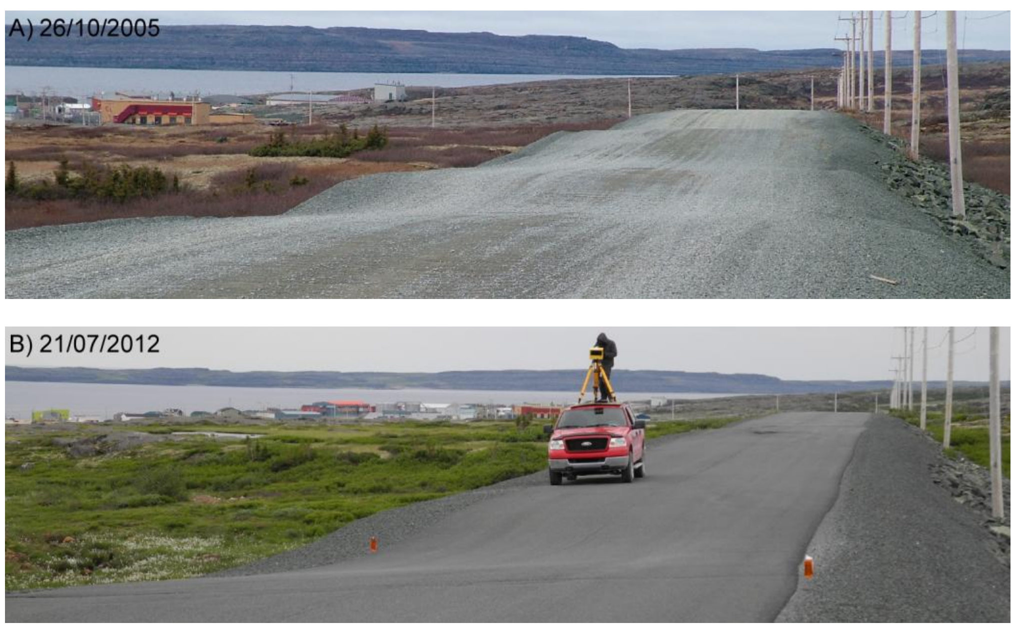

Figure 3. Photographs of the road segment affected by thaw subsidence taken on A) October 26th 2005 (from Denis Sarrazin, professional researcher, Centre d'études nordiques - CEN, Université Laval) and B) July 21st 2012. The partial reloading of the road embankment and the asphalt paving were done in August 2009. A ground based LiDAR survey was in progress when the photograph was taken on July 21st 2012 to produce high-resolution digital elevation models of the road surface, thaw subsidence zone and cracks (Figures 5 and 6). The Ilris-3D LiDAR scanner from Optech inc. was mounted on the roof of a pickup truck to increase the survey height and improve the reflection of light to the scanner.

2 ACCESS ROAD TO UMIUJAQ AIRPORT

The Inuit community of Umiujaq is located in the discontinuous permafrost zone along the east coast of Hudson Bay in Nunavik (Figure 2). The Umiujaq Airport and its access road are strategic man-made infrastructures for maintaining year-round access to this remote community. A 300 m long road segment from the distance 2+300 to 2+600 m according to the location system of the Ministère des transports du Québec (MTQ 1991) shows major structural problems due to thaw subsidence (Figures 2 and 3).

From its completion in 1991 to the beginning of twenty-first century, the road was not affected by any thaw subsidence. The first structural problem visible to a naked eye was reported in 2004. In 2005, the full width of the road embankment was affected by localised differential thaw subsidence and the road surface looked wavy (Figure 3a). Maintenance operations were done on the road embankment to improve the safety of the users. The road embankment was partially reloaded (unknown volume) and the road was recovered with black asphalt concrete in August 2009. Due to the progress of thaw subsidence in the coming years and the formation of a large depression and cracks hazardous for the users (Figures 3b and 5), the asphalt paving was then removed from the distance 2+355 to 2+512 m and partial reloading of about 80 m^3 from the distance 2+445 to 2+495 m was also done in July 2013 (Bureau 2013).

According to geophysical and geotechnical investigation and mapping of quaternary deposits carried out by Fortier et al. (2011), L'Hérault et al. (2009) and Poly-Géo inc. (2014), the 300 m long road segment crosses a small valley delimited by basaltic outcrops (Figure 2). This valley is partially filled from top to bottom with 1) eolian sands, 2) littoral and pre-littoral sands, 3) subaquatic pro-glacial fan sediments composed of silt, silty sand, sand and some gravel and 4) till. The third unit is frost-susceptible and ice-rich with water content in excess of 40% (L'Hérault et al. 2009). Its thickness varies between 4 and 7 m from the distance 2+370 to 2+570 m while the one of the two top sand layers is from 2 to 4 m (Fortier et al. 2011). The sand layers are thaw stable. The road embankment is 0.5 to 5.6 m thick (MTQ 1991). The thickest embankment is located at a distance of 2+425 m.

According to a geotechnical investigation carried out in August 1990 prior to the road construction (MTQ 1991), the seasonal freeze-thaw cycles were restricted to the top sand layers. Based on the results of numerical modeling of the thermal regime of road embankment and subgrade (Fortier et al. 2011), the permafrost degradation underneath the road embankment is due to not only the increase in air temperature over the last two decades (Figure 1) but also the thermal insulation of snow cover on the embankment shoulders and toes. The thawing front reached first the thaw instable layer of ice-rich silt in the middle of 2003. The estimated thawing rate in this layer is 0.317 m/year during the following years. The thawing of this layer should be completed at the end of 2014. If a decrease in void ratio of 25% from 40 to 15% is considered during the thaw consolidation, the rate of thaw subsidence is 0.076 m/year (Fortier et al. 2011).

3 MONITORING OF THAW SUBSIDENCE

An annual monitoring of thaw subsidence along the studied 300 m long road segment has been undertaken since 2006. Several types of leveling instrumentation were used to carry out this monitoring along the same survey line on the west side of the access road: 1) an electronic level (Chain Level, Model D, Instrumentation GDD inc.), 2) an optical level (C3 10, 26X, Sokkia), 3) a total station (Flexline TS06, Leica Geosystems) and 4) a ground based Light Detection and Ranging or LiDAR (Ilris-3D, Optech inc.). In addition, an airborne LiDAR survey carried out in August 2010 on the behalf of the Ministère des ressources naturelles du Québec is also included in this monitoring. All the leveling surveys are reported to the survey markers 83KP059 and BLGD 92-27 (Figure 2). The elevation of the survey marker 83KP059 relative to the CGVD28 (Canadian Geodetic Vertical Datum of 1928) is 60.7 m (Système de gestion des informations géodésiques du Québec). A closure procedure was used for the surveys with the electronic level while a closure backsight–foresight procedure was used for the surveys with the optical level. The error at the closure was less than 40 cm distributed linearly among the readings for the surveys with the electronic level and less than 1 cm for the surveys with the optical level. The total station was fixed near the distance 2+300 m for the whole surveys. The ground based LiDAR surveys were carried out to produce high-resolution digital elevation models (DEMs) of a major depression at a distance of 2+480 m and longitudinal cracks at a distance of 2+410 m. Two leveling surveys were carried out before and after the maintenance operations in August 2009 and July 2013 so that the monitoring of thaw subsidence could be pursued in the following years.

The elevation of the road surface for each leveling survey along the 300 m long road segment is given in Figure 4. The leveling surveys are grouped in several graphs to allow the comparison between annual surveys and highlight the partial reloading during road maintenances. The original road elevation according to the as-built drawings of the airfield and access road is also provided in each graph as a reference (MTQ 1991).

The DEMs from two ground based LiDAR surveys performed on July 1st 2013 are given in Figure 5. The difference in elevation relative to a best plan fitted on each DEM draped on this DEM appears in Figure 5. An artefact orthogonal to the road is visible in Figure 5B. For the large depression at a distance of 2+480 m, the interpolation of the difference in elevation relative to a best plan fitted on each DEM for the LiDAR surveys performed in 2012 and 2013 appears in Figure 6 for the width of the road surface and a 100 m long segment from the distance 2+420 to 2+520 m. The map of thaw subsidence assessed from these two LiDAR surveys is given in Figure 6C.

The cumulative thaw subsidence relative to the original road surface elevation (MTQ 1991) along the studied 300 m long road segment appears in Figure 7A. The thaw depth and the cumulative thaw subsidence as a function of the square root of time relative to 1991 are also given in Figures 7B and 7C at four different distances along the studied road segment.

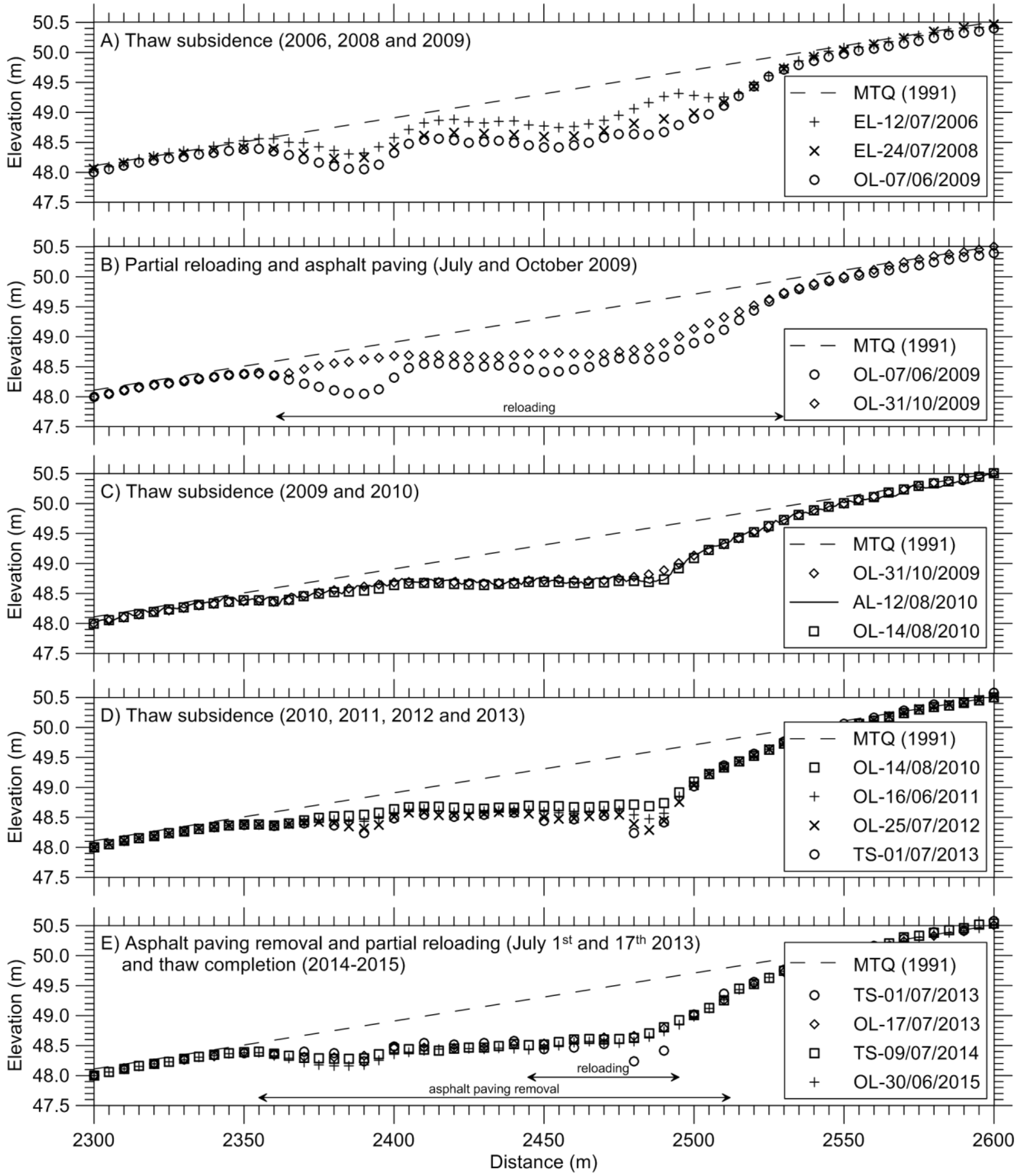

Figure 4. Monitoring of the thaw subsidence along the 300 m long segment of the access road to Umiujaq Airport from the distance 2+300 to 2+600 m since 2006. No leveling survey was performed in 2007. The road elevation according to the as-built drawings of the airfield and access road (MTQ 1991) is also given as a reference in each graph. The elevation is relative to the CGVD28 (Canadian Geodetic Vertical Datum of 1928). Note the vertical exaggeration of 20:1. Types of leveling survey: EL – electronic level (Chain Level, Model D, Instrumentation GDD inc.), OL – optical level (C3 10, 26X, Sokkia), AL – airborne LiDAR (Ministère des ressources naturelles du Québec), TS – total station (Flexline TS06, Leica Geosystems).

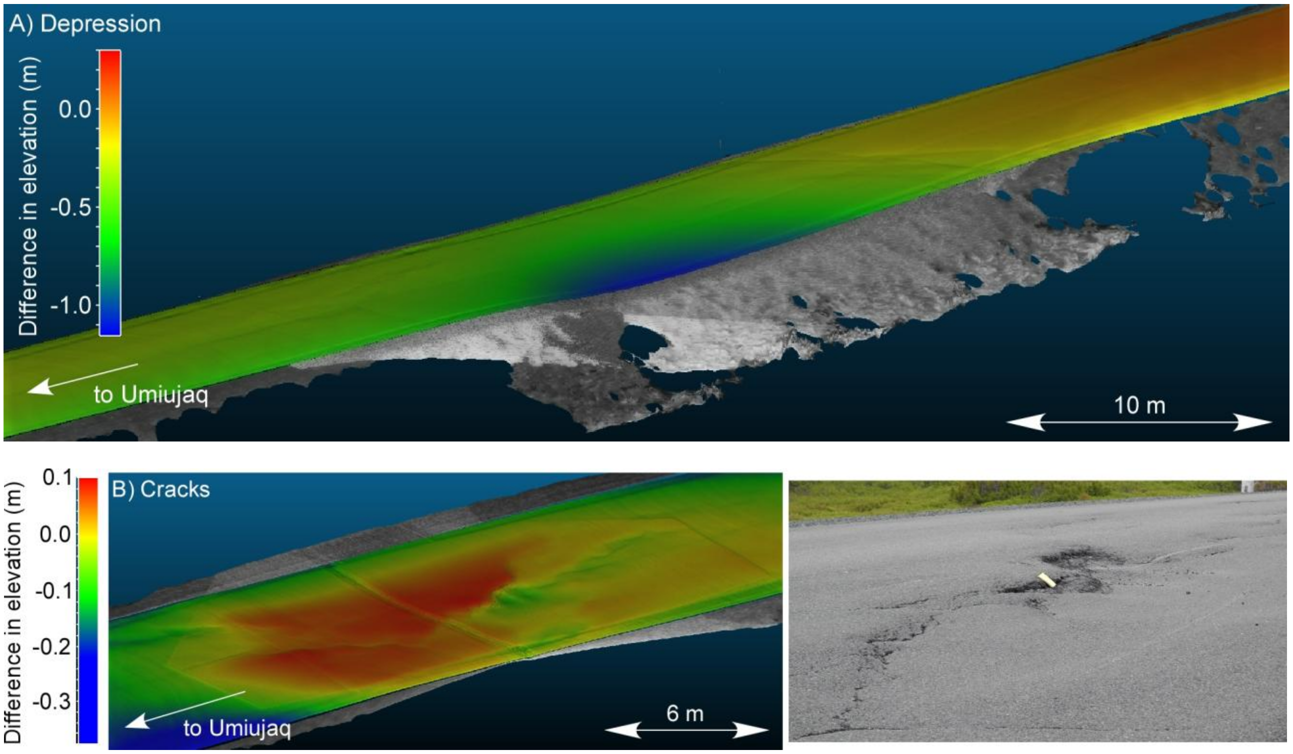

Figure 5. Ground based LiDAR surveys (see Figure 3B) carried out on July 1st 2013 along the access road to Umiujaq Airport. Difference in elevation relative to a best plan fitted on the digital elevation model and draped on the same model: A) major depression at a distance of 2+480 m and B) longitudinal cracks at a distance of 2+410 m.

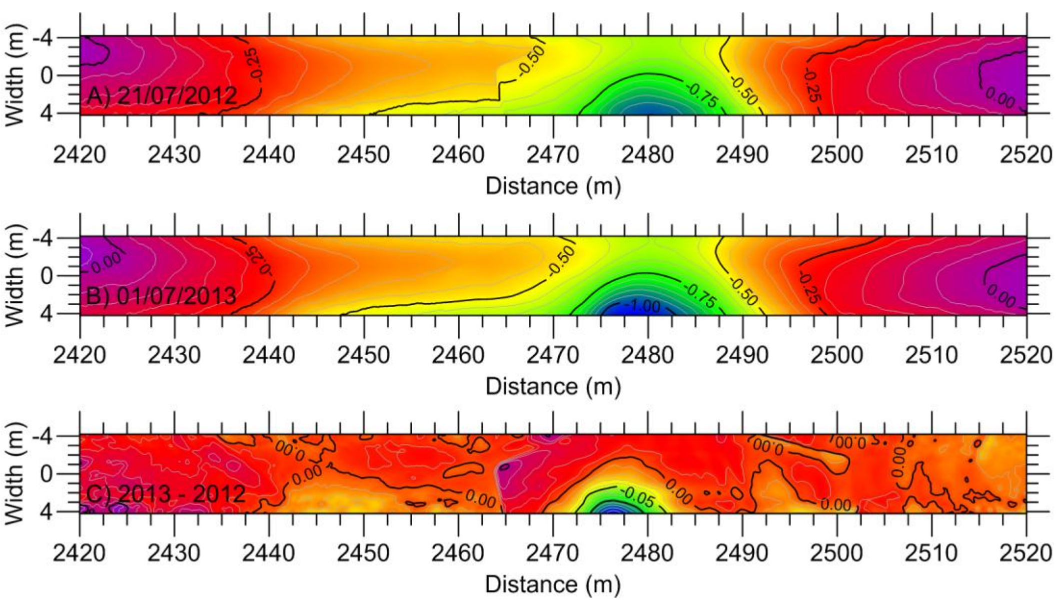

Figure 6. Difference in elevation relative to a best fitted plan on digital elevation model of a 100 m long segment of the access road to Umiujaq Airport from the distance 2+420 to 2+520 m. Ground based LiDAR surveys carried out on A) July 21st 2012 and B) July 1st 2013. C) Thaw subsidence assessed from the subtraction of the digital elevation models from the LiDAR surveys of 2013 and 2012 (difference in elevation between the two digital elevation models).

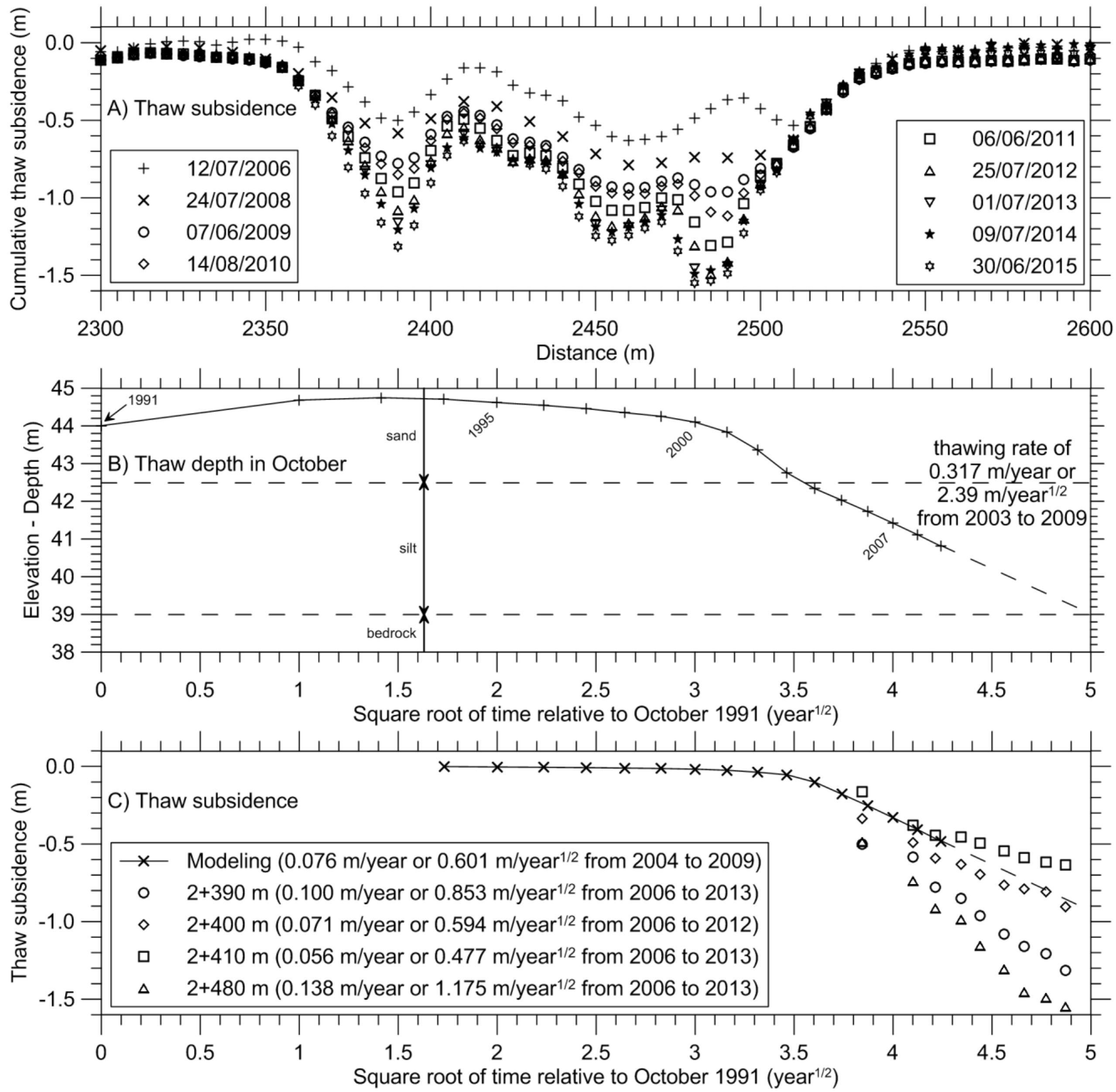

Figure 7. A) Annual cumulative thaw subsidence along the 300 m long segment of the access road to Umiujaq Airport from the distance 2+300 to 2+600. The thaw subsidence is assessed relative to the original road surface elevation according to the as-built drawings of the airfield and access road (MTQ 1991). The embankment reloading and asphalt paving in 2009 were subtracted according to the two leveling surveys carried out on June 7th and October 31st 2009 (Figure 4) while the asphalt paving removal and embankment reloading in 2013 were subtracted according to the two leveling surveys carried out on July 1st and 17th 2013 (Figure 4). B) Predicted depth of the thawing front in October of each year from 1991 to 2009 underneath the road embankment taking into account the simultaneous effect of climate warming (Figure 2) and thermal insulation of snow cover on the road shoulders and toes as a function of square root of time (see Fortier et al. (2011) for the details of numerical modeling of the thermal regime of the embankment and subgrade). C) Thaw subsidence as a function of square root of time at four different distances along the 300 m long segment of the access road. The predicted thaw subsidence according to the estimated thawing rate from numerical modeling and a decrease in void ratio of 25% during thaw consolidation (Fortier et al. 2011) is also shown. This predicted thaw subsidence is of the same order as the observed ones at the distances of 2+400 and 2+410 m. The rates of thaw subsidence as a function of time and square root of time are also given in the legend. The thaw subsidence affecting the studied road segment at the four selected distances is characteristic of the range of permafrost degradation occurring underneath the road embankment.

4 THAW CONSOLIDATION

The time rate of thaw consolidation of the layer of ice-rich silt underneath the road embankment of the access road to Umiujaq Airport can be assessed according to the annual monitoring of thaw subsidence (Figure 7) and using the fitting method of square root of time (Taylor 1948). The primary consolidation due to the excess pore pressure dissipation during thawing under load can be expressed as a linear function of the square root of time.

For instance, the thaw subsidence observed at the distance of 2+480 m is plotted against the square root of time relative to the reference year of 1991 in Figure 8. A straight line has been drawn through the data points from 2006 to 2013. This line has been projected backward to R_0 just before the beginning of thaw subsidence to define the zero time t_0 of 2002.9. The slope m of this line is -1.175 m/year$^{1/2}$. A second line with a slope m_{90} of -1.022 m/year$^{1/2}$, 1.15 lower than the previous slope m, has been also drawn with the same zero time t_0. According to the Taylor's method, the intersection of this second line and the curve of observed thaw subsidence defines the thaw subsidence R_{90} of 1.58 m at 90% of consolidation and elapsed time Δt_{90} of 12.70 years after the beginning of thaw subsidence. The coefficient of consolidation c_v is then given by (Taylor 1948):

$$c_v = \frac{T_{90}\, H_f^2}{\Delta t_{90}} = 1.60\ \mathrm{m^2/year} \qquad [1]$$

where $T_{90} = 0.848$ is the time factor at 90% of consolidation,
$H_f = H_0 + \Delta H = 4.95$ m is the thickness of the silt layer after thaw consolidation,
$H_0 = 6.49$ m is the initial thickness of the layer of ice-rich silt, and
$\Delta H = -1.55$ m is the thaw subsidence (Figure 7).

The drainage path of the thawing layer of ice-rich silt is only through the permeable sand layer on the top. The basaltic bedrock under the silt layer is considered impervious.

The thaw consolidation ratio R is expressed as (Morgenstern and Nixon 1971) and equal to:

$$R = \frac{\alpha}{2\sqrt{c_v}} = 0.945 \qquad [2]$$

where $\alpha = 2.39$ m/year$^{1/2}$ is the thawing rate estimated from numerical modeling (Figure 7B).

Values of c_v and R at the four distances along the studied 300 m long road segment are given in Table 1.

The load P_0 of the embankment and sand layer applied to the layer of ice-rich silt under thaw consolidation is estimated to 165.5 kPa for a 5.2 m thick road embankment (z_e), a dry density of 2200 kg/m^3 for crushed rocks (ρ_e), a 3.8 m thick sand layers (z_{sand}), a dry density of 2040 kg/m^3 for sands (ρ_{sand}), a water table at a depth of 1.5 m in the sand layers (z_w) and a gravitational acceleration of 9.8 m/s^2 (g):

$$P_0 = \rho_e\, g\, z_e + \rho_{sand}\, g\, z_w + \left(\rho_{sand} - \rho_w\right) g \left(z_{sand} - z_w\right) \qquad [3]$$

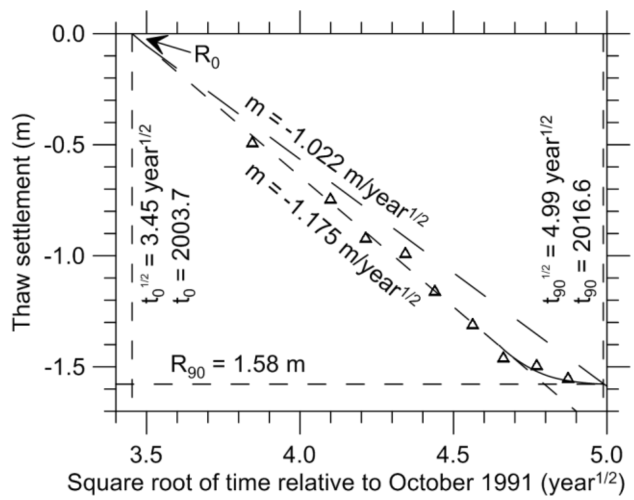

Figure 8. Thaw subsidence as a function of square root of time at the distance 2+480 m.

Table 1. Summary of observations from the monitoring of thaw subsidence along the access road to Umiujaq Airport.

X (m)	H_0 (m)[1]	ΔH (m)[2]	H_f (m)[3]	t_0 (year)	m (m/year$^{1/2}$)	m_{90} (m/year$^{1/2}$)	Δt_{90} (year)	c_v (m^2/year)	R
2+390	7.50	-1.32	6.18	2002.77	-0.853	-0.742	13.28	2.44	0.765
2+400	6.33	-0.91	5.43	2002.44	-0.595	-0.517	12.06	2.07	0.831
2+410	5.16	-0.63	4.53	2003.24	-0.477	-0.415	12.71	1.37	1.021
2+480	6.49	-1.55	4.95	2003.65	-1.175	-1.022	13.00	1.60	0.945

[1]Initial thickness of the layer of ice-rich silt underneath the embankment assessed from a geophysical investigation carried out by Fortier et al. (2011).
[2]Thaw subsidence (Figure 7).
[3]$H_f = H_0 - \Delta H$ is the thickness of the silt layer after thaw consolidation.

5 THAW SUBSIDENCE VOLUME

Considering the full width of the road embankment at the top of 7.4 m (MTQ 1991) and making the assumptions that the thaw subsidence affects the full width of the road (this assumption is valid until the road maintenance in 2009; see Figure 3A), the subsidence volume and the rate of subsidence volume can be assessed (Figure 9) from the annual monitoring of thaw subsidence (Figure 7A).

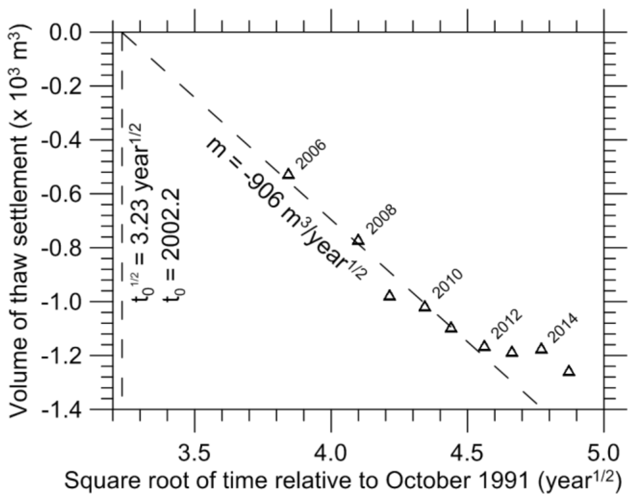

Figure 9. Volume of thaw subsidence along the 300 m long segment of the access road to Umiujaq Airport as a function of square root of time.

6 DISCUSSION

Based on the results of the annual monitoring of thaw subsidence along the studied road segment at Umiujaq (Figure 4), the thaw subsidence started in 2002-2003 (Table 1) when the thawing front reached the thaw unstable layer of ice-rich silt (Figure 7) under a load of 165.5 kPa. Slight thaw consolidation occurred also before in the top sand layers. In 2015, 12 years after the beginning of thaw consolidation in the silt layer, thaw subsidence as much as 1.50 m was recorded at a distance of 2+485 m (Figure 7). The rate of thaw subsidence varies from 0.056 to 0.138 m/year (Figure 7). The volume of thaw subsidence is close to 1250 m^3 in 2015 (Figure 9). The coefficient of consolidation varies between 1.37 and 2.44 m^2/year for corresponding thaw consolidation ratio from 1.021 to 0.765 (Table 1) according to a thawing rate of 2.39 M/YEAR$^{1/2}$ (Fortier et al. 2001). These values of c_v assessed from this full scale experiment of thaw consolidation of a layer of ice-rich silt underneath a road embankment are slightly lower than the ones assessed from thaw consolidation tests on silty permafrost samples in the laboratory (Nixon and Morgenstern 1974) while the ones of R are slightly higher. Maybe the assumptions of one-dimensional loading situation and pore pressures dissipation for the theory of thaw consolidation are not respected in this full scale experiment.

7 CONCLUSIONS

At the authors' knowledge, the case study on the annual monitoring of severe thaw subsidence affecting a road embankment built on thawing ice-rich permafrost presented herein is a first documented full scale experiment of thaw consolidation while this geohazard is observed all over the Northern Hemisphere.

The primary thaw consolidation of the silt layer due to the melting of ground ice and excess pore pressure dissipation is alomost completed. Secondary compression is still occurring. Only little thaw subsidence is expected along the monitored road segment at Umiujaq.

ACKNOWLEDGEMENTS

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