Permafrost characterization at the Iqaluit International Airport, Nunavut, in support of decision-making and planning

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Abstract

The Iqaluit International Airport is a key and strategic infrastructure on which the well-being of eastern Canadian Arctic residents depend. Increased passenger traffic and mineral exploration and development in the Arctic have put pressure on improving this key regional facility. Proposed renovation and expansion of the Iqaluit International Airport must address existing thaw settlement and frost cracking problems that are affecting the pavement and foundations of the runway and taxiways. Climate warming will also necessitate additional improvements in engineering design in order to adapt to changing terrain and environmental conditions. In order to support informed decision-making and reduce risk to public investments in northern transportation infrastructure and resource development, a joint Canada-Nunavut Geoscience Office, Natural Resources Canada and Université Laval study on the sensitivity of permafrost and terrain conditions at the airport began in 2010. In 2012, geophysical investigations, including electromagnetic and electrical resistivity surveys, were used to enhance permafrost characterization and monitor spatial and seasonal changes in unfrozen water content in sensitive areas. RADARSAT-2 image acquisition was also completed in summer 2012 and provided the second year of ground surface movement information by interferometric synthetic aperture radar mapping. Results based on one year of ground temperature records from under the runway, and interpretation of geophysical surveys and remote sensing data indicate that 1) permafrost temperature is slightly warmer and active layer thickness is slightly thicker under the runway than the surrounding undeveloped ground; 2) the thawing front under the runway penetrates through the existing embankment into the underlying, largely glaciomarine deltaic sediments and therefore settlement due to melting ice wedges will probably continue; 3) electrical conductivity anomalies present below taxiway A and under at least one section of the runway are associated with localized settlement problems; and 4) interferometric synthetic aperture radar data on ground surface motion related to frost heave and thaw settlement provide a good correlation with underlying surficial geology.

Résumé

L’aéroport international d’Iqaluit est une infrastructure stratégique de grande importance au bien-être des résidents de l’Est de l’Arctique canadien. Avec l’augmentation du trafic passagers et des activités d’exploration et de mise en valeur minière dans l’Arctique, il devient impératif d’améliorer cette importante installation régionale. Les travaux proposés de rénovation et d’agrandissement de l’aéroport international d’Iqaluit doivent tenir compte des problèmes actuels de tassement dû au dégel et de fissuration gélivale qui touchent le revêtement et l’assise de la piste et des voies de circulation. Le réchauffement climatique rendra également nécessaire la mise en place d’améliorations additionnelles à la conception technique en vue de permettre l’adaptation aux conditions changeantes touchant le terrain et l’environnement. Afin d’éclairer la prise de
décisions et de réduire les risques auxquels doivent faire face les investissements publics dans les infrastructures de transport et le développement des ressources dans le Nord, le Bureau géoscientifique Canada-Nunavut, Ressources naturelles Canada et l’Université Laval ont entrepris en 2010 une étude conjointe sur la sensibilité du pergélisol et les conditions du terrain de l’aéroport. En 2012, des études géophysiques, y compris des levés de résistivité électromagnétique et électrique, ont été réalisées pour mieux caractériser le pergélisol et suivre l’évolution spatiale et saisonnière de la teneur en eau non gelée dans les zones sensibles. L’acquisition d’images RADARSAT-2 a également été achevée à l’été 2012 et a fourni pour une deuxième année des données sur les mouvements de la surface du sol au moyen de la cartographie par interférométrie radar à synthèse d’ouverture. Les résultats d’une année de données sur la température du sol sous la piste et l’interprétation des levés géophysiques et des données de télédétection indiquent ce qui suit : 1) la température du pergélisol est légèrement plus chaude et la couche active est légèrement plus épaisse sous la piste que dans le sol environnant non aménagé; 2) le front de dégel sous la piste traverse le remblai existant vers les sédiments sous-jacents, en grande partie deltaïques et de nature glaciomarine, et, ainsi, le tassement dû à la fonte des coins de glace va probablement se poursuivre; 3) les anomalies de la conductivité électrique sous la voie de circulation A et sous au moins une section de la piste sont associées à des problèmes de tassement localisé; et 4) les données obtenues par interférométrie radar à synthèse d’ouverture sur le mouvement de la surface dû au travail du gel et du dégel présentent un haut degré de corrélation avec la géologie de surface sous-jacente.

Introduction

The city of Iqaluit is growing rapidly. Its airport is the gateway hub for the eastern Canadian Arctic and is also an international airport. This airport is not only vital for maintaining year-round links between southern cities and remote communities, but is essential to support active mineral and resource development, particularly in the Qikiqtaaluk Region. Since its construction by the United States Army during the Second World War, the history of the Iqaluit International Airport has been punctuated with noticeable stability problems (Eno, 2003). Because the underlying permafrost is now experiencing warming and degradation, decision-makers are facing new challenges in order to maintain the existing infrastructure and plan future expansion. In order to support the Government of Nunavut in ensuring growth, safety, informed decision-making and reduced risk to infrastructure investment, and therefore, to investments in northern resource development, a joint Canada-Nunavut Geoscience Office (CNGO), Natural Resources Canada (NRCan; Geological Survey of Canada [GSC] and Canada Centre for Remote Sensing) and Université Laval (Centre d’études nordiques) study on permafrost sensitivity and terrain conditions within the Iqaluit International Airport area was initiated in 2010. Several field studies have been conducted. Remote sensing data were used in support of mapping and for spatially determining terrain surface motion utilizing interferometric synthetic aperture radar (InSAR) technology. A major component of the project was the development of a multidisciplinary earth sciences approach involving Quaternary geology, permafrost science, geophysics and geotechnical characterizations. The aims of the project are to provide a comprehensive vision of how the current infrastructure interacts with warming permafrost and to support the development of improved engineering designs to ensure infrastructure safety, performance and sustainability in the coming decades. All subsurface and surface terrain data and interpretations are integrated in a geographic information system (GIS). Ultimately, the GIS will be used as an interactive tool to communicate results and to better enable the inclusion of geoscientific information in the engineering design of repairs and infrastructure expansion. It is also the aim of this project to provide a better understanding of the thermal and physical processes affecting permafrost degradation under paved infrastructure. This paper presents a summary of the work that has been conducted thus far, including results from summer 2012 and current permafrost conditions.

Study area

Iqaluit is located in southeastern Baffin Island at the head of Frobisher Bay (63°45’N, 68°33’W), in a zone of continuous permafrost. Environment Canada weather station data collected adjacent to the airport from 1971 to 2000 yielded a mean annual air temperature (MAAT) of −9.8°C and annual precipitation of 412 mm, of which 48% occurs as rain (Environment Canada, 2011). Since 2000, the MAAT has been higher than the reference period; the warmest year was 2010 at −4.2°C. The airport is built on flat terrain surrounded by hills and rocky plateaus of the Precambrian Shield (St-Onge et al., 2006).

Methodology

A combination of traditional surficial geology mapping, near-surface drilling, shallow geophysical surveys, and ground thermal and ground movement instrumentation was used during the summers of 2010, 2011 and 2012 and the winter of 2011; InSAR mapping of ground surface movements was also undertaken. Details of the research and the location of surveys and instrumentation are shown in Figure 1.
Figure 1: Location of the geophysical surveys and instrumentation at the Iqaluit International Airport, Nunavut. Background image (WorldView-1; DigitalGlobe, Inc., 2008) includes copyrighted material from DigitalGlobe, Inc., all rights reserved. UTM zone 19. Abbreviations: CCR, capacitively coupled resistivity; EM31, electromagnetic; GPR, ground penetrating radar; GR, galvanic resistivity.
Field observations

The surficial geology of the Iqaluit area was mapped by Allard et al. (2012) and is described below. Observations of permafrost features were also made as part of this mapping activity (Mathon-Dufour, 2011). To measure the spatial variability of ground temperatures, one thermistor cable was installed in 2010 in the undeveloped terrain (AERO-2010, Figure 1), while four others were installed in 2011 within various embankment locations (DDH-01, DDH-03, DDH-07, DDH-10, Figure 1). A total of four piezometers were also installed in 2011 (DDH-02, DDH-05, DDH-07, DDH-08, Figure 1). Only visual observation of disturbed soil samples and approximate stratigraphic depths was possible during the borehole installation since an air rotary drill was used. Two thaw tubes were installed in 2010, one in well drained sediments (T1, Figure 1) and the other in poorly drained sediments (T2, Figure 1), in order to validate the remote sensing data using annual maximum heave/subsidence measurements (cf., Nixon and Taylor, 1994). Electrical resistivity imaging (ERI), including galvanic resistivity (GR) and capacitively coupled resistivity (CCR) along with electromagnetic surveys (EM31) and ground penetrating radar (GPR), were conducted in 2010, 2011 and 2012 to support the field and airphoto-based observations (Figure 1). In addition to the standard characterization of permafrost by geophysical investigations, a permanent array of 72 electrodes at 2 m spacing was buried along the shoulder of taxiway A during summer 2012 (see GR 2012 on Figure 1). This installation is part of an innovative experiment for imaging the in situ seasonal and spatial variability of unfrozen water content. Unfrozen water content is an important parameter in calculating the thermal properties of soil, which is used to predict the behaviour of the ground upon warming and thawing. Results from this research will be used in a new coupled heat and water transport model to simulate the thermal regime within and under airport embankments. Interpretation of InSAR displacement values will also benefit from knowledge of the seasonal variation in soil water and ice contents in relation to freezing and thawing.

Remote sensing data

Field observations can be complemented by ground displacement values using InSAR data (Gabriel et al., 1989; Massonnet and Feigl, 1998). The method is based on the principle that local surface elevation can be detected and measured from returning active microwave radar signals transmitted from a satellite to a reflective surface on the Earth. From the analysis of the phase shift between repeat-track synthetic aperture radar (SAR) acquisitions separated by a time interval (interferograms), the ground displacement in the SAR line-of-sight (LOS) can be calculated. In flat areas like the airport, satellite geometry can be used to convert the LOS observation to a vertical displacement. RADARSAT-2 Spotlight scenes (C-band SAR) on a descending orbit with an incidence angle of 45° were acquired on June 22, July 16, August 9, September 2 and September 26, 2011 and on May 23, June 15, July 10, August 3, August 27 and September 20, 2012. For each summer, the data were interferometrically stacked and vertical displacement was projected from the calculated LOS displacement. Each displacement measurement represents an area of approximately 1.5 by 1.5 m on the ground, and is a smoothed product of neighbouring pixels.

Permafrost characterization

Surficial geology

Approximately 67% of the length of the runway, which represents the initial runway built during World War II along with aprons and access roads, is built on glaciomarine deltaic deposits composed mainly of sand, boulders and gravel with the noted presence of some silty layers in the stratigraphy (Figure 2; Allard et al., 2012). Alluvial channels and lacustrine deposits are also present under the aprons and access road embankments. The northwestern extension of the runway built after 1948 overlies a glaciofluvial outwash terrace, a small esker and bedrock. Till and marine veneer complete the surficial geology surrounding the airport. Results shown by Mathon-Dufour (2011) and Mathon-Dufour et al. (2012) clearly indicate a strong link between surficial geology, permafrost features and the recurrent settlement and frost cracking problems affecting asphalt surfaces and embankments. Among these features, a dense network of ice wedge polygons present in the glaciomarine deltaic deposits appear to currently affect surface cracking on the runway. At least one pre-existing lake and one small stream (Lv and Ap, Figure 2) also appear to affect the largest apron (apron I, Figure 1) and one of the access roads (taxiway A, Figure 1).

Ground thermal regime

The permafrost temperature was recorded over two years (summer 2010 to summer 2012) at the AERO-2010 natural terrain site (Figure 1). During the second year of recording, the permafrost temperature was approximately −5.3°C at a depth of 10 m, with a maximum active layer thickness of 1.5 m (Figure 3, AERO-2012). However, additional data collected at thermistor site DDH-01 (Figure 1) from summer 2011 to summer 2012 shows that the active layer under a paved embankment reached a thickness of 2.5 m with a permafrost temperature of −4.6°C at a depth of 10 m (Figure 3, DDH-01).

Geophysical characterization

Surface observations made in the field and on airphotos indicated that some features now buried under embankments (e.g., ice wedges, filled river channels, drained lakes) are related to recurrent asphalt and embankment damages. The
Figure 2: Surficial geology in the area of the Iqaluit International Airport, Nunavut (from Allard et al., 2012). Background image (WorldView-1; DigitalGlobe, Inc., 2008) includes copyrighted material DigitalGlobe, Inc., all rights reserved. UTM zone 19.
GPR surveys were used to characterize the general stratigraphy and identify possible ice wedges under the paved surfaces at locations of prominent frost cracks. The ERI (CCR and GR) and EM31 surveys were used to delineate ice-rich permafrost areas and conductive anomalies.

LeBlanc et al. (2012) presented the results of GPR and CCR surveys conducted in 2010 and 2011 for the total length of the runway. The GPR results along the centre line of the runway show that within the glaciomarine sediments, the contact between the embankment and the natural ground does not correspond to a clear GPR reflection, possibly due to the similarity of the material used to build the embankment and the underlying deposit. Furthermore, Mathon-Dufour et al. (2012) reported a maximum embankment thickness over the glaciomarine sediments of approximately 2.5 m, which is similar to the maximum active layer thickness (Figure 3). The thawing front would produce a stronger GPR reflection due to the transition from unfrozen to frozen pore water as opposed to the transition between underlying natural ground and embankment of similar material. Along the centre line of the runway, hyperbolic reflectors indicative of ice wedges (Fortier and Allard, 2004) were also visible below the base of the active layer and beneath most of the major frost cracks (see Figure 2 for frost crack locations). Mathon-Dufour et al. (2012) studied in detail one area particularly affected by frost crack depressions (see GPR 2012, Figure 1). One GPR line conducted parallel to the runway, along with its interpreted cross-section, is shown in Figure 4. Results corroborate the GPR results obtained in 2010. However, according to the ground temperature record at DDH-01 and the maximum 2.5 m active layer thickness (Figure 3), it was possible to better calibrate the depth of the thawing front on the 2012 GPR profile at approximately 2.5 m depth (Figure 4). Hyperbolic reflectors below the active layer (interpreted as ice wedges) coincide with locations of frost cracks observed at the surface, whereas hyperbolic reflectors observed within the active layer are probably associated with open frost cracks (void left by melted ice veins within the active layer; Figure 4). This interpretation suggests that the thawing front has now reached the natural ground below the embankment and that settlement due to melting ice wedges will probably continue with further climate warming. Further interpretation of GPR profiles will allow a better assessment of the size of these ice wedges.

The 2011 CCR survey along the total length of the runway shows a conductive anomaly with resistivity below 200 Ω·m starting at the junction of taxiway A and extending approximately 650 m to the southeast (LeBlanc et al., 2012). There is a lack of ground information over this area.
Figure 4: a) Ground penetrating radar (GPR) survey conducted over a section of the runway in 2012 and b) its interpreted cross-section, Iqaluit International Airport, Nunavut.
since the initial runway was already built before the earliest available aerial photographs were taken in 1948. The only information available up to now is a topographic map from 1942 indicating that there was a small lake adjacent to the west side of the runway close to the junction of taxiway A and the runway. The size of the lake is too small to fit with the extent of the conductive runway anomaly and the runway anomaly is more resistive than that associated with the historical lake sediments along taxiway A. Preliminary 2012 GR results along taxiway A indicate resistivity values below 20 $\Omega \cdot m$ (Figure 5), similar to resistivity values given by a previous CCR survey over the same section. To investigate the spatial extent of the conductive anomaly observed below the runway and taxiway A, EM31 data were collected in 2012 along several lines on and adjacent to the runway and taxiway A. Apparent resistivity maps for shallow and deep EM31 measurements are shown in Figure 6. The shallow map represents an integrated measure of conductivity to approximately 3 m depth (Figure 6a) and the deep map represents an integrated measure of conductivity to approximately 6 m depth (Figure 6b). The maps are produced by interpolation between widely spaced lines and thus, care must be taken when interpreting features away from actual measurement points (Figure 1). However, in general, both shallow and deep expressions of a conductive anomaly (in blue, Figure 6) are observed along taxiway A. The anomaly strengthens with depth and to the southeast. It extends across the undeveloped region between the runway and taxiway A and seems to have some presence along the runway. Although the depth of investigation of the EM31 does not correspond to that of the CCR data or the GR data, there may be some connection between taxiway A and runway anomalies. Further data integration is required to investigate this relationship. In general, conductive anomalies are often associated with fine-grained permafrost soils that are thaw sensitive.

The InSAR-derived vertical displacement map

The InSAR data acquisition for the summer 2012 had just been completed over Iqaluit at the time of this report and its analysis has only begun. To give a sense of the results that are expected for this year, the InSAR vertical displacement map for 2011 is shown and described in this section (Figure 7). The 2011 summer InSAR data provided the seasonal distribution of relative ground surface displacement in the area of the airport and was used to identify thaw sensitive areas that might affect the performance of infrastructure. The InSAR results were interpreted based on surficial geology, knowledge acquired from the geophysical investigations and a comparison of ground movement with settlement values from two thaw tubes (LeBlanc et al., 2012; Short et al., 2012). The second set of InSAR images acquired in summer 2012 will

- improve understanding between the calculated displacements and the observed movement and properties of the underlying permafrost;
- assess how results may vary year to year; and
- start to differentiate between seasonal and multiyear trends in ground surface displacement.

Unfortunately, the smooth and asphalted surfaces of the runway, taxiways and aprons appear as areas of no data (Figure 7), as a result of loss of interferometric coherence. However, the displacement data can be analyzed on the adjacent shoulders and the terrain on both sides of the paved surfaces. The results of summer 2011 correlate very well with the mapped surficial geology (Figures 2, 7). Stable ground or very low downward surface movement correlates with bedrock and till units. In the airport surroundings, the greatest downward displacements were associated with marine and glaciomarine deltaic deposits. These displacements reflect seasonal settlement caused by thawing of the active layer and may also reflect thawing in near-surface permafrost. On both sides of the runway embankment, southeast of the junction between taxiway A and the run-

![Figure 5: Electrical resistivity survey (GR) conducted along the embankment shoulder of taxiway A in 2012, Iqaluit International Airport, Nunavut. Abbreviation: RMS, root-mean-square.](image-url)
Figure 6: Electromagnetic survey (EM31) data collected along several lines along and adjacent to the runway and taxiway A, Iqaluit International Airport, Nunavut: a) integrated measure of conductivity to approximately 3 m depth, b) integrated measure of conductivity to approximately 6 m depth. Background image (QuickBird; DigitalGlobe, Inc., 2006) includes copyrighted material DigitalGlobe, Inc., all rights reserved. UTM zone 19.
Figure 7: Interferometric synthetic aperture radar (InSAR)–derived vertical displacement map, showing the spatial distribution of the relative ground surface displacement during summer 2011 (June 22–September 26, 2011) in the area of the Iqaluit International Airport, Nunavut. Negative values represent downward displacement (from Short et al., 2012). Circle adjacent to the western end of taxiway A corresponds to the conductive anomaly shown in Figure 6. Background image (WorldView-1; DigitalGlobe, Inc., 2008) includes copyrighted material DigitalGlobe, Inc., all rights reserved. UTM zone 19.
way, a linear corridor about 30 m wide shows a deeper downward displacement compared to the surroundings. The trench at the embankment toe on the southwest side of the runway is deformed and saturated with water. Furthermore, the InSAR linear feature is more or less located between two major frost cracks and matches the conductive linear feature shown by the EM31 results (Figure 6). The InSAR 2012 results will help determine if this linear depression is recurrent over time or if it is deepening with time.

Although, the 2011 InSAR results correlate very well with the surficial geology, the results did not exactly match with the thaw tube settlement values. The calculated displacements were about half the settlement values observed in the field. Besides the fact that highly variable local conditions around thaw tubes may not have been reproduced by the averaging of the approximately 1.5 by 1.5 m ground pixel in the InSAR data, the InSAR acquisition of 2011 also started June 22nd, one month after ground settlement initiation, which can make a significant difference in measured total downward displacement. To overcome that, the data of 2012 were acquired from the beginning of the thawing season (May 23). Furthermore, in 2012, field observations, such as near-surface soil moisture and settlement, were taken at the same dates as the satellite image acquisition. Since InSAR is an emerging technology, its application to permafrost terrain will certainly improve the way permafrost is characterized at a useful scale for infrastructure monitoring and for assessing terrain for resources development.

Economic considerations

Development of Nunavut’s mineral resources and the infrastructure required to service development and communities are important factors supporting the territory’s economy (Aboriginal Affairs and Northern Development Canada et al., 2012). The Iqaluit International Airport is one piece of infrastructure on which mineral exploration and exploitation in Nunavut, and particularly of the Qikiqtaalik Region, strongly depend on for their growth. Several exploration projects in the region use Iqaluit as their main centre for supplies and services. As an example, Baffinland Iron Mines Corporation operates weekday flight service, providing transport for workers from Iqaluit to the Mary River mine development site. The recently announced construction phase of the mine will probably add more pressure on the use of airport facilities.

Each year, considerable investments need to be made by the Government of Nunavut to repair and maintain transportation infrastructure. In addition, the Iqaluit runway is now due for resurfacing along with a need for a general enhancement of airport buildings. Recently announced by the federal government, new funds granted to the Government of Nunavut will allow significant improvement of the Iqaluit airport (new terminal building, expanded aprons, upgraded runway, etc.) and thereby highlights the crucial importance of this ongoing research. This study has already documented some of the difficult permafrost conditions on which the airport was built in the early 1940s. With the onset of climate warming, the underlying permafrost will continue to degrade causing additional maintenance and sustainability problems. This information and understanding generated by this study will contribute to informed decision-making, and application of improved engineering design and development.

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