Submitted: 01/15/19

Research Article

Tabatha Rahman[1], Jeremiah Lee[1]

[1]McGill University, Montreal, QC, Canada

Keywords

High Arctic runway, Soil compaction, Periglacial environment, Hydrogeomorphology

Email Correspondence

tabatha.rahman@mail.mcgill.ca

Physical Responses to Anthropogenic Disturbance on a Runway in the Canadian High Arctic

Abstract

Background: The McGill Arctic Research Station (MARS) runway on Axel Heiberg Island, Nunavut, has been subject to intense compaction from aircrafts since the 1960's, causing alterations to the landscape across time and space. This study investigated the thermal, hydrological and physical responses of repeated aircraft compaction of the runway to characterize its vulnerability to land use, and the effects of long-term and repeated compaction.

Methods: In late July and early August 2018, the island's summer thaw season, topographic, soil, hydrological and frost table data were collected along four transects across the MARS runway.

Results: Topography and effective porosity differences caused by compaction were found to affect soil moisture contents, leading to the observed differential frost heaving and insulation properties of soil across the runway. Soil was found to be mostly silt on and off disturbed areas, indicating that compaction does not affect grain-size but rather pore space and soil bulk density. The frost table mapping suggested statistically significant variations in depth of the frost table across undisturbed, disturbed, and indirectly disturbed areas, showing that compression from aircrafts has both direct and indirect spatial impacts on the hydrogeomorphic system. Furthermore, this research examined possible solutions to mitigate thaw consolidation of the runway.

Limitations: The method of probing used to determine frost table depths introduced significant error to the data. Probing discrepancies arose between people probing and between sampling days, as techniques differed and/or improved. Future studies should consider using electrical resistance tomography to map the frost table, as this would eliminate inconsistencies. Furthermore, while pore size distributions were inferred based on grain-size and extent of compaction, subsequent studies should consider a quantitative approach to pore space analysis.

Conclusion: This study suggests that aircraft travel to the remote McGill Arctic Research Station causes spatially and temporally significant changes in the local hydrogeomorphology, especially in fine-grained and wet, frost-susceptible soils. Thaw consolidation, which results indicate is caused by the direct and indirect effects of soil compaction, compromises the prolonged use of the runway.

Introduction

The runway at the McGill Arctic Research Station (MARS), near Expedition Fjord on Axel Heiberg Island, Nunavut, has undergone significant physical disturbance since Expedition Fjord gained scientific interest following Fritz Müller's first expedition in 1959 (1). Small aircrafts have repeatedly compacted the MARS runway, and the ice-wedge polygons found on the runway have been infilled over the years to counter the effects of subsidence, as shown on Fig. 1. As thaw consolidation of the ice-wedges continues, an understanding of the hydrogeomorphic system in this dynamic periglacial environment becomes crucial for the prolonged use of the runway.

Fig 1. Transect 3 with its polygon troughs infilled with gravel and rounded stones.

The MARS runway has summer air temperatures averaging 5°C (2) and is considered a polar desert (3). During the late spring and summer, its mineral soils are moist and even saturated, as soil water and groundwater are restricted to the thin portion of thawed ground above the perennially frozen soil. This is referred to as permafrost. Soils in polar regions are subject to intense mechanical weathering causing patterned ground, such as polygonal terrain or ice-wedge polygons. Considering water expands by 9% when freezing, and freeze-thaw cycles cause rock and soil weathering, erosion, and displacement (4). Thus, frost action and frost heaving are leading processes in landscape alteration of this environment.

Soil and water interactions (i.e. hydrogeomorphic processes) are of major importance to this study (5). Hydrological properties, such as hydraulic conductivity, moisture content, drainage, and water retention capacity of the soil affect the magnitude of frost heaving and the formation of ice-wedge polygons. Ice formation within the active layer, also known as the cryostructure, affects the ground's susceptibility to subsidence, which is a safety concern for the MARS' runway.

Through analyses of the frost table depth, topography, soil moisture content and particle size distribution of soil, this research sought to spatially and temporally define the thermal, hydrological and physical responses of repeated aircraft compaction on and around the runway of the McGill Arctic Research Station. This paper provides a qualitative and quantitative overview of the responses of repeated compaction of the runway, which could be used for future mitigation efforts to ensure the continued use of this Arctic tundra runway.

Methods

Field Methods

The runway (79°24'55.1" N; 090°45'51.0" W) lies in an unglaciated valley with significant soil development. Its gentle slope allows for water drainage towards the areas of lowest elevation: Colour Lake and the marsh (Fig. 2). Low-lying polygonal troughs (i.e. ice-wedges) act as surface preferential flow paths, further supporting drainage towards the lake and marsh. The ice-wedge polygons are present on and around the runway, displayed in Fig. 1 and Fig. 3.

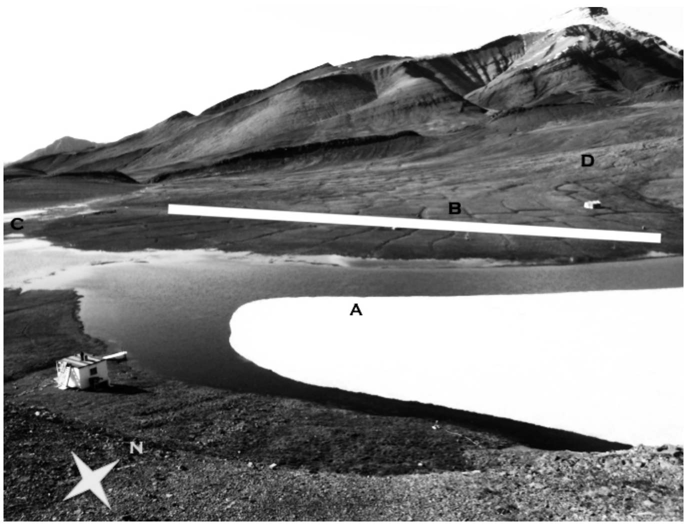

Fig. 2. The topographic profile of the runway, from SW to NE. Transect 1 is the left-most, followed by transects 2, 3 and 4.

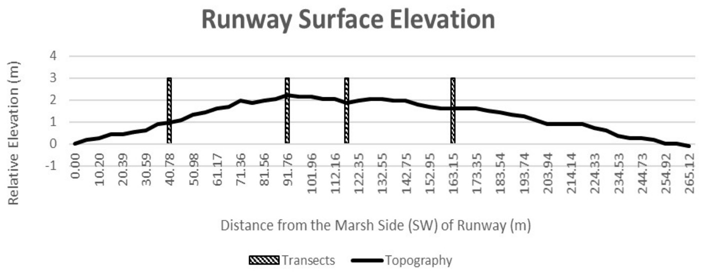

Fig. 3. View of the runway, here shown by the white arrow line at the center, from MARS. A is Color Lake (partially covered by ice), B is the polygonal terrain, C (at the very left) is the marsh and D is the alluvial fan.

Field data was collected in late July and early August 2018, during the local summer thaw period. The length of the runway is 265 m Southwest to Northeast and 10.5 m wide. Four 35 m transects, henceforth named T1, T2, T3 and T4, were established perpendicular to the length of the runway to incorporate the variability in the conditions along its length. Among the four transects, only T3 and T4 were defined by polygonal terrain, while T1 and T2 had desiccation cracks. T3 had some gravel and a large cobble-filled polygon trough, while T4 had polygon troughs filled with Styrofoam and gravel. The difference in surface patterns on each transect illustrates the small-scale hydrogeomorphic differences across the runway.

A 1 m resolution topographic profile of each transect was built using a level string at an arbitrary height above each transect, from which the soil-string distance was measured at every meter along the transect.

A 5 m resolution topographic profile of the length of the runway was also built (Fig. 2). Two poles, held vertically and interconnected by a 5m rope, were transported across the runway, while the horizontal distance between them was measured. Using a Brunten (Forestry Suppliers, Inc), the angle formed by the rope from the horizontal was measured. Basic trigonometry then allowed for the changes in elevation to be calculated.

Each transect was subdivided into three sections: undisturbed, disturbed, and indirectly disturbed. The undisturbed sections comprised points 1 to 8 along the transects, or the first eight meters upslope (North) of the runway. The disturbed regions were the runway portions of the transects, from point 9 to point 21. The indirectly disturbed sections were the section downslope (South) of the runway, from points 22 to 36. It was hypothesized that this third region was indirectly affected by aircrafts through disturbances in the hydrological and thermal regimes radiating from the disturbed locations. This was tested by comparing the mean frost table depth in each section.

The frost table depth was measured using a 1.5 m stainless steel rod. Although depths were measured to the nearest centimeter, a significant error was introduced due to the high presence of rocks and compacted soil material. When it was assumed that the rod hit a rock rather than frozen ground or when there was a discrepancy of more than 3 cm from the previous day's probing depth, four additional data points within a 0.4 m radius were taken. The deepest data point was kept and considered to be the frost table depth. If all data points were 3 cm closer to the surface than past probe depths, the data was excluded from analysis, as bottom-up freeze up is unlikely at that time of year. Probing discrepancies also arose between people probing and between days, as techniques improved. Future studies should consider using electrical resistance tomography to map the frost table, as this method would eliminate inconsistencies and would be more precise, albeit more expensive.

For particle-size and moisture content analyses, two soil samples were collected per transect on either side of the runway (upslope and downslope). The purpose of these samples was to compare moisture contents upslope and downslope from the disturbance to determine if compaction affected the hydrological system.

Laboratory Methods

The gravimetric field moisture content was calculated in lab using differential weighing of dry and moist soil, to find the percentage air-dry mass of soil. All soil samples' grain size distributions were tested using Kroetsch et al. (2007) (6) hydrometer method to separate silt, sand and clay. Soil solutions were then poured into 2mm and 63um sieves to separate larger particles such as gravels and sand.

Results

Transect Topography and Frost Table Depth

Using an ANOVA F-test with a completely randomized design to compare 3 treatment means and $\alpha = 0.05$, T1, T2 and T4 were found to have statistically different frost table depth between their undisturbed, disturbed and indirectly disturbed sections, and only the third transect's frost table was found to be statistically unchanging across. However, this finding is believed to be caused by an outlier. T1, T2 and T4's three sections had at least two of their sections' mean frost table depth that differed from one another, suggesting that the anthropogenic disturbance to the runway caused significant changes to the frost table depth. As shown in Table 1, T1 and T4 saw a general deepening of the frost table going downslope. T1's frost table decreased by 12.5 cm from the undisturbed to the disturbed area, and stayed relatively constant from the disturbed to the indirectly disturbed section. T2 saw a local depression in its frost table on the runway, as there was a decrease of 19.2 cm from the undisturbed section to the disturbed, and a 20.0 cm increase in the frost table from the disturbed to the indirectly disturbed. T3's variations in frost table depths were less than 5.6 cm and statistically insignificant. T4's frost table descended by 6.9 cm, and then again by 2.1 cm.

	Mean depth of the frost table			
	T1	T2	T3	T4
Undisturbed	40.8	54.8	53.0	60.3
Disturbed	53.3	35.6	50.1	67.2
Indirectly Disturbed	53.1	55.6	55.8	69.3

Table 1. Mean frost table depth (cm) within three subsections of each transect of the runway.

Grain Size Distribution

Grain size distribution was used to infer hydrological and thermal properties of the soil. Silt was determined to be the main component of the soils on and around the runway. Soils analysed from a nearby undisturbed polygon trough and top were compared to the disturbed runway soil. The grain size distributions were consistent to the ones on the runway, suggesting compaction does not affect grain size.

Soil Moisture Content

As shown on Fig. 4, T1 and T3 saw a decrease of moisture content downslope. The difference in moisture content between the upslope and downslope edges of the runway suggests that compaction on T3 alters the ability of water to flow in the subsurface. Evidence of pooling of water at the upslope edge of the runway on T3 further corroborates this theory, as compaction of soil acts as a physical barrier to groundwater flow. Compacted soils have less pore space in which water may travel in and cause water accumulation, in turn causing subsidence.

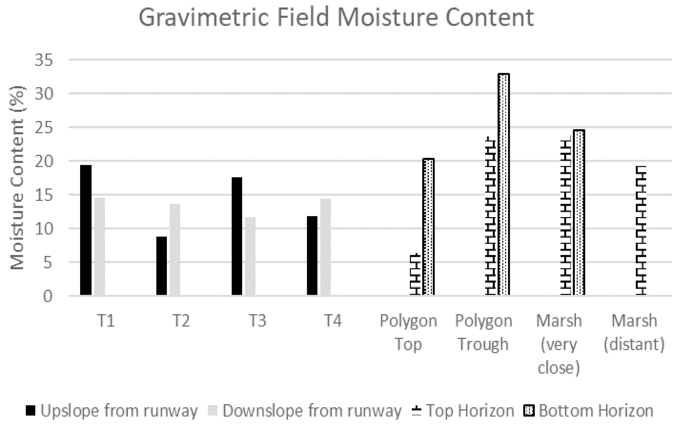

Fig. 4. Gravimetric field moisture content of soils and around the runway at MARS. Samples were taken upslope (e.g. North) of the runway and across the runway (e.g. South) along each transect.

The most prominent difference in moisture contents was found between the topmost horizons of the polygon peak and trough. This is most likely due to the topographic difference between the two, as the trough lies closer to the water table than the peak.

Discussion

Polar soils are most susceptible to disturbance in late spring, while thawing of the active layer has begun and there is a thin layer of thawed and saturated soil above the frozen ground (7). Much of the aircraft traffic on the MARS runway happens during this crucial time, as access to the research station is restricted during winter.

Aircrafts' usage of the runway at Expedition Fjord certainly disrupts the natural equilibrium of the land, but the extent to which is does so depends on the frequency, intensity, scale and timing of these disturbances (7). The intensity of impact between the aircraft and the runway is relatively constant. Only helicopters and bush planes, including Twin Otters with empty weights varying between 2653 kg and 3363 kg (8), can land at the MARS runway. The frequency is restricted to less than 20 landings and takeoffs per year, over several decades. This repeated disturbance does not allow the system to reach a new steady-state, but rather creates a dynamic, evolving system.

One of the most important responses to the runway's land use on a safety point of view is the subsidence of ice-wedge polygons on the runway. An uneven surface is a safety hazard for aircrafts, and remediating this problem is necessary for the prolonged use of the runway. Gravel, stones and Styrofoam have been inserted into subsiding polygon troughs to prevent further thawing and to flatten the surface of the runway (Fig. 1). Kevan et al. (1995) (6) studied vehicle tracks' effects on soil and vegetation at Hazen Camp, on Ellesmere Island (Nunavut), and observed that ice-wedge polygons deepened and widened where tracks were present. Their paper argued that subsidence in wet areas was the effect of direct compression from vehicle tracks. Ice-wedge polygon subsidence is indeed related to the thermal and hydrological systems. Usually, the amount of water in frozen soil is superior to that which can be held in thawed soil (4). When thawing begins, sediments settle as the excess water drains, causing thaw consolidation. At the MARS runway, as subsurface water flows encounter the compacted soil of the runway as they flow downslope, there is a damming effect on the North (upslope) side of the runway in polygonal terrain. The preferential flow paths within the polygonal troughs are assumed to have been disturbed and supressed by the compacted soil of the runway, causing water to pool and thus causing thaw consolidation, as shown on Fig. 5. This is an example of the radiating effects of the disturbance, as this feedback effect is not located on the runway itself, but rather on ground that is not directly used by the planes. This reinforces the idea that in the Arctic, disturbances have rapid cascading feedback effects (9) that tend to extend through space and time.

Fig. 5. The white box shows the local depression that formed on the NW side of the runway near T4, as a response to the disturbed subsurface water flow.

Variations in the active layer and frost table depths are other responses to the disturbance by aircrafts. As shown in Table 1, there is a statistically significant difference in frost table depth across transects 1, 2, and 4. The active layer depth depends on thermal systems within soils, as thawing is enabled through the thermal conductivity of soils and soil-waters. Forbes (10) showed that physical disturbances cause greater variations in diurnal and seasonal soil temperatures than undisturbed soils. Greater variations imply increased potential for freeze-thaw cycles, imposing greater mechanical strain on soils. In depths greater than 5.0 cm – 10.0 cm, only annual freeze thaw cycles take place (4), suggesting that most of the frost action (e.g. frost heave) takes place in the upper 10 cm of soil. As a result, most of the preferential sorting occurs within this topmost layer of the ground, which coincides with the layer that is subject to the greatest compaction.

Some soils are prone to stronger compaction feedback effects. Studies suggest that the ability of soils to compact is related to numerous factors, notably the cohesive force between particles (11, 12). Compaction of Arctic soils by vehicles has shown to result in shifts in ground albedo, soil moisture, pH, active layer development, soil temperatures, vascular plant biomass, total species richness and mineral nutrition (10). High Arctic thermal and plant nutrient cycling regimes have shown to be affected for decades after a single vehicle pass (10), demonstrating the extended temporal effect of vehicular use on Arctic soils. Lowery and Schuler (1991) studied silt loam, similar in particle-size to the MARS runway soils, and concluded that compaction by heavy farm equipment over one year lowers plant height for over 4 years (13). Vegetation differences were clear between the runway and the areas adjacent to it; the runway had extremely few plants growing on it. Because plants are important sources of insulation, since they create an organic layer that buffers air temperatures from the soil, the removal of plants further affects the thermal regime of the runway.

Furthermore, compaction affects water retention curves and hydraulic conductivity, as porosity is altered in compacted soils (14). In the event of stagnation of water during freeze-up, thaw consolidation is more likely to happen upon thawing the following spring, as large amounts of water within the soil matrix are released. The soil on the MARS runway would therefore benefit from both high porosity, to allow for drainage, and from fine pores, to allow moisture movement under dry conditions. As large clasts are less likely to see a reduction in effective porosity with compaction, infilling subsiding troughs on the runway with gravel and small stones would allow for pore spaces to be maintained, even under immense compaction.

Compaction also leads to a decrease in the insulative properties of soil, as pore spaces are reduced and gas, which acts a buffer between surface air temperatures and soil temperatures, is pushed outside of the soil matrix. While the results of this study do not suggest compaction impacts soil texture, future studies should look at pore size distributions on and off the runway, as compaction does affect the soil's ability to store and transmit water and heat (15, 16) by changing the effective porosity of soils, which in turn affects plant growth and periglacial processes.

Compaction, combined with the increased thermal conductivity of soils due to the removal of vegetation, increases the runway's susceptibility to thermal erosion. Shilts (1978) found a thicker active layer in bare ground and fine-grained soils, compared to vegetated, coarse grained soil (17). This finding is consistent with T1 and T4's frost table depth on the runway, and suggests that the fine-grained bare soils of the runway are not good insulators. However, a deeper thawing was not present on T2, as the frost table was closer to the surface. T2's location in relation to the other transects indicates that it is at a high point (Fig. 2), allowing for relatively better drainage. Because thermal conductivity of soil rises with increasing moisture content (18), it was hypothesized that this transect was dryer than the others, as its frost table was shallower than the other transects'. However, the results from the gravimetric water content tests do not fully corroborate this.

The scale of the disturbance response is also influenced by the topography of the landscape, as it affects thermal and hydrologic cycles within the soil. Microtopography determines subsurface and surface water flow velocities and determines some of the sources of water made available to the system. In active layer hydrology, flowing subsurface water has been known to have a warming effect on the underlying frozen ground (18). For example, water tracks in the Antarctic polar desert had active layers twice as thick as adjacent areas (19). However, for a warming effect to take place, the residence time of water must be long enough to allow for advection (14). The shallow slope of the MARS runway enabled advection from the water to the surrounding soil because surface and subsurface water flow had negligible velocity. Advection may be involved in the thaw consolidation of polygon troughs and of the upslope boundary of the runway near T3 (Fig. 5). However, the source of subsurface water also influences its ability to warm the active layer. While snow or ground ice melt releases water with little available heat, rain events deliver more heat to the ground. As rain is expected to be the dominant form of precipitation in the Arctic by the 2080 (20), there will be considerably more heat entering the soil system of the runway at MARS, causing further subsidence.

Conclusion

Scientific research at Expedition Fjord has caused landscape and hydrological alterations of the MARS runway. As the scale of impact is not equivalent to the scale of response, mitigation measures should be taken to prevent further thaw consolidation and subsidence, yet solutions are limited. A static equilibrium recovery cannot be envisioned for the runway, as disturbances are repeated from year to year. Becker and Pollard (2016) found that a High Arctic airstrip, unused for the past 60 years, still has not reached its pre-disturbance conditions, but rather has moved towards an ecological succession with a new stable-state community (21). Considering the ongoing repeated disturbance events on the MARS runway, this study suggests that disturbance responses can be mitigated by allowing the thawed active layer to transport water and by increasing the insulative properties of the soil.

Airports and landing strips across northern latitudes have faced similar problems with frost heave and thaw settlement; the main problem is the obstruction of groundwater flow paths. Major Northern airports that welcome large freight and passenger aircrafts and that have, as a result, more regulated safety measures, have paved asphalt runways, with excavated material beneath them filled with non-frost susceptible structural fill. However, this is not a viable option for smaller airstrips, where the use of gravel and rocks as infill (7), similar to MARS' runway, is more common (4). Future studies of the MARS runway should investigate subsurface water flow paths, which would provide insight on how to potentially redirect water flow to artificial preferential flow paths, thus diminishing subsidence on crucial locations on the runway.

Acknowledgements

This research was funded by McGill University's Dr. Olav Loken Undergraduate Geography Award for Northern Canadian Research, Irene Woods Field Study Award, Laboratories without Borders and Undergraduate Basic Mobility Award, and by the Polar Continental Shelf Program (PCSP). We are very thankful to Dr. Wayne Pollard, Dr. Christopher Omelon, Dr. Laura Thomson, Dr. Tim Moore, Mike Dalva, Alouette Zhang, Theresa Gossmann, Martine Dolmiere and the people of PCSP for their contributions to this project.

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