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Challenges from North to South
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The Inuvik Airport Runway – An evaluation of 50 years of performance

Ed Hoeve
Tetra Tech EBA Inc., Yellowknife, Northwest Territories, Canada
Don Hayley
Hayley Arctic Geoconsulting, Kelowna, British Columbia, Canada

ABSTRACT
The runway at Inuvik airport was constructed in the late 1950's entirely as a fill section, using locally quarried rock. The fill thickness was selected by balancing the objectives of limiting the thermal impact on the underlying permafrost and keeping the cost of the embankment to an acceptable amount. The runway was paved in 1969. Ground temperature monitoring until 1974 indicated that the runway was exceeding expectations, from a ground thermal response perspective. The active layer was being maintained within the embankment fill. Current ground temperatures in the vicinity of the runway indicate that significant warming has occurred. Observations indicate that seasonal thaw is now extending below the embankment at some locations. The thaw of ice-rich subgrade soil has resulted in settlement, which is an operational and safety concern. Proposed measures to stabilize the settlement by controlling seepage are described. The implications for a future runway extension are also described.

RÉSUMÉ
La piste à l'aéroport d'Inuvik a été construite avec du remblai, vers la fin des années 1950, en utilisant la pierre extraite localement. L'épaisseur du remblai a été déterminée en considérant les effets de l'impact thermique sur le pergélisol sous-jacent tout en essayant de maintenir un coût de construction acceptable. La piste a été asphaltée en 1969. Les données de surveillance de la température du sol ont indiqué qu'en terme de réponse thermique du sol, la piste avait dépassé les attentes jusqu'en 1974. La couche active avait été maintenue dans le remblai. L'analyse des données de températures actuelles du sol au voisinage de la piste indique qu'il y a eu une augmentation significative de la température du sol. Les observations indiquent que la fonte saisonnière s'étend désormais jusqu'en dessous du remblai à certains endroits. Le dégel du sol de fondation riche en glace a entraîné le tassement du sol, ce qui constitue une préoccupation opérationnelle et sécuritaire. Les mesures proposées pour stabiliser le tassement en contrôlant les infiltrations sont décrites. Les implications pour une extension future de piste sont également décrites.

1 INTRODUCTION

The Northwest Territories spans the permafrost regions from sporadic, discontinuous permafrost to continuous permafrost (Heginbottom et al. 1995). Consequently, much of the infrastructure in the Northwest Territories has been constructed on permafrost. Engineering practice has developed to account for the integrity of the permafrost, and often this is an integral part of the design. Mean annual air temperature records reveal that air temperatures have been warming in the area since about the mid-1970's (Burn and Kokelj 2009). Climate warming is expected to continue, with a predicted mean annual air temperature increase of approximately 3 C° over the next 60 years (CSA 2010).

The runway at Inuvik was designed and constructed in the late 1950's, in accordance with the state of practice at the time (Johnston 1981). There is good documentation of the geotechnical conditions of the site prior to and following initial development. Engineering work is underway in connection with a proposed runway extension. This paper compares the present permafrost conditions with those reported previously. The implications of changes that have been noted are considered, both in the context of the performance of the existing runway and for the proposed extension.

2 INUVIK AIRPORT SITE DESCRIPTION

2.1 History

In the early 1950's, Aklavik was the main centre in the western Arctic. Increased government activity and development in the area was constrained by the generally poor construction sites and flood risk in this community, situated in the Mackenzie Delta. Therefore, in 1953, the Government of Canada conducted a study to identify an alternative location for Aklavik. The site originally identified as East-3, and later renamed Inuvik, was selected for development. The location of the community is shown in its broad geographical context in Figure 1.
Inuvik was Canada's first community engineered for continuous permafrost terrain. As such, there was much study undertaken into the site conditions. The baseline geotechnical conditions are documented in Pihlainen (1962).

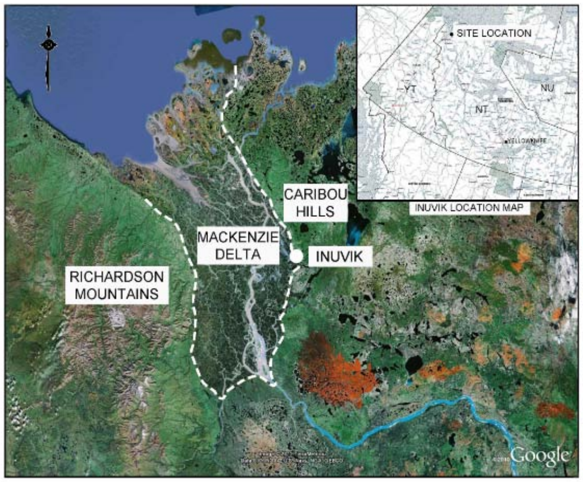

Figure 1. Inuvik Site Location

The airport is about 12 m southeast of the community at 68° 18' N latitude and 133° 29' W longitude, about 190 km north of the Arctic Circle. The site is an upland about 4 km east of edge of the Mackenzie Delta.

The runway (Runway 06-24) was among the first pieces of infrastructure to be constructed, in 1957 and 1958 (Johnston 1981). The following paragraphs summarize the design and construction.

Thaw depth was analyzed using the one-dimensional modified Berggren equation. It was determined that a gravel-surfaced embankment would need to be at least 3.6 m thick, and an asphalt surfaced embankment would need to be at least 4.2 m thick to prevent thawing of the underlying permafrost. This was not considered to be practical to achieve. Therefore, the design was for a minimum embankment thickness of 2.4 m. However, to satisfy grade requirements, the average fill thickness would be about 3.0 m, and the maximum fill thickness would be about 4.2 m.

The site was cleared but not stripped of organic cover. The use of 150 mm minus quarried rock fill was planned, but run of quarry rock fill was used, due to good fragmentation during blasting in the dolomite quarry to the west of the airport. Rock fill was placed for an originally designed 1,520 m runway length in 1957. Early in 1958 it was decided to extend the runway to its current 1,830 m length, with additions to each end of the runway. A 230 mm thick surface course of 40 mm minus crushed gravel was also placed on the runway in 1958.

Two small ponds were filled during the construction of the runway, one near its west end and the other near its east end. These areas exhibited less than 0.1 m of settlement for about a year following construction, but stabilized after that.

In 1969 the apron was enlarged and the airside surfaces were paved. The 40 mm minus crushed gravel thickness was increased to about 300 mm and a 90 mm thickness of asphalt was placed. In subsequent years the apron was enlarged again and Taxiway B was constructed.

Between 1970 and 1974 settlement occurred near the junction of the apron and Taxiway A; totaling about 0.5 m. This was attributed to impeded drainage percolating through the fill. Additional fill was placed, and a ditch was excavated to divert the runoff.

The apron and Taxiway E, associated with the Forward Operating Location, were constructed in about 1990. The current configuration of the airport is shown in Figure 2.

2.2 Geology

The bedrock geology of the Inuvik airport area consists of Precambrian argillite, Devonian carbonates, and lower Cretaceous shale (Norris 1975). Precambrian argillite bedrock is exposed along the lakeshore to the south of the airport, and Devonian dolomite is extracted from the quarry to the west of the airport (Dyke 1990). Under the runway, the upper bedrock is Cretaceous shale (Tetra Tech EBA 2014a).

The overburden is mapped as till veneer over bedrock (Rampton 1981). This unit, deposited during the late Wisconsin glaciation, reportedly varies from clayey to stony in deposits up to about 5 m thick.

Figure 2. Airport Plan

The terrain slopes gently down from north to south. The bedrock bears east-west oriented glacial fluting that is reflected in the surficial topography (Rampton 1981). Consequently, the terrain is locally overlain by fluvial, lacustrine and organic deposits (Tunnicliffe and Burn 2011; and Tetra Tech EBA 2014a).

The terrain has relatively low gradients, especially in the east-west direction, which means streams flow slowly, are probably intermittent, and are associated with thin peat. In some locations streams flow into a wide wet area and reappear further down-gradient (Tetra Tech EBA 2014a).

2.3 Climate

Environment Canada maintains a weather station in Inuvik, NT, and has records available since 1957 (Environment Canada 2015). Climate is presented in terms of "*Normals*", with parameters compiled as averages over 30-year intervals, and updated every decade. The latest Normals available are for the period 1981-2010. Table 1 compares the current climate Normals for air temperature and precipitation to the average values reported by Johnston (1981). The differences, noticed with air temperature in particular, are described more fully in the following paragraphs.

Mean annual air temperatures over the period of record are plotted in Figure 3. It is evident that there is large year-to-year variability. Despite the scatter, it is also evident that there has been an overall warming trend.

The premise of the climate Normals, that is, the average of the preceding 30 years, is useful for identifying trends from the annual variability. Thus, the 30-year moving average of the mean annual air temperatures is also plotted in Figure 3. This concept has been referred to as a "*dynamic normal*". The trend of the 30-year moving average is warming at the rate of about 0.07°C per year, and it appears to have been quite consistent over the almost 30 year period that 30-year moving averages can be calculated.

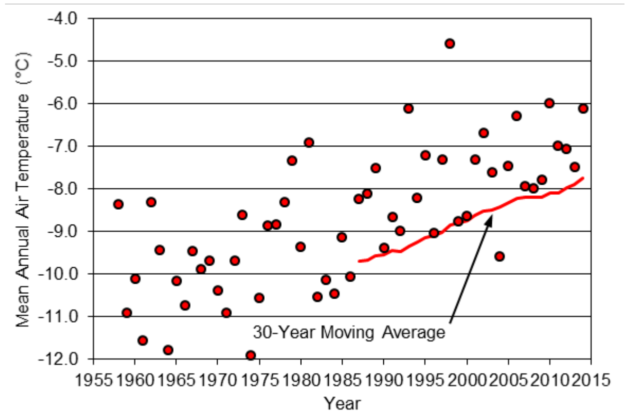

Figure 3. Inuvik Annual Air Temperature Record

Table 1: Average and Normal Values of Air Temperature and Precipitation, Inuvik, NT

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
						Air Temperature (°C)							
1958-1974	-31	-27	-25	-14	-1	11	14	10	3	-9	-22	-28	-10
1981-2010	-27	-26	-22	-12	0	12	14	11	4	-8	-21	-24	-8
						Precipitation (mm)							
1958-1974	22	8	8	12	17	24	39	42	18	29	22	13	254
1981-2010	12	13	12	10	17	17	35	39	29	24	16	15	241

It is interesting to note in Figure 3 that the 30-year moving average appears to represent the lower bound of the mean annual air temperature. Since the late 1980's, with only one exception, the mean air temperature in a given year has not been lower than the average of the previous 30 years. This indicates that in a time of changing climate, even a 30-year moving average may not be a good indicator of current conditions.

Over the last 30-years, the mean annual air temperature for Inuvik has averaged -7.7°C. The annual freezing and thawing indices for Inuvik have averaged 4,113 and 1,324°C-days respectively, during this same interval. The freezing index has been decreasing by about 19°C-days per year and the thawing index has been increasing at the rate of about 4°C-days per year. This indicates that winter temperatures are increasing more than summer temperatures.

Total annual precipitation over the period of record is plotted in Figure 4. The data were reasonably complete up to 2007. The data has become less reliable since 2007. While there is considerable scatter throughout the period of record, it appears that the annual variability may have increased since the mid 1990's. The 30-year moving average is also plotted in Figure 4. While no strong trend is indicated, there does appear to be a slight decrease in annual precipitation, at the rate of less than 1 mm/year.

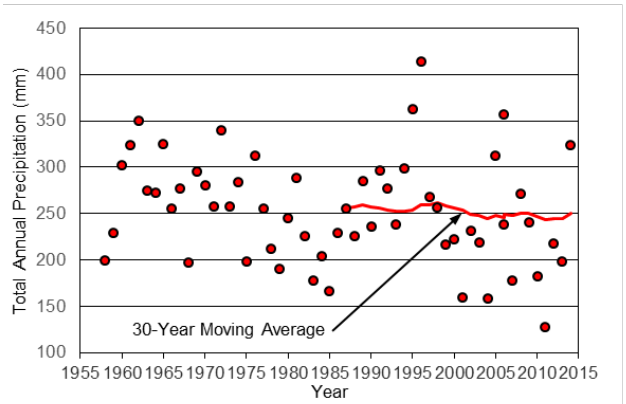

Figure 4. Inuvik Annual Total Precipitation Record

Air temperature and precipitation parameters reported by Johnston (1981) are compared with the most recent Normals and the current 30-year moving averages in Table 2.

Table 2: Inuvik Climate Data Summary

Parameter	1958-1974	1981-2010 Normal	Current 30-Year Moving Average
Mean Annual Air Temperature (°C)	-10.1	-8.2	-7.7
Freezing Index (°C-days)	4825	4212*	4113
Thawing Index (°C-days)	1190	1297*	1324
Total Precipitation (mm)	254	241	250

*these values differ slightly from the Environment Canada Normals, as they were calculated from monthly means

2.4 Permafrost Conditions

Inuvik lies in the continuous permafrost zone (Heginbottom et al. 1995). This means that permafrost underlies more than 90% of the terrain. The airport is underlain by permafrost. While ice contents are variable, the upper 3 to 5 m of the clay till is typically ice-rich. Ice contents decrease such that the deeper till and underlying shale bedrock is generally not ice-rich (Tetra Tech EBA 2014a).

2.4.1 Ground Temperatures

Pihlainen (1962) presents ground temperature measurements from a thermocouple in undisturbed terrain at the airport. The deepest sensor was at a depth of 4.6 m below ground surface. Nine months of readings from late January to late October 1958 indicate a range of -1.7°C to -5.8°C, and were interpreted to suggest an annual average of about -3.6°C.

Johnston (1981) presents plots summarizing 5 to 10 years of ground temperature measurements at four airside locations, one on the apron, two on the runway centreline, and one on the runway shoulder. All installations indicate a mean ground temperature of in the range of -5.0°C to -5.5°C, at the maximum installation depth of 4.6 m. This suggests that an early response to runway construction was cooling of the ground, likely due to a decrease of the buffering effect of vegetation and organic soil at the ground surface, and from snow compaction and clearing in the winter.

Thermistor cables were installed along the edges of the runway during a site investigation in 2014. Dataloggers were installed in September 2014. Six months of daily data was available at the time of writing. Figure 5 summarizes the data for the three installations where data was available. The range of ground temperature measurements drop below 1°C between about 1 m and 2 m below grade, such that the measurements from below those depths can be considered to approximate annual averages.

For consistency with the depth of previously reported ground temperatures, the ground temperatures at a depth of 4.6 m ranged from -0.6°C to -0.8°C, and averaged -0.7°C. While these off-embankment locations may not have experienced the cooling exhibited under the embankment, warming of about 3°C over the 60 years since initial site development is indicated. At a depth of about 10 m below grade, the mean annual ground temperatures range from -1.0°C to -1.4°C and average -1.2°C, thus indicating warming of about 2.4°C since site development.

Hoeve (2012) concluded that ground temperature changed roughly in step with air temperature at a site in the town. A review of the air temperature records indicates that mean annual air temperature began to increase in the mid-1970's. After 4 decades, at the 0.07°C/year rate interpreted Section 2.3, gives a cumulative mean annual air temperature increase in the range of -2.5°C to -3°C. So, the recorded ground warming of about 2.4°C does seem to be attributable to the increase in air temperatures.

Often, ground warms near the toe of embankments in permafrost, as a result of increased snow accumulation in the winter. As the current ground temperatures seem to be attributable to climate warming, it is not obvious that the warming effect of snow accumulation has occurred along the runway. The embankment side-slopes are at 10 horizontal to 1 vertical, so perhaps are gentle enough to mitigate differential snow accumulation.

2.4.2 Active Layer Thickness

It is difficult to draw conclusions about changes to active layer thickness over time, when observations come from different locations with different surface conditions and different subsurface material properties. However, observations on active layer thickness are reviewed in the following paragraphs.

Pihlainen (1962) reports active layer thickness in undisturbed areas to range from 0.3 m in peat, to 1.3 m in gravel (under 0.1 m of peat), in 1954, prior to community development.

In 1957, at the onset of community development, active layer thicknesses were observed to be 0.6 m in undisturbed areas or relatively undisturbed areas where the surficial moss was left intact (which was the surface treatment at the airport); 1.5 m in areas stripped of organics and underlain by fine-grained soil; and 2.4 m in areas stripped of organic soil and underlain by coarse-grained soil.

Interpretation of the 10 and 5-year mean ground temperature envelopes presented in Johnston (1981) shows the active layer thickness ranging from 2.0 m to 2.7 m, and averaging about 2.4 m at four locations in the runway and apron embankment. The active layer thickness at the one gravel-surfaced location was in the middle of the range of asphalt-surfaced locations, suggesting that surface treatment did not have a large influence in this instance (i.e. in relatively large fill thicknesses). In general the active layer thickness increased with the fill thickness.

The variation of the active layer depth was less in relation to the bottom of the fill. The active layer was contained within the fill, reaching from 0.5 m to 0.7 m, and averaging 0.6 m, above the bottom of the fill. Or, stated another way, the permafrost aggraded an average of about 0.6 m into the fill, regardless of the embankment thickness, within the range of thicknesses monitored.

The ground temperature envelopes in Figure 5 indicate active layer thicknesses ranging from 1.4 m to about 2.0 m, and averaging about 1.6 m. These installations compare most closely with the relatively undisturbed location underlain by fine-grained soil, at which an active layer of thickness of 1.5 m was reported by Pihlainen (1962). This suggests that climate warming has not significantly impacted the active layer thickness to-date. This also supports the previously discussed conclusion that significant warming at the toe of slope, as a result of embankment construction, is not evident.

2.4.3 Ground Temperature Gradient

There is no information on the near-surface ground temperature gradient in the vicinity of the airport prior at the time of site development. However, Hoeve (2012) interpreted that data presented in Brown (1966) to indicate a ground temperature gradient of about 0.03°C/m at an undisturbed site about 1 km east of Inuvik in the early 1960's. This is on the same order as the geothermal gradient of about 0.05°C/m indicated in Burn et al (2009).

While the ground temperature data presented in Johnston (1981) only extends to a depth of 4.6 m, the means do reveal a near-surface gradient. The ground temperature gradients at the four locations presented are interpreted to range from 0.08°C/m to 0.15°C/m, and average 0.11°C/m. Thus, near-surface cooling at roughly double the geothermal gradient, or three times the predevelopment near-surface ground temperature gradient is indicated. This is attributable to runway construction and operation.

The data presented in Figure 5 suggests near-surface ground temperature gradients ranging from -0.06°C/m to -0.11°C/m, and averaging -0.09°C/m. Thus the gradient has become inverted from what has previously been observed. This suggests a heat flux into the ground that can be attributed to climate warming. The key permafrost parameters that have been discussed are summarized in Table 3.

Table 3: Summary of Ground Temperature Parameters

Time/ Reference	Setting	MAGT (°C)	Active Layer Thickness (m)	Ground Temperature Gradient (°C/m)
Late 1950's (Pihlainen 1962)	Off runway	-3.6	1.5	n/a
Early 1960's (Brown 1966)	Off runway	-2.9 to -4.2	n/a	+0.03
Early 1970's (Johnston 1981)	Under runway	-5.1	2.4	+0.11
Present (Tetra Tech EBA 2015)	Off runway	-1.2	1.6	-0.09

3 PERFORMANCE TO DATE

Johnston (1981) reported some relatively minor instances of settlement soon after construction, but the overall conclusion was that the runway and associated airside infrastructure had performed very well since construction and subsequent paving. This has remained the case until about 5 or 10 years ago, and no extraordinary maintenance requirements have been reported to the authors for the intervening few decades. In 2011, the authors participated in a site visit of the Network of Expertise in Northern Transportation Infrastructure Research, and two areas of subsidence were examined:

- The north side of the runway, approximately 300 m from its east end (Figure 6). This area is an infilled thermokarst pond, where permafrost likely aggraded with high ice contents, and former shallow drainage channel to the south (Tetra Tech EBA 2014a); and
- Taxiway E, near the intersection with the runway (Figure 7). The intersection formed a barrier to natural surface drainage to the southwest, following taxiway construction. A previous attempt to stabilize the area involved the installation of insulation within the fill and a concrete apron in 2008.

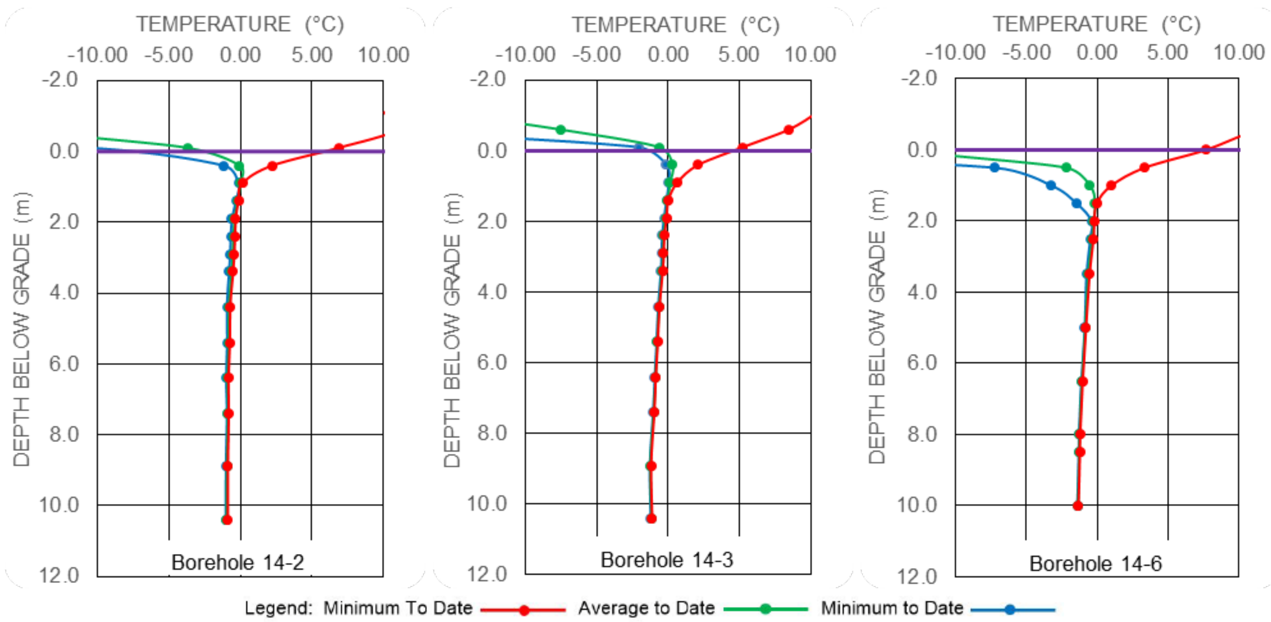

Figure 5. Recent ground temperature profiles along the edge of the runway

Figure 6. Subsidence area on north side of Runway 06-24; summer

Figure 7. Runoff collecting along east side of Taxiway E, and associated subsidence; summer 2011

The locations of these areas are shown in Figure 2. Both areas exhibited water at the toe of the embankment, indicating interrupted surface drainage; and longitudinal tension cracks in the gravel shoulders, indicating permafrost degradation. Both areas were given particular attention during a geophysical investigation at the airport (Tunnicliffe et al. 2011).

In the late summer of 2013 a sinkhole developed rapidly in the north side of the runway, at the previously identified subsidence area, about 300 m from the east end. Within about 5 days, the sinkhole reached a maximum depth of about 0.5 m, was about 10 m long and several metres wide (Figure 8).

Figure 8. Settlement location looking southwest along historic drainage path; fall 2013 (Neil Parry)

The area was repaired by filling and casting a reinforced concrete apron, at least as a temporary measure. A geophysical investigation was undertaken to evaluate the extent of the impacted area and the risk of further sinkhole development (EBA 2013). The area continues to be monitored, and subsidence is ongoing, but not at the rate exhibited in 2013.

4 ENGINEERING CONSIDERATIONS

4.1 Runway Stabilization

The performance issues described in the previous section are impacting the availability and operation of the airport for civil and defence purposes, and therefore warrant rehabilitation. It is obvious that both settlement areas are experiencing permafrost degradation as a result of seepage through or under the base of the embankment. The previously aggraded permafrost prevented this from occurring until recently in the life of the airport. It is believed that climate warming has resulted in an increase in the active layer thickness under the airside embankments. Geothermal modeling indicates that permafrost is not sustainable within even the maximum existing embankment thickness under current Normal climatic conditions (Tetra Tech EBA 2014b).

Annual precipitation records do not suggest that there has been any increase in the quantity of runoff to contribute to the initiation of seepage. However, the annual pattern of precipitation may be changing, with more fall snow cover delaying active layer freeze-back, hence allowing for prolonged seepage. (Kokelj et al. 2014).

While the available ground temperature data suggests that the active layer thickness in fine-grained soil has not been particularly sensitive to climate warming, the active layer response will be more pronounced in free-draining coarse-grained rock fill. It was noted that the active layer thickness is greater in areas of deeper fill. Previous drainage paths invariably represent topographic lows and areas of deeper fill, thus providing avenues for preferential seepage routes for runoff accumulating at the toe of the slope. In time, thermal erosion has progressed into the ice-rich permafrost below the embankment.

Control of surface drainage is an obvious response and measures have been implemented:

- An insulated drainage structure was installed across the settlement area in Taxiway E in 2011, in connection with relevelling and embankment slope regrading. The area continues to undergo settlement. It is considered to be too soon to know if this ongoing settlement is the result of further permafrost degradation, or consolidation of previously thawed soil.
- Ditch clearing and regrading was undertaken in 2014, to limit the collection of water along the east side of Taxiway E and the north side of the runway.

A seepage barrier has been designed for the north side of the runway, adjacent to the settlement area, but construction has not yet occurred. In concept the seepage barrier involves excavating down through the organic soil to the native fine-grained till, then constructing an insulated berm with fine-grained fill. The configuration is shown in Figure 9. This structure has three purposes:

- Impede the flow of water under the runway, with a low-permeability, physical barrier;
- Thermally stabilize the ground, by placement of insulation; and
- Redirect flow towards existing drainage, through improved surface grading.

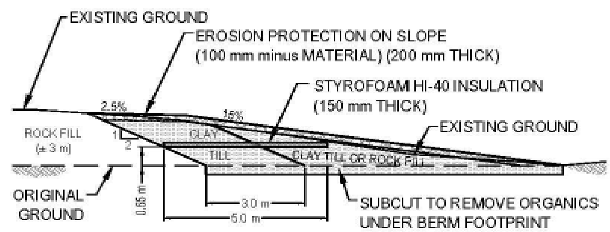

Figure 9. Cross-section of insulated seepage control berm

Once seepage is controlled, further permafrost degradation should be prevented, at least for some time. Geothermal modeling predicts permafrost aggradation in the insulated berm for at least the next 30 years, assuming continued climate warming (Tetra Tech EBA 2014a).

4.2 Runway Extension

A 915 m extension to the runway has been considered. To-date preliminary design has been undertaken, but detailed design remains to be completed. While alternative configurations have been considered, it is likely that the runway extension will be constructed entirely to the east.

Drainage in connection with the runway extension is being given serious consideration. Overall surface drainage in the area is to the southwest, meaning that runoff will collect along the north edge of the extended runway embankment if measures to redirect the runoff are not implemented. Currently, a ditch around the east end of the runway carries most of the runoff that would otherwise accumulate against Taxiway E and the north side of the east end of the runway. Construction of the runway extension will block the path for the ditch. Two concepts for handling the runoff have been examined:

- Construct a ditch upgradient (north) of the runway extension to intercept runoff and direct it to the east around the runway. The challenge with this alternative is that it is a major excavation in ice-rich permafrost; or
- Construct a drainage structure under the runway near the junction of the existing runway and its

extension. The challenge with this alternative is to construct a stable structure in the ice-rich ground and then manage the transitions to the adjacent embankment.

A design challenge for the runway extension is that the terrain and runway geometric considerations constrain the fill thickness that can be used. There is insufficient vertical clearance for an uninsulated embankment of sufficient thickness for permafrost to aggrade into the embankment. However, geothermal modeling indicates that an insulated embankment can be constructed, within the available grades, to maintain permafrost in the embankment for at least the next 30 years, assuming continued climate warming (Tetra Tech EBA 2014b). Consideration is being given to installing a low permeability seepage control berm along the upgradient edge of portions of the runway extension.

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