



NVF stipend 2017

Road engineering field investigation Salluit, Nunavik, Canada



Benoit Loranger

PhD candidate

NTNU

*Department of Civil and
Environmental Engineering*

benoit.loranger@ntnu.no

ACKNOWLEDGEMENTS

The author thanks the Nordic Road Association for financing this research with an NVF stipend for international studies in road and traffic. The author would also like to acknowledge the technical and the financial support from Laval University in Canada and the Norwegian University of Science and Technology in Trondheim as well as Transport Canada for financing this research with a grant from Northern Transportation Adaptation Initiative.



Airport access road, Salluit, Quebec, Canada.

CONTENTS

ACKNOWLEDGEMENTS.....	1
INTRODUCTION.....	3
PROJECT PARTICIPANTS.....	7
RESEARCH SITE: SALLUIT, NORTHERN QUEBEC, CANADA.....	9
PREPARATORY WORK.....	13
FIELDWORK.....	13
FROST HEAVE TEST AT LAVAL UNIVERSITY.....	24
PROCESSING DATA FROM FROST HEAVE TEST.....	27
EROSION AND SEGREGATION POTENTIAL.....	28
CONTINUATION OF RESEARCH.....	29
CONCLUSION.....	30
REFERENCES.....	32

LIST OF FIGURES

Figure 1 : The village of Salluit, Nunavik, Northern Arctic Quebec, Canada.	9
Figure 2 : Localisation of the Salluit community (L’Hérault, 2009).	10
Figure 3 : Heat drain mitigation technique, east side of the road (August 2017).	11
Figure 4 : Schematic of the heat drain operation installed on the embankment in Tasiujaq (Doré et al., 2007).	11
Figure 5 : The gentle slope technique and the interceptor ditch protected by riprap implemented on the road west side (August 2017).	12
Figure 6 : Installation of the fiber optic cable in 2012 (Lemieux et al., 2013).	12
Figure 7 : Thaw depth measurements with a frost probe.	14
Figure 8 : Culvert internal water ponding due to.	15
Figure 9 : Water flow measurements at the outlet of a culvert.	15
Figure 10 : (Left) ERT survey at a culvert outlet; (Right) ABEM Terrameter LS.	16
Figure 11: ERT profile over a natural drainage in permafrost affected terrain. Blue and green colors show areas of lower resistivity (unfrozen ground).	17
Figure 12 : Topography measurements with a ZIPLEVEL PRO-2000.	17
Figure 13 : Thermo-erosion that developed at the culvert outlets after the airport access road construction in 1988 in Salluit (Allard et al. 2010).	18
Figure 14 : Cohesive Strength Meter MK IV from Partrac Ltd.	19
Figure 15 : An example of a transmission curve from a cohesive strength meter run. A 10% reduction in transmission was used as the operation definition of erosion (Grabowski, 2014).	19
Figure 16 : (Top): Measurements of the critical shear stress of permafrost with a Cohesive Strength Meter (Bottom): Levelling of the permafrost surface prior to make a test.	20
Figure 17 : Erosion scars observed on one of the embankment shoulder	21
Figure 18 : Taking measurements at a vertical inclinometer located at the road embankment toe. ...	22

Figure 19 : High albedo coatings after their implementation on September 1st, 2015 (Richard, 2018).
..... 22

Figure 20 : Pyranometer dimensions CMP3 (Kipp & Zonen, 2016) 23

Figure 21 : PVC tubes and temperatures sensors #UTBI-001 used for this research project (Richard, 2018). 23

Figure 22: Molding of a Saluit soil sample in preparation of a frost heave test. 24

Figure 23: Frost cell schematic (modified from Bilodeau, 2009). 25

Figure 24: Unmolding the silt sample directly on the bottom plate (left), and frost cell containing the sample, ready to be conditioned. 26

Figure 25: Completed frost heave test. The left picture is showing the sample still in the cell. Rings separation can be visible where the ice lens have grown. The right picture is showing the sample pulled out from the cell, with details of the ice lens. 27

INTRODUCTION

My PhD project aims at reviewing and assessing frost heave susceptibility of various aggregates and soils, ultimately for implementing frost design criterion of linear transport infrastructures. An extensive study of the frost action behaviour of unbound crushed rock material aggregates (use for base, sub-base and frost protection layer) and problematic sub-ground fine material (fine sand, silt) is now ongoing. National administration in Norway is facing many challenges concerning frost action in transport infrastructure. Actual standard requirements are mostly qualitative classification and/or particle size distribution (grading) requirement. The development or use of existing segregation potential theories could be the answer to assess quantitative based criteria for aggregates and natural materials. For instance, the use of the segregation potential gives good results in Finland and Quebec province (Canada). In order to achieve the research objectives, this project has succeeded to establish an international collaboration with the Department of Civil and Water Engineering from Laval University in Quebec City, Canada.

In Canada, moderate to severe frost action affects all the territory and about 50% of the land is underlain by permafrost. I was given the opportunity to participate as a co-researcher in a road engineering field investigation project that will be held in summer 2017 in Salluit, Northern Nunavik, Canada. This field investigation is lead by Julie Malenfant-Lepage, a PhD candidate at the Department of Civil and Water Engineering at Laval University, Quebec City, Canada.

The main objectives of the fieldwork are to:

- study the watershed and flow subsurface network along the test road,
- assess culverts performance and water debit measurement,
- perform electrical resistivity tomography surveys,
- adapt cohesive strength meter to permafrost condition
- investigate the test sites (heat drains and high albedo surface)
- perform inclinometers measurements and finally,
- perform high albedo surface reflectance measurements.

It is for me the perfect opportunity to carry out field investigation transport infrastructures affected by thawing permafrost. Furthermore, I think that there could be a correlation

between erosion sensibility of frozen soils and their segregation potential. Nobody has work on this relation yet and very interesting output are expected for risk management, civil engineering and water engineering field of study. Since this road site is highly instrumented with optical fiber cables DTS (*Distributed Temperature Sensing*), which can measure temperature at any point along a cable, and that permafrost in Salluit has been extensively studied in the past decades, it is a great place to corroborate my research results. This investigation will be of major significance for my future research regarding segregation potential of soils. It could therefore extend the application of the methods beyond structural road layers and consider the soil-infrastructure as a completely interactive system.

This report provides a description of the Salluit test site, a description of the preparatory works done before the field trip, the explanation of the different tasks undertaken in the field, the description of the frost heave test performed at Laval University, a attempt to explain the relation between the segregation potential and the erosion susceptibility and finally, a brief conclusion with references.

PROJECT PARTICIPANTS



Benoit Loranger: Recipient of the NVF stipend and PhD candidate at NTNU. His research is mainly focused on the frost susceptibility of crushed rock material, as a part of the FROST project. The main goal of his research is to develop and implement a quantitative frost heave susceptibility criteria in Norwegian regulation.

Guy Doré: Professor in the faculty of Science and Engineering at Laval University since 1997. Director of the Arquluk research program and the NSERC Industrial Research Chair on heavy loads/weather/pavement interaction (I3C). He has a strong background in transportation infrastructure engineering in seasonal frost and permafrost context.



Julie Malenfant-Lepage: Ph.D. candidate from Laval University in Canada and research collaborator with SFI SAMCOT WP6 from NTNU in Norway. Her research topic aims at developing a methodology for the design of low-impact drainage systems along transportation infrastructure in permafrost environments.

Chantal Lemieux: Coordinator of the Arquluk northern engineering research program from Laval University in Canada where she supervises the students involved and helps to plan the research and the development of experimental programs and data collection.



Elena Scibilia: Researcher at NTNU in Trondheim and project manager of the Frost protection for roads and railways (FROST) research project. The objective is to build new knowledge on the behavior of crushed rock materials, insulation material and subgrade soils used in road and railway construction under cold climate conditions. Her research background is in the field of permafrost and cold climate engineering.

Inge Hoff: Professor in the Environmental and Civil Engineering Department at NTNU since 2009. Participant and supervisor of the PhD students in the FROST research project. His main research interests are: rehabilitation of roads and airfields, laboratory testing of unbound granular materials for pavement structures, mathematical modelling of materials for pavement structures, finite element analyses, pavement design, climatic influence on road construction materials.



RESEARCH SITE: SALLUIT, NORTHERN QUEBEC, CANADA.

Salluit is a community of about 1500 inhabitants located in Nunavik on the south shore of Sugluk Fjord, on the coastline of Hudson Strait (Figure 1 and 2). The Nunavik is located north of the 55th parallel of the province au Quebec in Canada, in a zone of continuous permafrost. This territory consists of 14 Inuit villages, all located along the arctic coast. No road network connects communities to each other as well as to the southern province of Quebec. During the winter period, only the airport infrastructures serve the inhabitants of the villages. In Salluit, like in most other Canadian Arctic communities, the population is growing fast. It is expected to reach between 1700 and 2000 peoples by 2025 (Allard et al., 2010).



Figure 1 : The village of Salluit, Nunavik, Northern Arctic Quebec, Canada.

The main part of the village is built on a low terrace in a valley surrounded by steep slopes. The southern part of the valley, next by the village, is floored by ice rich permafrost with various slope orientations making it more sensitive to landslides and permafrost

erosion (principally thermal erosion by surface water flowing in rills and vehicle tracks in the tundra). The community has a great need for expansion to increase its living domain but is facing difficult permafrost and topographic conditions. Climate change will also likely affect the stability of permafrost, therefore creating the need for better planning and designs of foundations and road infrastructures (Allard et al., 2010).

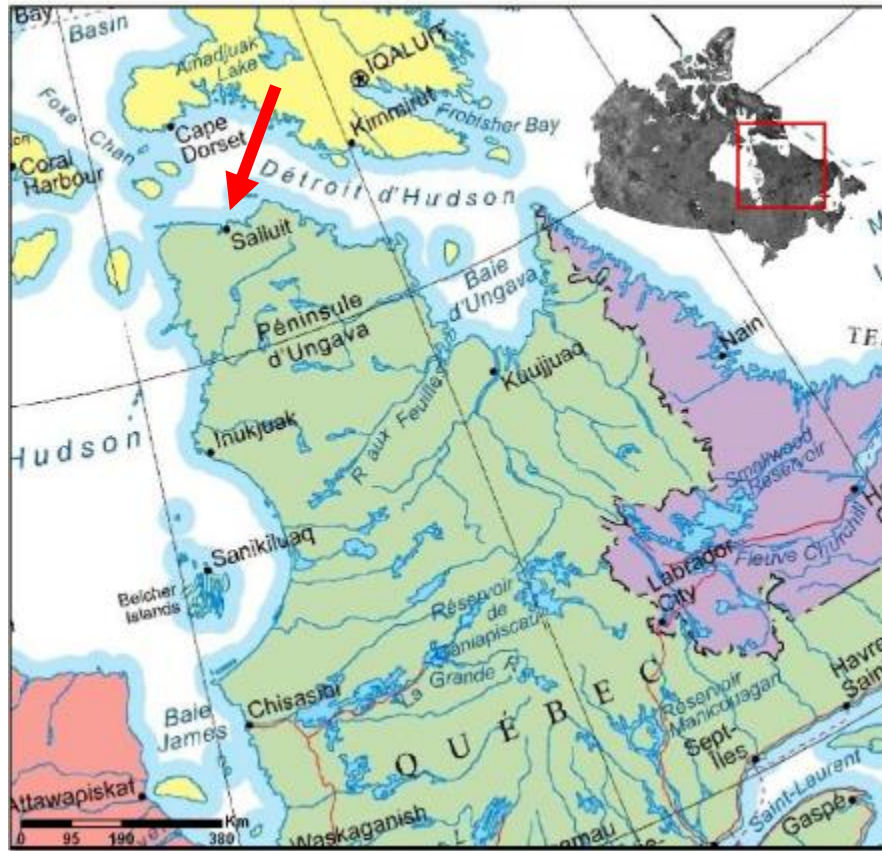


Figure 2 : Localisation of the Salluit community (L'Héroult, 2009).

In the summer and fall 2012, 1.2 km of road rehabilitation and stabilization works were carried out on the airport access road. This road is essential for the community and had shown important degradation signs in the previous years. To stabilize the embankment, two mitigations techniques were implemented: the *heat drain* on the embankment east side slope and a *gentle slope* on the west side slope. These two techniques have demonstrated their effectiveness during previous experimental tests done on the Tasiujaq airstrip, a village also located in the Nunavik. They succeeded to: 1) raise the table of permafrost

inside the road embankment; 2) to reduce differential settlements due to permafrost thawing and; 3) to minimize the risks of road slopes failure.

The objective of the heat drain is to promote heat extraction during winter by placing a high permeability 25 mm-thick geocomposite in the embankment shoulder. The heat generated when soil freezes is first transmitted by conduction to the drain. To make the heat drain system functional, the geocomposite needs to be connected to drains pipes located at the base and top of the drainage layer to allow upward air movement in the geocomposite (Figures 3 and 4). While the gentle slope technique (1V: 5,7H) especially helps in this case reducing snow accumulation on the road west slope and is also intended to keep water away from the embankment toe, thus limiting the heat transfer to the underlying soil. Snow is a good insulator preventing an efficient soil cooling during winter and subsequently its accumulation must be avoided along the road (Figure 5).



Figure 3 : Heat drain mitigation technique, east side of the road (August 2017).

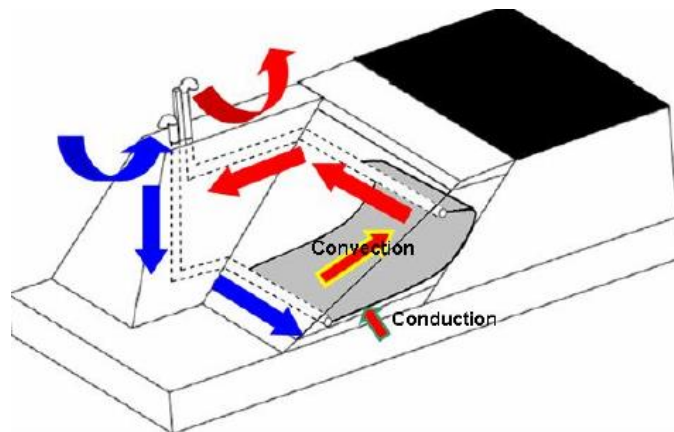


Figure 4 : Schematic of the heat drain operation installed on the embankment in Tasiujaq (Doré et al., 2007).

A new highly instrumented drainage system was also implemented in 2012 along the road to impede flowing water through the embankment at any location. A shallow interception ditch protected by riprap was laid out along the road upstream side (west side) to disseminate water and reduce the risk of thermal erosion (Figure 5). This research project aims in addition to develop an innovative approach to performance monitoring and early detection of permafrost degradation using optical fiber technology "Distributed Temperature Sensing" (DTS), which can measure temperature at any point along a cable. This technique allows continuous measurement of the soil temperature at the bottom of the



road embankment to detect the occurrence of heat sources that might be associated with flowing water and permafrost degradation. In total, the cable covers 4 km, 1 km one way and 1 km back on each side of the road (Figure 6).

Figure 5 : The gentle slope technique and the interceptor ditch protected by riprap implemented on the road west side (August 2017).



Figure 6 : Installation of the fiber optic cable in 2012 (Lemieux et al., 2013)

PREPARATORY WORK

The stay in Salluit was preceded by a 2 weeks period of field organization in Laval University (August 2017). The planning for scientific field trip in remote areas requires attention to every details. The north of Quebec is indeed a region where the only means of access is by air or by boat, and the loss or forgetting of any specialized equipment or tools could lead to let go some expected works.

During those 2 weeks, extensive preparation was done such as: gathering all needed equipment for the entire field trip, shipping by plane heavier equipment in advance, finding an air cylinder for the erosion tests, buying equipment (i.e. marine battery for the electrical resistivity tomography ERT), testing the erosion meter, renting and learning of to use the ERT equipment, learning how to use the debit meter FLOW SIREN, learning how to use the pyranometer, discussing the field trip agenda with participants and supervisors, organizing the accommodation with the Center of northern studies (CEN), etc. This part took almost 2/5 of the time spent in Canada and was an intensive process.

I learned that you must be very systemic and organized in order to complete the preparation for a field trip in remote areas.

FIELDWORK

The field campaign as part of this research project occurred in the second half of August 2017. The main objectives were to 1) assist as a co-researcher, Julie Malenfant-Lepage, by helping her gathering the data needed for the road field investigation; 2) develop a fieldwork procedure for the use of the Cohesive Strength Meter on the active layer and permafrost soil layers; 3) do the inspection and lists maintenance needs of the road test site and its instrumentation.

To assess the thermal and mechanical performance of the new road and drainage system implemented in 2012, the following tasks were done:

TASK 1: Study of the watershed and the flow subsurface network near the test road

A 1.3-meter-long graduated metal rod called «frost probe» was used in this study to measure the active layer thicknesses (ALT) of the ground at different locations within the watershed (Figure 7). The frost probe is a simple instrument used to measure thaw depth in the soils by simply pushing manually into the ground a long and thin metal rod. Active-layer thickness is the maximum development of the seasonally thawed layer, reached at the end of the summer or early fall. ALT can vary substantially both spatially and on an inter-annual basis. In general, it is greater in years with warmer summers and thinner in those with cooler temperatures.



Figure 7 : Thaw depth measurements with a frost probe.

ALT display large spatial variability over short lateral distances in response to the properties of surface and subsurface materials (International Permafrost Association, 2008). In this study, we wanted to investigate the variability of the ALT regarding the subsurface water flows observed at the site. Flowing water in the form of permanent and intermittent streams or sheet flow has a warming impact on the underlying permafrost and results in accelerated thawing of surrounding frozen soils (TAC, 2010). The minimum ALT measured was 30 cm in the natural slope where there is not water flow occurring west of the road experimental site and the maximum value reached was more than 1.3 m at the culvert outlets on the east site of the road where water flow has been canalized.

TASK 2: Assessment of the culverts performance and measurement of water flows

In areas underlain by permafrost, culverts often act as heat sources and cause deeper thawing. During the culverts investigation in Salluit, one of the culverts was found to be not performing adequately. An important settlement in the middle of the road due to permafrost degradation caused the bending of the culvert and prevent now water from being well drained (Figure 8). Excessive settlement of culverts can lead to frequent pipe breakage, sediment blockage, internal water ponding and subsequent freeze-up, which can completely block the drainage system. It is therefore important to follow carefully their operation on an annual basis.

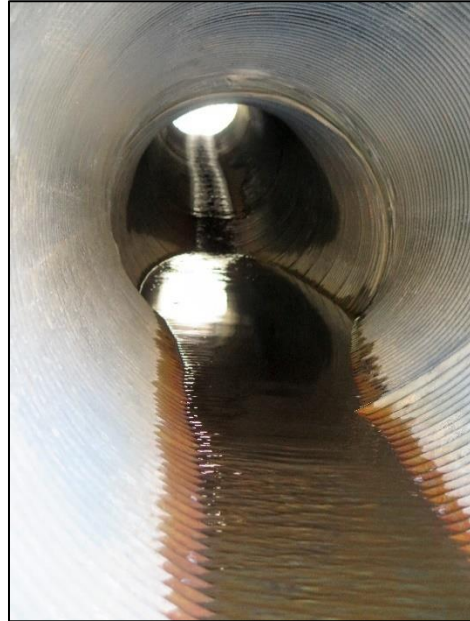


Figure 8 : Culvert internal water ponding due to permafrost degradation underneath the road.

To compare the thermal impact of different water flows in culverts, a FLOW SIREN Device was used in this study (Figure 9). The speed of water was then measured in



every culvert as well as the height of the water layer present. The thermistors placed underneath the road will be further used to obtain the depth of permafrost degradation associated with the water flows measured.

Figure 9 : Water flow measurements at the outlet of a culvert.

TASK 3: Electrical Resistivity Tomography surveys

The thermal impacts of surface and groundwater flow paths in permafrost terrain are often hard to predict and thus rarely considered in the design of embankments in permafrost environments. However, Electrical Resistivity Tomography (ERT) is one of the most effective geophysical methods presently used to map and characterize permafrost, as it is very sensitive to the transition from unfrozen to frozen sediments, to the increase of ice content and to the decrease of temperature below 0°C which is closely related to the unfrozen water content (Hauck and Kneisel (2008); Sigalas et al. 2012). The resistivity values significantly increase in accordance with water's phase change from liquid to solid (Ishikawa, 2008). The electrical resistance of water in the ground is very low while the electrical resistance of ice in the ground is up to several orders of magnitude higher (Lewkowicz et al., 2014).

A dozen of ERT surveys were performed with an *ABEM Terrameter LS* at the culvert outlets and perpendicularly to the new interceptor ditch to quantify the permafrost state underneath water flows around the road infrastructure (Figure 10 and 11). The total length of each profile is 40 m with 1 m spacing between two electrodes to obtain a better horizontal and vertical resolution at the soil surface. The electrodes were set out in a dipole-dipole and a gradient array configuration.



Figure 10 : (Left) ERT survey at a culvert outlet; (Right) ABEM Terrameter LS.

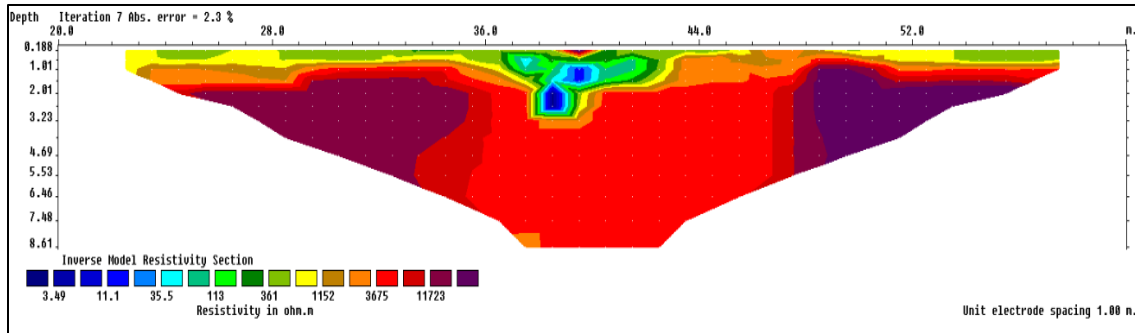


Figure 11: ERT profile over a natural drainage in permafrost affected terrain. Blue and green colors show areas of lower resistivity (unfrozen ground).

TASK 4: Field topography measurements with a ZIP LEVEL

On each ERT survey line, the topography was measured with the high precision altimeter ZIPLEVEL PRO-2000 (Figure 12). This will add more accuracy during the ERT profiles analysis while using the software *RES2DINV*.

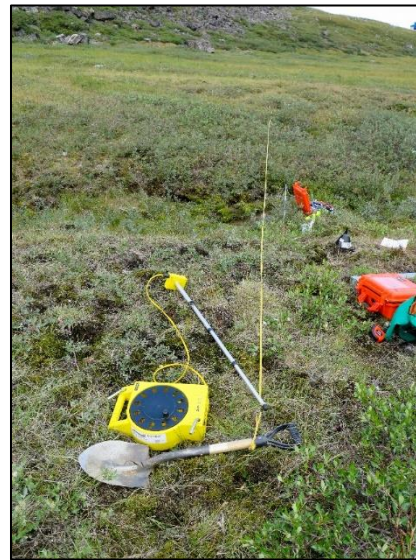


Figure 12 : Topography measurements with a ZIPLEVEL PRO-2000.

TASK 5: Adaptation of the Cohesive Strength Meter to permafrost

To assess the mechanical performance of the drainage system implemented to limit soil erosion around the road infrastructure, an in-situ method developed for unfrozen cohesive soils, the Cohesive Strength Meter (CSM) was applied at the test site. This device allows to measure the critical shear stress (CSS) of soils which are fundamental properties to assess the soil sensibility to erosion. CSS values helps quantifying the energy required

to remove soils by running water on the soil surface. The Salluit test site was the perfect location to test the CSM on permafrost since the permafrost properties in Salluit is well documented and due to its known high thermo-erosion soil sensitivity. Allard et al. (2010) reported the occurrence of important thermo-erosion events after the road construction in 1988 (Figure 13 : Thermo-erosion that developed at the culvert outlets after the airport access road construction in 1988 in Salluit (Allard et al. 2010).



Figure 13 : Thermo-erosion that developed at the culvert outlets after the airport access road construction in 1988 in Salluit (Allard et al. 2010).

The CSM is a portable instrument that measures rapid in situ critical entrainment stress of surficial sediments. It is a modern, portable version of the laboratory jet test used by soil scientists for over 50 years to measure the erodibility threshold of clayey soil samples. The CSM is composed of a main instrument unit containing the computer and a reservoir of water pressurized by an external air cylinder and connected to a sensor head that will be inserted into the sediment surface (Figure 14). Inside the sensor head, there is a nozzle, located 2 cm above the sediment surface, that can produce a water jet applying a wide range of hydraulic stresses on the soil surface. A light transmitter and receiver are also present within the test chamber 1 cm above the sediment surface to measure sediment resuspension after the jet pulse.



Figure 14 : Cohesive Strength Meter MK IV from Partrac Ltd.

Erosion thresholds are defined by the manufacturer (PARTRAC) as the jet pressure P_1 at which average light transmission within the test chamber drops below 90% of the maximum (Figure 15).

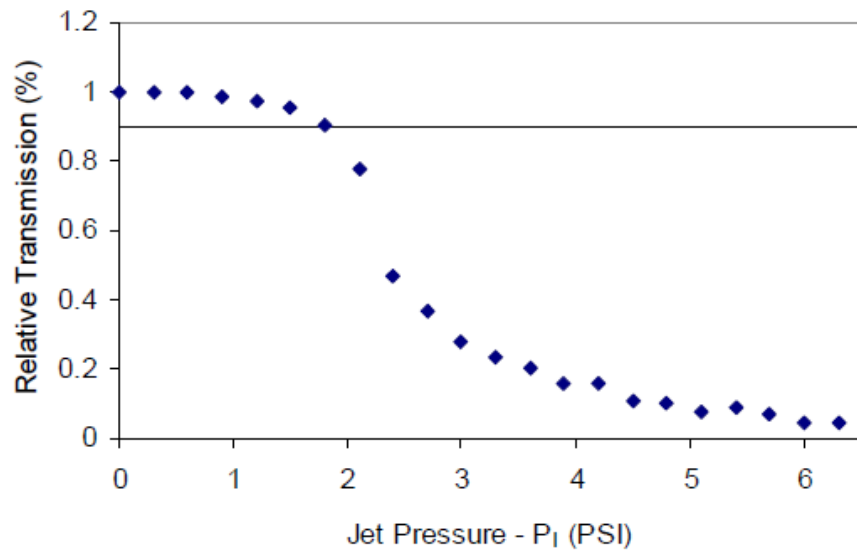


Figure 15 : An example of a transmission curve from a cohesive strength meter run. A 10% reduction in transmission was used as the operation definition of erosion (Grabowski, 2014).

Since the CSM has never been applied on frozen soils, a methodology of used was developed as part of this research. Here are the main steps:

1. Search with the frost probe the top of permafrost to find a good location where there are no rocks, the permafrost table is not too deep and where there are no subsurface flows;
2. Prepare the Cohesive Strength Meter equipment and remove the unfrozen soil above the permafrost surface.
3. Level the surface of permafrost with a trowel. Use a hand-drill and a hole-saw that has the same diameter than the sensor head to make a hole on the permafrost surface.
4. Position the CSM sensor head into the previous hole, add water into the sensor head with a syringe, and make sure that the luminosity in the sensor is above 70% and start the test.



Figure 16 : (Top): Measurements of the critical shear stress of permafrost with a Cohesive Strength Meter (Bottom): Levelling of the permafrost surface prior to make a test.

Results obtained from the fieldwork done in summer 2017 in the village of Salluit show very low values of CSS corresponding to a very high erodibility potential. A methodology to calculate the critical slope and the maximum flow allowed to limit erosion according to the measured critical shear stress with the CSM was also proposed by Julie Malenfant-Lepage as part of her research. The outcomes of this fieldwork can become good working tools for engineers and scientists working in the Arctic to select the proper and cost-effective drainage system design and erosion protection techniques if required. The values obtained of CSS can also become important input parameters for the coastal erosion models used in the Arctic regions (Malenfant-Lepage et al. 2018).

TASK 6: Road test site investigation

Important erosion scars were observed on the east embankment shoulder of the road test section (Figure 17). This is a good (and unexpected) example of erosion problematic of roads shoulder. Here, the slope of the roads allows water to accelerate to reach a critical velocity at which erosion begin. The resulting scar is impressive and appear to be a fast process. Integrity of the road shoulder, the guard rail and the heat drain system could be endangered at short term if no preventive maintenance work is done.



Figure 17 : Erosion scars observed on one of the embankment shoulder

TASK 7: Inclinator

For the geotechnical monitoring of the embankment and the subgrade, five inclinometers total (3 verticals and 2 horizontals) were installed. The inclinometer is a device that measures soil movement in three dimensions over time, using a probe equipped with accelerometers. The probes can operate at temperatures from -30°C to 50°C ; are weather and shock-resistant and; and have an accuracy of 0.005 mm by 500 mm. The

measurements were taken manually (Figure 18) and the data was processed with the Software *Inclinalysis* from RTD Instrument Ltd.



Figure 18 : Taking measurements at a vertical inclinometer located at the road embankment toe.

TASK 8: Coating reflectance measurements

Four new test sections were implemented to thermally stabilize the road embankment near the Salluit airport in the summer of 2015. Three different high albedo coatings were applied on the pavement surface to reduce the heat absorbed by the road and preserve the underlying permafrost. The 4th section is a reference section which has a standard pavement (Figure 19).



Figure 19 : High albedo coatings after their implementation on September 1st, 2015 (Richard, 2018).

During the fieldwork, coating reflectance measurements were made following the standard ASTM E1918. As part of this project, a compact pyranometer, the CMP3 from Kipp & Zonen's, was used and its dimensions are shown in Figure 20. A pyranometer is an instrument measuring the reflectance of a surface by determining the incident solar radiation and the solar radiation reflected by the surface. The albedo is then obtained by dividing the solar radiation reflected by the incident solar radiation. Prior to the measurements, the road test surfaces need to be cleared from any rock and dust and the weather conditions must be favorable. A cloudless sky is required, as well as an angle of less than 45° between the sun and the normal of the measured area, to capture a minimum of 70% of solar radiation. In addition, the distance between the pyranometer and the measured surface must be 50 cm (Richard, 2018).

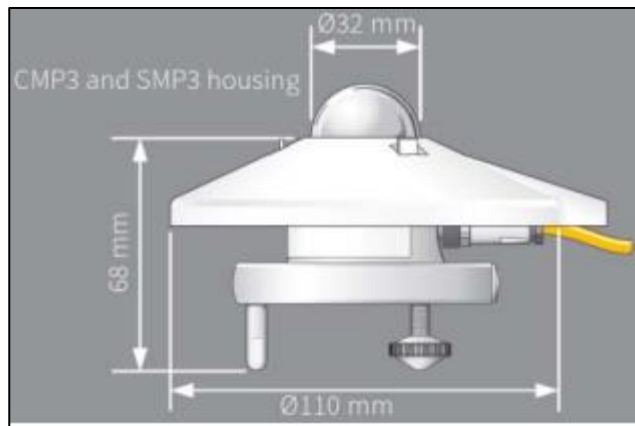


Figure 20 : Pyranometer dimensions CMP3 (Kipp & Zonen, 2016)

Each road test section has in its middle a PVC tube equipped with several temperature sensors (Figure 21). Their operating range varies between -20°C and 30°C with an accuracy of $\pm 0.21^\circ\text{C}$. During fieldwork, the temperature sensors were removed from the road to download the temperature measurements registered during the year 2016-2017.



Figure 21 : PVC tubes and temperatures sensors #UTBI-001 used for this research project (Richard, 2018).

FROST HEAVE TEST AT LAVAL UNIVERSITY

The laboratory works took place at the beginning of September 2017. Clayey silt soil was sampled along the airport access road in natural terrain. The sample was taken at 15-30 cm depth (base of the active layer). The sample was brought back to Laval University where a frost heave test was performed on it. The standard regulation from the Quebec road administration (MTQ) was followed to complete the test. The steps for completing a frost heave test are briefly resumed here.

The sample is first compacted into a split mold for shaping a 100 mm diameter per 150 mm high sample (Figure 22). The sample was kept into a hermetic bag and the natural water content of 15% found into the active layer in the field was conserved for the test.



Figure 22: Molding of a Saluit soil sample in preparation of a frost heave test.

Laval University is using a freezing cell that allows sample to heave and avoid friction and bound force. This type of cell is called a multi-ring freezing cell. A transversal cut of the cell with all its components is presented in Figure 23.

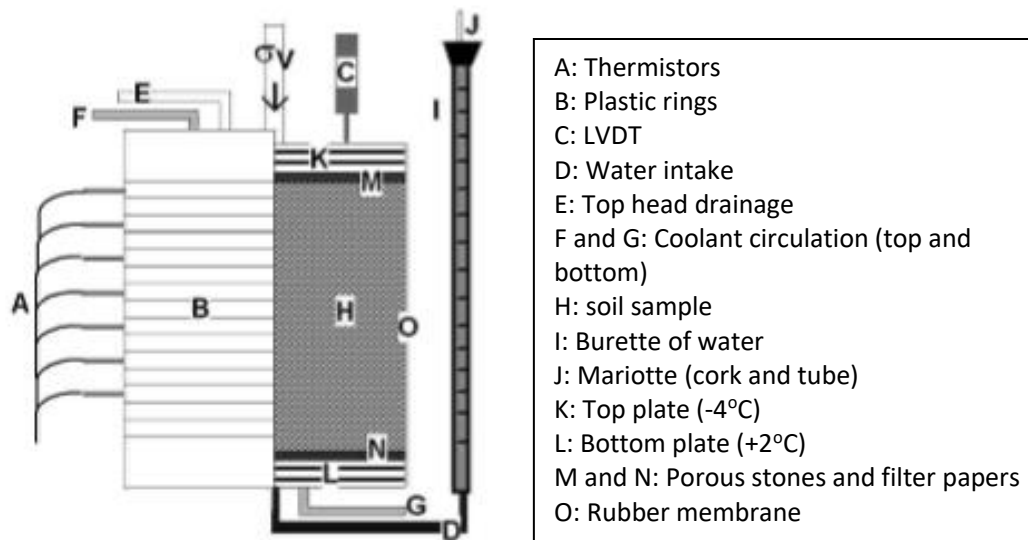


Figure 23: Frost cell schematic (modified from Bilodeau, 2009).

A porous stone and a filter paper is placed on the bottom plate. The sample is directly unmolded on the plate (figure 24, left). The top head is next put on the sample. A rubber membrane is placed to have a completely water proof system. The rings are afterward place one by one until the top. Steel collars are sealing the system hermetically at top and bottom rings. The cell containing the sample is then ready for the conditioning phase (Figure 25, right).

The whole cell is placed into a cooling cabinet to limit transversal heat transfer from the side of the cell. The cooling cabinet is set to the same temperature than the bottom plate. The conditioning phase have two purposes. The first is to completely saturate the sample if needed. This phase was not done since we were using directly the natural water content of the silt. The second purpose is to set a uniform temperature regime into the sample. The top and bottom plates are therefore putted to 2°C for about 24 hours.

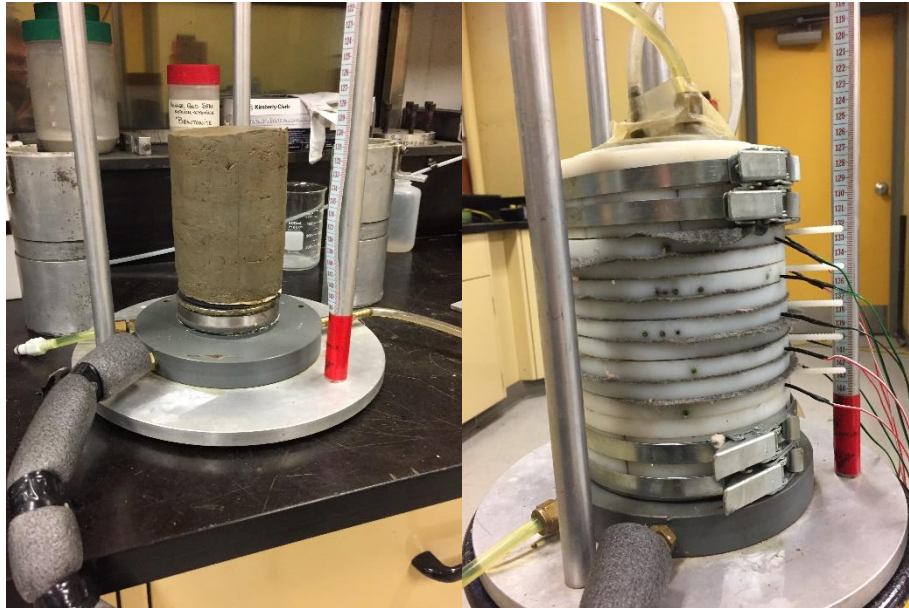


Figure 24: Unmolding the silt sample directly on the bottom plate (left), and frost cell containing the sample, ready to be conditioned.

The freezing test starts after the conditioning phase. The burette providing the water to the sample is closed with a cork in which a tube is inserted. This Mariotte's principle allows to set the water table at the bottom of the sample and to prevent any hydraulic pressure gradient into the sample. From that point, the water that can enter the system will have to be sucked by cryosuction effect. The top plate is then set to -4°C and the cell is wrapped into an insulation material such as mineral wool, to avoid heat transfer from the cell side. The frost front (0°C isotherm) will penetrate gradually into the sample to reach a stable depth. The water inside the sample will then freeze. The pore water will contribute to a certain amount of heave but the frost susceptibility of a soil is its capability of forming ice lenses by cryosuction effects. At a certain depth, the temperature regime will switch from transient to permanent. It is at that time that the last ice lens will start to grow. Some other ice lens will be formed before, but the measurement of the segregation potential is measured at the exact moment when temperature regime become permanent and/or when the last ice lens begins to grow.

The freezing phase is commonly maintained for 72 hours. Heaving and temperatures are recorded using a data acquisition system. After the freezing phase, the

sample is pulled out from the cell and a visual inspection can be done. Figure 25 is showing the frost heave test pictures for the Saluit silt.

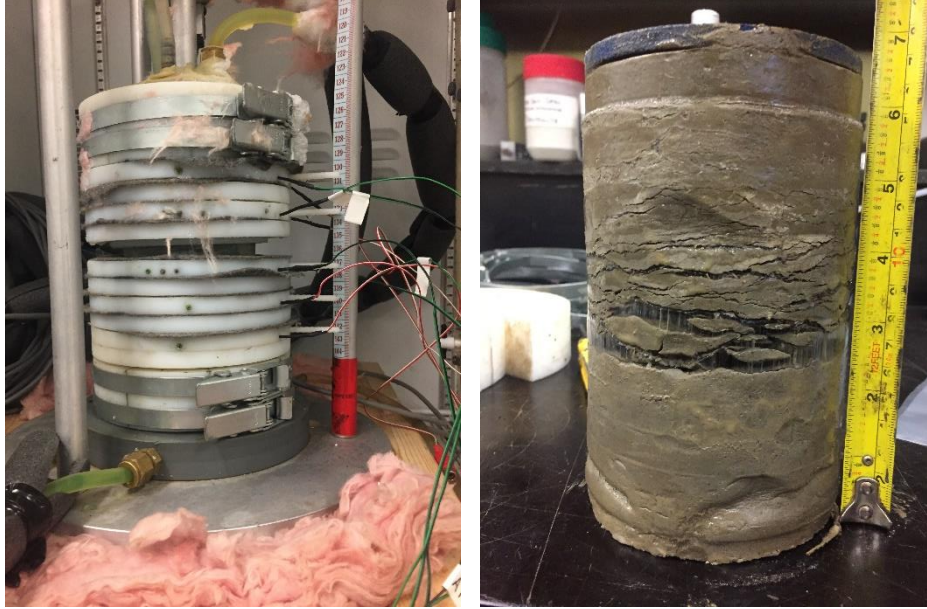


Figure 25: Completed frost heave test. The left picture is showing the sample still in the cell. Rings separation can be visible where the ice lenses have grown. The right picture is showing the sample pulled out from the cell, with details of the ice lens.

PROCESSING DATA FROM FROST HEAVE TEST

The data are processed to find the segregation potential of the soil. The segregation potential is based on the fact that under a one-dimensional freezing, at the formation of the last ice lens, the water intake flux is proportional to the temperature gradient across the frozen fringe (Konrad and Morgenstern, 1981). The segregation potential, commonly noted as SP , is then expressed as;

$$SP = V / grad T$$

where SP is the segregation potential, V is the water intake flux and $grad T$, the temperature gradient, both last into the frozen fringe. The segregation potential allows to

quantify the frost susceptibility of a soil and to evaluate later the expected magnitude of frost on field condition.

EROSION AND SEGREGATION POTENTIAL

For now, it did not seem that a simple correlation is unifying the SP and the erosion susceptibility of a soil. Depending of numerous parameters (soil temperature, unfrozen water content, water and/or ice content, water availability, consolidation and over consolidation ratio and salinity) the effect can vary significantly. Here are shown 2 cases to illustrate the complexity of the phenomena and preliminary correlations.

Case 1: non cohesive soil, low segregation potential value, nearly saturated.

Low SP are normally associated with non-cohesive soil. When nearly saturated and when in a frozen state, the freezing of the pore ice will likely ‘cement ‘ the soil particles together and its erodibility potential will decreased. However, if the soil is nearly saturated, the soil particles will likely separate from each other when the pore water will freeze, causing the skeletal web to dislocate. This can also happen if small ice lenses are created in some zones. Therefore, during thawing season, no more grain to grain bound will act to prevent erosion by friction, and the soil will therefore likely to be more erodible.

Case 2: cohesive soil, high segregation potential, nearly, to over-saturated.

High SP values are associated with cohesive soil such as silts and clays. When in a frozen state, multiple ice lenses can grow rapidly. The ice lenses are acting as a sliding discontinuity. Even if this is not linked to a critical shear stress value, this erosion phenomena is commonly encountered in permafrost terrain with slopes. The cryosuction in those soil (high SP values) will have the effect to over saturate the soil in form of multiple tiny ice lenses when the frost front is penetrating rapidly. Then, when thawing, the soil will become in a state of liquefaction, where the bearing capacity is more or less 0. Those soils

are extremely erodible. Therefore, high segregation potential values, associated with water availability and fast frost front penetration, will create an extremely erodible soil when thawing.

CONTINUATION OF RESEARCH

Future works will be done regarding erodibility of soils, mainly through the Ph.D. of Julie Malenfant-Lepage. Extensive laboratory works with the cohesive erosion meter will be done, and collaboration between my work on frost susceptibility and erosion will continue. In fact, erosion tests will be performed on silt samples submitted to a frost heave test, and laboratory conditions will allow to limit some uncertainties that have been encountered on field.

This research project will be presented at the 5th European Conference on Permafrost (EUCOP 2018), held in Chamonix-Mont Blanc, France, from June 23rd to July 1st. This conference of major importance aims to cover all relevant aspects of permafrost research. The title of the presentation is: Critical shear stress of the active layer and permafrost. Further publication are planned regarding the results.

CONCLUSION

A full 2 weeks expedition was planned at Salluit, Northern Quebec, during summer 2017. This extensive field trip was part of Julie Malenfant-Lepage Ph.D. research project to study the erodibility sensitivity of natural soil in permafrost environments in order to protect the integrity of the transportation infrastructure drainage systems.

The erosion properties of both cohesive and non-cohesive soils according to their ice content, unfrozen water content and segregation potential are still not well understood. This field trip allows for the first time, to use of a cohesive strength meter device to characterize permafrost soils sensitive to thermo-erosion.

A complex correlation seems to link the capacity of a soil to produce ice lenses (segregation potential) to the ice content and therefore, to the erodibility potential of a soil. Numerous parameters will affect the soil/ice matrix as temperature (unfrozen water content), water (and/or ice) content, water availability, consolidation and over consolidation ratio (soil fabric) and salinity.

As preliminary results, for frozen state soils:

- The erodibility of non-cohesive soils seems to decrease when a substantial amount of frozen water at a relatively cold temperature ($< -2^{\circ}\text{C}$) is present. The hypothesis that the ice can bound the non-cohesive soil and make it act as a cohesive one is possible but has to be verified furthermore.
- As the soil will warm toward 0°C , the unfrozen water content will increase, and the soil will be more easily erodible.

For thawing state soils

- The erodibility of a soil seems dependent of the initial ice content. If the soil matrix is dislocated when pore water freezes (non cohesive soil) or when ice lenses are generated (cohesive soil and fine non-cohesive soil), the erodibility potential will increase substantially when thawing.

- For a cohesive soil with a high segregation potential, ice content can be really high (oversaturation) and this situation is likely to create a liquefied soil when thawed, leading to extremely low critical shear stress values.

REFERENCES

- Allard, M., L'Hérault, E., Gibéryen, T. and Barrette, C. (2010). *L'impact des changements climatiques sur la problématique de la fonte du pergélisol au village de Salluit, Nunavik*, Rapport final : Salluit : s'adapter et croître, Centre d'études nordiques, Université Laval, Québec, Canada, 69 p.
- Grabowski R. C. 2014. Measuring the shear strength of cohesive sediment in the field. In Cook SJ, Clark LE, and Nield JM (eds), *Geomorphological Techniques*. British Society for Geomorphology, Part 1, Sec. 3.1, 1-7.
- Hauck, C. and Kneisel, C. (2008). *Applied Geophysics in Periglacial Environments*, Cambridge University Press, 240 pages
- International Permafrost Association, (2008). *Manual for monitoring and reporting permafrost measurements*, CALM Circumpolar Active layer Monitoring, 12 p.
- Ishikawa et al. (2008). *Applied Geophysics in Periglacial Environments*, Chapter 6: ERT imaging for frozen ground detection, eds. C. Hauck and C. Kneisel. Published by Cambridge University Press. pp.109-117.
- Konrad, J.M. and Morgenstern N.R. (1981). *The segregation potential of a freezing soil*. Canadian geotechnical journal, Vol.18, p.482-491.
- Lemieux, C., Grabundzija, D., Doré, G. and Allard, M. (2013). *Suivi du comportement thermique de la route d'accès de Salluit et expérimentation d'une méthode de détection de la dégradation du pergélisol le long des structures linéaires*, Report GCT-2013-02 submitted to the Ministry of Transportation of Quebec, Department of Civil and Water Engineering, Université Laval, Quebec, Canada, 49 pp.
- Lewkowicz, A., Miceli, C., Duguay, M. and Bevington, A. (2014). *Electrical Resistivity Tomography (ERT) as an essential tool to investigate sites in discontinuous permafrost*, Communication presented at the 4th European Conference on Permafrost, 18-21 June, Évora, Portugal.
- L'Hérault, E. (2009). *Contexte climatique critique favorable au déclenchement de ruptures de mollisol dans la vallée de Salluit, Nunavik*, Master's thesis in Geographical Sciences, Université Laval, Quebec, Canada, 163 pp.
- Malenfant-Lepage, J., Doré, G. and Lubbad, R. (2018). *Critical shear stress of frozen and thawing soils*. Proceedings of the 5th European Conference on Permafrost, June 23 to July 1, Chamonix, France.
- Richard, C. (2018). *Stabilisation thermique des infrastructures routières construites sur pergélisol sensible au dégel à l'aide de surface à albédo élevé.*, Master's thesis in civil engineering, Université Laval, Quebec, Canada, 163 pp.

Sigalas, L., Tomaskovicova, S. and Ingeman-Nielsen, T., (2012). *The application of geophysics to characterize the ice-rich permafrost at the area close to the airport in Ilulissat*, 111427 Arctic Technology Project, Technical University of Denmark, 33 p.

TAC: Transportation Association of Canada (2010), *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions*, Ottawa, 177 p.