Arquluk Program
Summary – long version

The engineering research program, Arquluk, aims to improve the current ability to adapt by developing an expertise on mitigating permafrost instabilities under transport infrastructure, in a climate change context. It focuses on developing cost-effective solutions for design and management. Arquluk is addressing the need to have a better understanding of factors that contribute to permafrost degradation; improving investigative techniques to identify thaw-sensitive permafrost; and developing engineering tools to support the design and management of transport infrastructure in Northern Canada.

The objectives are to:

1) Develop a better understanding of factors that influence the performance of transportation infrastructure built on thaw-sensitive permafrost;
2) Improve techniques for detection and characterization of soils and unstable embankments;
3) Develop guidelines for applying different construction and maintenance strategies to reduce permafrost degradation problems resulting from road construction and climate change, based on cost, feasibility, and effectiveness of applicable solutions;
4) Develop a work frame and support tools for the management of transport infrastructure built on permafrost.

To attain these objectives, the program is divided into three themes structured as to facilitate the participation of postgraduate students in master's and doctoral projects:

THEME 1: Improve the current understanding of permafrost degradation and its effects on transport infrastructure;
THEME 2: Identify and characterize thaw-sensitive soil;
THEME 3: Develop adaptation techniques for transport infrastructure built on unstable permafrost.

In the early years of research, the Arquluk program evolved and the three themes were restructured all while keeping the initial objectives in mind. Theme 1 will provide data for Theme 3. Moreover, the two design projects (snow and drainage), initially in theme 1 were moved to theme 3 as they not only improve the understanding of the factors that influence pavement performance (objective 1) but they also produce design tools and adaptation guidelines. All of the program's projects are now completed or will be in the coming months, except for two doctoral projects (drainage and mitigation) that began in 2014 and 2015.

THEME 2 ACHIEVEMENTS

The four projects from theme 2 address the 2nd objective that is to improve the investigative techniques used to identify thaw-sensitive permafrost.

PROJECT 2a

Massive-Ice Detection Using the Geophysics Method of Gravimetry

Benoît Loranger completed this master's project, co-directed by Daniel Fortier of the Université de Montréal.

At first the project was comprised of two components, being a geophysical method to detect buried massive ice using microgravimetry and analyze underground temperatures in order to detect thermal anomalies. The second component (thermal profiling) was not conclusive, so efforts were focused on microgravimetry, which aims to detect anomalies between materials with different densities in the ground. Massive ice (ice content >250%), which has about half the density of the surrounding soil, will be represented by a negative anomaly. Field surveying was carried out with a gravimeter in Beaver Creek and Dry Creek, Yukon. The in-kind contribution from Kryotek, a partner, made it possible to validate the presence of buried massive ice through drillings done at these sites. Collaboration with Thomas Ingerman-Nielsen from the Technical University of Denmark also made it possible to conduct surveys in Greenland, near Kangerlussuaq; first on a well documented ice wedge polygon site and then around the edge of the ice sheets where the ice thickness is measurable. The objectives of the project were met. A high precision gravimeter can detect buried massive ice of different shapes and volumes, for various depths (improved accuracy between 0 and 5 m) and various permafrost areas. A simple 2D model (vertically elongated columns) was then developed and is consistent with the measured gravimetric anomalies. The method can be applied in diverse fields, specifically in civil engineering for the design, construction, maintenance and evolution of transport infrastructures built on thaw-sensitive permafrost in a climate change context.

PROJECT 2b

Pavement Profiles: Effect of Seasonal Frost and Permafrost Degradation

This project started as a short internship project by **Céline Carreau** and later became a master's project completed by **Laurie-Anne Grégoire** co-supervised by Nicolas Martel from Englobe.

The main objective of this project was to develop a profilometry analysis tool from existing linear transport infrastructure profiles. It is comprised of two distinct components: characterizing the evolution of permafrost degradation and the problems related to seasonal freezing in Quebec, which was completed in collaboration with the industrial research Chair i3C. Arquluk was only involved in the first component of this project. The project uses the International Roughness Index (IRI), which uses a mechanical model to measure the ride quality by analyzing vertical deviations relative to a perfectly straight profile. IRI was measured by a portable profilometer (SurPRO) over three 1 km-long sections, on the Alaska Highway, Yukon. Measurements were taken in April (maximum freezing) and in September (maximum thawing) of 2015. The data were then filtered to differentiate the wavelengths: short wavelengths (0.7 to 2.8 m) represent surface degradations, such as cracking; where as long wavelengths (11.3 to 45.2 m) represent deep degradation, which could be linked to instable permafrost. The difference in IRI between September and April was obtained after analyzing the field measurements. The analysis showed that in areas where patching was done, short wavelengths are predominant; in areas where deep permafrost degradation is visible, long wavelengths are predominant and; a negative IRI, thus a road in better condition in September than in April, in areas where there are no permafrost related problems. The results showed trends with respect to permafrost related problems. The cost related to field logistics in Northern sites limited the quantity of sites studied for this project. A greater number of study sites is necessary to create a detection tool. Nevertheless, a data analysis method was developed.

PROJECT 2c
Development of an Oedometric Core-Barrel for In Situ Characterization of Permafrost

This master's project was completed by **Cédric Flécheux**, co-directed by Louis Gosselin from the department of Mechanical Engineering at Laval University, who greatly contributed to the supervision of the mechanical design of the core barrel.

Characterizing thaw-sensitive permafrost is only possible by drilling samples: an expensive and difficult operation in remote areas. The purpose of this project was to develop a core-barrel capable of carrying out in situ thaw consolidation tests. Instead of collecting frozen samples and transporting those to a laboratory for tests, the system allows the soil to thaw in the core-barrel while measuring its consolidation properties under a given vertical stress. A prototype, for which a Canadian patent has been granted, was built to meet these criteria. Laboratory tests led to several improvements of the prototype, so field tests couldn't be performed. However, few modifications need to be made before it can be used on the field. Through the collaboration between Laval University (Mechanical Engineering Department) and partners of the Arquluk program, the final adjustments will be made and the prototype will be tested on the field. The final product will then be manufactured and commercialized by the partners. Lastly, the oedometric core-barrel was qualified as a "major breakthrough in permafrost engineering" at the International Conference on Cold Regions Engineering in Utah, 2015.

PROJECT 2d
Mechanical Behaviour of Marginally Frozen Soils

Mathieu Durand-Jézéquel completed this master's project.

Embankment spreading by shoulder rotation and creep is an important problem in permafrost regions. The problem, relatively well documented in the literature, is generally attributed to shoulder creep under the static weight of the embankment. Little information is available on the effect of dynamic load induced by repeated passage of heavy vehicles and trains circulating on these embankments. The purpose of this project was to develop a methodology to characterize the mechanical behaviour of marginally frozen soils (between 0° and -2° C) and to quantify the effect of repeated deviatoric stresses to validate if heavy vehicles have an impact on creep. The innovative configuration of a triaxial cell was developed in the laboratory to strictly control temperatures at -0.5 °C and required several adjustments. By using this new methodology, it is possible to do triaxial creep tests under drained conditions on frozen soils. It was shown that it is necessary to consider the effect of heavy vehicles on thin embankments. Two charts were produced. The first chart, for static creep, uses data obtained from three laboratory tests and results recorded in the literature to evaluate the minimum strain rate (%/year) with respect to temperature. The second chart presents the dynamic creep of an embankment with a thickness of 1 m and makes it possible to evaluate the axial strain (%) with respect to the number of cycles, thus heavy vehicle passages. As conditions vary greatly from one site to another, this chart requires more data from additional testing that could not be carried out due to the complexity of the developed setup. Through these two charts, it is possible to evaluate static and dynamic settlement and also see that for an embankment thickness of 1 m and in specific conditions (summer, traffic, warm permafrost), dynamic loads accounts for about 70% of total settlement.

THEME 3 ACHIEVEMENTS

The five projects in theme 3 address the 3rd and 4th objectives, which are to develop tools, methods and guidelines to apply different design, construction and maintenance strategies as well as to assist in managing transport infrastructures built on thaw-sensitive permafrost.

PROJECT 3a
Thermal Stabilization of Transport Infrastructure Built on Thaw-Sensitive Permafrost Using High Albedo Surface Treatments

The first master's project, completed by **Simon Dumais**, quickly indicated the possibility of expanding this research beyond the original mandate. Following the interest of the partners involved and given their significant in-kind contribution, **Caroline Richard** completed the second master's project and **Jade Haure-Touzé** from the University of Technology of Troyes, France, completed a 6-month internship on this subject.

The heat absorbed by a dark coating contributes to heating the soil, which leads to permafrost degradation. To avoid this problem, high albedo surfaces treatments (HAST) can be used to limit heat intake by solar radiation. The main purpose of this project was to develop a stabilization method based on surface albedo. Since there is a known relationship between the surface temperature of a pavement coating and its albedo, a simple calculation model of the surface temperature of pavement coatings with respect to their albedo was developed using a simplified energy balance. This model was validated on several sites and quickly assess the relevancy of using HAST from surface temperatures and thaw penetration. An evaluation frame of the technical properties of HAST, in the laboratory and in situ, was proposed, thus guaranteeing an effective, durable and safe use of these products in a northern context. The project established a relationship between albedo and the age of the coating, using several field measurements, and explored the difference in albedo with respect to the type of aggregate. Three sites were tested in collaboration with partners of the program, who provided information and data essential for the completion of this project. The first site is located at Forêt Montmorency, Quebec, where accessibility made it possible to test and improve the application procedures of the product and select suitable instrumentation. The products were then installed on the Alaska Highway, Yukon, and at Salluit, Nunavik. Lastly, thermal modeling was done using TEMP/W from GeoSlope software, to determine the temperature gradient between permafrost (zero annual variation) and the interface between the embankment and the natural soil. Thus, the thermal stabilization approach developed includes a chart (thermal model), which allow to assess the required temperature difference between the interface and the permafrost, to limit heat intake and stabilize the permafrost, depending on various embankment heights. This model was validated at Beaver Creek, but by adding different simulations, air and permafrost temperature variations, would improve its precision. Thereby, the managers can use the embankment height (reload) and albedo to attain thermal stabilization.

PROJECT 3b

Design Procedure Taking Into Account Accumulation of Snow Along Embankments

Florence Lanouette completed this project, co-directed by Daniel Fortier from Université de Montréal.

The purpose of this project is to understand and to document the impact of heat retention in soil, due to the accumulation of snow, on the degradation of embankments built on thaw-sensitive permafrost; in order to develop an engineering tool to provide guidelines for the design and management of transport infrastructure. This project required a thermal regime analysis in the embankment and the natural soil of the Tasiujaq runway in Nunavik, as well as measurements of the height and temperatures of the snow along the edge of the runway and the Alaska Highway in the Yukon. The data collected at these two test sites were used to develop and calibrate a 2D thermal model created using the TEMP/W software from which the mechanical behaviour of the embankments may be evaluated. A design chart was developed to determine the slope ratio (V : H) of the embankment required to respect the temperature difference required between the embankment/natural soil interface and the permafrost, thus restricting the heat intake of the infrastructure. The designers now have access to a design method adequate for embankments where wind and alignment of the infrastructure favour snow accumulation. The effectiveness of this method also depends on the height of the embankment.

PROJECT 3c

Development of a Methodology for the Design of Low-Impact Drainage Systems

The ADAPT program cofinanced this doctoral project which is realised by **Julie Malenfant-Lepage** and co-directed by Daniel Fortier from Université de Montréal.

One of the main causes of embankment degradation on permafrost is heat transfer to the embankment and the infrastructure soil by surface run-off and groundwater. Degradation reduces the structural and functional capacity of the infrastructure and, in certain cases, can lead to embankment failure. The project aims to evaluate the admissible amount of water that can be concentrated in a canal to prevent and control heat transfer to permafrost, and soil erosion. To this end, two relationships are being developed: the relationship between flow rate and erosion by using an erodimeter (in collaboration with the Norwegian University of Science and Technology, NTNU, in Trondheim) and the relationship between flow rate and convective heat transfer using the Peclet number. Measurements were taken at three experimental sites located in Greenland (in collaboration with Thomas Ingerman-Nielsen, Technical University of Denmark, DTU), in Yukon and in Salluit, Nunavik, to determine the influence of flow rate and water temperature on soil temperatures and heat flux. These data will be used to calibrate a 2D thermal model, developed using SVHeat software. Electrical resistivity was used and clearly shows permafrost degradation due to the flow of water. This geophysical method has the potential to become a useful and cost-effective tool for the design of drainage systems on permafrost. It will be possible to provide an approach based on new strategic and technical designs by combining the two relationships developed with the thermal model. This approach will help designers determine the geometry of a drainage system and the optimal number of passages (culverts) to consider for a given infrastructure section, to reduce the impact on the permafrost.

PROJECT 3d
Quantitative Risk Analysis of Linear Infrastructure on Permafrost

Heather Brooks is completing this doctoral project, co-directed by Michel Allard from the Department of Geography and Ariane Locat from the Department of Civil and Water Engineering of Laval University.

Qualitative analysis processes are currently used to design, and allocate maintenance monies for, linear infrastructure on permafrost. The goal of this project is to develop a tool for quantitative risk assessment. Risk corresponds to the probability of a danger (e.g. culvert breakdown, thaw settlement) occurring within an interval of time and the consequences associated, which are calculated with respect to the damage anticipated. The method developed considers the hazards that could affect the viability of the structure, as well as the consequences that service interruption or service malfunction could have on operation costs and on populations that rely on infrastructure. It is based on a quantitative assessment of geotechnical risk associated to linear infrastructure built on permafrost, using a probabilistic approach and an assessment of consequences. It also takes global warming into account. Direct consequences such as equipment loss, are quantifiable, whereas indirect consequences such as injuries, are difficult to quantify. As such, a social scale factor is used to help managers adapt according to the site. A practical risk assessment tool, which can be used by transport infrastructure managers in northern regions, was developed in Microsoft Excel. This analysis tool is being validated with the Iqaluit airport in Nunavut, a well-documented field site.

PROJECT 3e
Development of Design Tools for Convective Mitigation Techniques to Preserve Permafrost Under Transportation Infrastructure

Xiangbing Kong is completing this doctoral project. It is partially financed by Yukon Highways and Public Works through the Yukon Research Centre and is receiving additional funding from related sources.

This project was not included in the initial research program, but a student became available and additional funding from related sources made it possible to integrate this project into the program. The project is about developing adaptation techniques for transport infrastructure built on thaw-sensitive permafrost and therefore addresses theme 3 of the program. The goal of this project is to improve engineering tools used to design permafrost protection systems by convective heat transfer. The specific objectives are to determine a field of application for each technique developed, to produce a decision tree to help select the best method to apply considering local needs, and to improve the design of two techniques of heat extraction from soil using convective air (heat drain and air convection embankment). A 2D finite element model, developed using the SVOffice software (SVHeat and SVAir modules) from Soil Vision, is being used to simulate the temperature distribution in a transversal section of a road embankment and in infrastructure soil. Modelling makes it possible to compare the effectiveness of different convective mitigation techniques with respect to their design parameters by using energy balance (heat absorbed by the embankment and the soil vs. heat removed) and therefore optimize the design. The final product will guide stakeholders in their selection of adaptation methods for Northern transport infrastructure to preserve underlying permafrost.

Annual meetings with the partners were an opportunity to clarify and exchange ideas on different projects. Meetings took place in Whitehorse, for partners from the west, and in Quebec, for partners from the east. In 2015, a single meeting took place in Quebec since several partners attended the GeoQuebec conference, while those who were unable to attend the conference participated through a videoconference. This form of communication was used for the 2016 meeting and for several project-supervising committees. The committees were formed to help partners better invest in specific projects of interest for them, give input on the direction a project is taking and guide the outcome according to the needs of the users. The contribution of the partners ensures that the tools and methods developed are accessible and easy to use.

Moreover, to keep Northern stakeholders up to date about the availability of these new tools and methods, an Arquluk Symposium took place, in French, at Laval University in May 2017. The 70 participants, 50% of whom were engineers, really enjoyed the event. In order to cover the issues, the challenges, the science and the engineering related to transport infrastructure built on permafrost, Arquluk invited the research teams of Michel Allard (Laval University) and Daniel Fortier (Université de Montréal), and the Northern Quebec coordination office from the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET). A second symposium, in English, is planned for February 2018 in Whitehorse, in Yukon, to facilitate the presence of Northern stakeholders from the western Canada. All the final tools (Excel spreadsheets, charts) and documents will be available on the Arquluk website arquluk.gci.ulaval.ca.

Lastly, despite minor adjustments to the objectives of certain projects, the four objectives of the program were met. Indeed, the projects helped improve the understanding of factors that influence the performance of roads built on thaw-sensitive permafrost (1^{st} objective), as well as the detection techniques and the characterization of soils and unstable embankments (2^{nd} objective). The research program also provided tools, methods, and guidelines to adapt the design and maintenance of infrastructure to permafrost degradation associated with construction and climate change (3^{rd} and 4^{th} objective). The risk assessment tool developed will lead to better management of transport infrastructure built on permafrost, and this before it is even designed (4^{th} objective). Developing an expertise on thermal stabilization of permafrost under transport infrastructure will improve current adaptation abilities and will help stakeholders (deciders and engineers) in terms of planning, designing, allocating funds and maintenance.