Preservation of Canada's northern transportation infrastructures The ARQULUK program

Transportation infrastructure plays a vital role in the subsistence, economic development and quality of life of populations living in northern regions. Construction of roads, highways and airstrips in permafrost areas unavoidably affects the thermal regime of frozen soils and causes thermal degradation of the underlying permafrost. The extent of thermal degradation depends on the design methods employed and the amount of underlying ice-rich thaw-sensitive permafrost. When ice-rich permafrost thaws, it causes pavement to settle and lose important structural and functional capacity. In many northern areas, pavements that were formerly stable and adequately designed are now showing signs of instability, likely as a result of permafrost degradation related to recent climate change. This is becoming a significant engineering problem for northern transportation infrastructure.

Climate change is having a significant impact on permafrost stability in northern climates. In this context, maintaining stable and safe transportation infrastructure in remote northern communities is a major engineering challenge. The development of cost-effective solutions to this growing problem requires a better understanding of factors contributing to permafrost degradation, improvement of investigation techniques for identifying sensitive permafrost and the development of cost effective preservation and mitigation techniques.

In Inuktitut language, "Arquluk" means "Bumpy road". The problem and its social and economic impacts will be addressed as part of the ARQULUK program. The results of the proposed research program will directly support social and economic development in Northern Canada. It will also generate expertise and know-how which will be available for the communities and the industry involved in northern development.

CONTEXT

Construction and maintenance of roads, airstrips and railways in permafrost environments is a major engineering challenge. The major causes of embankment degradation are: 1) Increased absorption of heat from solar radiations and infiltration of precipitations through the embankment materials; 2) heat retention in soils caused by increased thickness of snow cover on the slopes of the embankment and adjacent areas; and 3) heat transferred to the embankment and subgrade soils by surface and subsurface water flows (Kondratiev, 1998; Cheng and Li, 2003; Humlum et al., 2003; de Grandpré et al., 2010). The main type of degradation resulting from these mechanisms is thaw settlement of the embankment. Other type of degradations such as thermal erosion along channelized runoff water flow, creep under thick embankments and frost heave in the active layer are also likely to occur. These problems will reduce the structural and the functional capacities and even possibly cause the failure of embankments. The degradation of the important northern transportation infrastructure now tends to intensify due to climate changes affecting permafrost temperature [Etzelmüller et al., 2008; Gavrilova, 2008; Slater and Lawrence, 2008; Smith et al., 2008; Instanes, 2003].

Social and economic consequences of these problems can be considerable. Cole et al., (1999) have estimated to $12 M (US) the additional maintenance cost attributed to permafrost degradation on the Alaska road network. Reimchen et al. (2009), have estimated that the additional maintenance cost per year per kilometer of road to compensate for thawing permafrost in Yukon is about $22,000 (CAD) which, for the Alaska highway alone, represent more than $4 M per year in additional cost. In addition, the poor condition of roads and airstrips affected by permafrost degradation increases vehicle operating cost, reduces the effectiveness of commercial transportation and increases the risk of accidents. In extreme cases, embankment failure can force road or airstrip closure putting at risk local populations and commercial operations.

The condition of Canadian highways and airstrips in permafrost contexts have been documented through several research and expertise projects [Doré et coll., 2006; Beaulac et Doré, 2006; Doré et coll., 2008; Allard et al., 2009]. These problems have also extensively been documented in Alaska, Greenland, China and in Russia [Esch, 1996; Kondratiev, 1998; Cheng and Li, 2003; Humlum et al., 2003; Jin et coll., 2006]. Different types of solution have been proposed and evaluated through research projects. These solutions include the use of natural convection to cool embankments during winter using porous embankment materials [Goering, 2003] airducts [Ma et al., 2009] and drainage geocomposites [Beaulac and Doré, 2006; Chataigner et al., 2009; Stuhr-Jorgensen and Doré, 2009; Ficheur and Doré, 2010]. They also include techniques to control solar radiations during summer such as reflective surfaces [Stuhr Jorgensen et al., 2008] and sunsheds [Ma et al., 2009]. Despite these promising developments, key information is still missing for the design and the management of transportation infrastructure on thaw sensitive permafrost. Amongst other things, design parameters and tools as well as management tools are required to facilitate risk assessment and decision making processes.

RESEARCH PROGRAM PROPOSAL

The research program will focus on the development of cost-effective solutions for the design and the management of road, airstrips and railways constructed on permafrost. This will require a better understanding of factors contributing to permafrost degradation, improvement of investigation techniques for identifying sensitive permafrost and the development of engineering tools to support design and management of transportation infrastructure in Northern Canada.

<u>Program goal</u>

The goal of the proposed program is to improve current adaptive capacities by developing expertise for mitigating permafrost instability beneath transportation infrastructure. In order to achieve this goal, the following objectives are proposed:

1. Improve knowledge of factors affecting the thermal regime of pavements built on sensitive permafrost
2. Improve techniques for detection and characterization of instable soils and embankments
3. Develop guidelines for the application of different construction and maintenance strategies to mitigate permafrost degradation problems resulting from pavement construction and climate change based on the cost, the feasibility and the effectiveness of applicable solutions
4. Develop a practical framework as well as support tools for the management of transportation infrastructure on permafrost

The proposed research will lead to the development of expertise, procedures and techniques for mitigating permafrost degradation beneath transportation infrastructure. The project will specifically focus on the role of climate change and methods for improving existing cold-region engineering practices.

Research themes

In order to achieve the goal and the objectives stated, the proposed program is divided into 3 themes addressing the specific objectives of the program. The themes are structured to facilitate the involvement of graduate students through MSc and PhD. projects:

Theme 1: Improvement of current knowledge on permafrost degradation and its effect on transportation infrastructures (1 PhD project)

Considerable efforts have been made to understand the mechanisms involved in permafrost deterioration under transportation infrastructure. The main factors affecting embankments built on permafrost include the change in thermal surface thermal properties caused by vegetation removal and construction of a granular structure (including in some cases an asphaltic surface), geometric effects inducing snow accumulation on embankment slopes, surface and sub-surface water flow underneath embankments and creep sensitivity of marginally frozen ice-rich soils and saline soils under thick embankments (Kondratiev, 2008; Humlum et al., 2003; Cheng and Li, 2003). These issues are becoming more important in the face of increasing development in northern regions where climate change is occurring more rapidly than in most other parts of the world. The focus of this research theme will be on understanding and documenting the main factors involved in the degradation of embankments built over thaw sensitive permafrost and on the development of engineering parameters to account for those factors in design and management of transportation infrastructure. In addition to a detailed review of the literature on these subjects, the project involves the following research activities:

a) Monitoring the thermal performance of the Alaska highway and of the Tasiujaq experimental sites

This part of the project involves detailed monitoring of thermal regimes in two pavement experimental sites built in 2007 in Nunavik and in 2008 in Yukon to assess the impact of climate change on transportation infrastructures and to assess the performance of selected mitigation techniques designed to prevent permafrost degradation under highway embankments. The Beaver Creek test section includes a reference section, monitored by Yukon Highways and public works (YHPW) since 1997. It also includes 11 additional test sections built in 2008 and designed to test different types of mitigation techniques. The Tasiujaq test site includes 4 test sections including a reference section and 3 sections including protection techniques. Both test sites are fully instrumented for thermal monitoring of the sections. The proposed work plan involves monitoring and detailed analysis of thermal regimes at different locations across a transverse section at each test section. This activity will involve improving the monitoring equipment at the Tasiujaq test site including the installation of a new reference section to replace the existing one strongly affected by water ponding along the embankment.

b) Development and calibration of a 2D thermal model

Data collected at the Tasiujaq and at the Beaver Creek test sites will be used to support the development and the calibration of a 2-D thermal model. The needs and the implications of the development of a 3-D version of the model will also be evaluated for the assessment of specific field conditions such as discontinuous permafrost or crossing of linear features such as ice-wedge or streams.The intent is to capture all significant physical processes including convection between the air and ground; conduction through the soil layers, heat and mass transfer of moisture in soil, and phase change. When the thermal aspects will be mastered in the model, a thermo-mechanical coupling will be done based on the work done by Verreault et al. [2011] on the mechanical behaviour of warming and thawing permafrost. The governing equations will be solved with a finite element code. The COMSOL and FLUENT softwares will be the main development tools. The numerical model will allow determining the evolution of the temperature and mechanical fields and the extent of the active layer. Once calibrated using the data from the test site (soil and embankment material characteristics, climatic conditions, temperature data, site characteristics, etc.), the model will become a powerful tool to assess the effect of projected climate change on transportation infrastructure. A sensitivity analysis will be performed to determine properties and input data that are the most influential. This will be useful to determine on which inputs the attention should be put when using the model to approach a new situation. The model will be used mainly for the development of engineering parameters (project 1-c) and for the assessment of mitigation techniques (project 3-a). Model reduction techniques will be used to propose simplified “engineering” models.

c) Development of engineering parameters

As mentioned earlier, the three main factors affecting thermal performance on embankments in Northern Canada are: 1) Increased absorption of heat from solar radiations; 2) heat retention in soils caused by increased thickness of snow cover on the slopes of the embankment and adjacent areas; and 3) heat transferred to the embankment and subgrade soils by surface and subsurface water flows. The effect of surface thermal properties is relatively well understood and documented in the literature. Surface energy balance and resulting surface temperature is a complex phenomena taking into consideration several factor including the albedo and thermal conductivity of embankment materials. To facilitate incorporation of these phenomena in engineering calculation, an index referred to as the “n-Factor”, has been developed (Lunardi, 1978) to convert readily available air temperature into surface temperature. Despite being considered as over simplistic and possibly misleading, the n-factor is still widely used in cold-climate engineering practice nowadays. This research project will focus on the development of mechanistic based index to to allow consideration of these factors in engineering practice. It will include the following activities:

1. The 2D thermal model developed in research activity 1b will be used to simulate different conditions of surface exposition to solar radiation, of snow accumulation on embankment slopes and of water infiltration underneath the embankment. To account for absorption of solar radiation, we propose to adapt the concept of the “radiation index (RI)” developed by Dysli et al. [1997; cited in Doré and Zubeck, 2009] for pavement engineering practice in seasonal frost areas. The RI uses the physics of heat transfer by solar radiation to quantify a correction to be applied to surface temperature. It is a more rigorous approach to the quantification of the effect of solar radiation than the “n” factor but it has never been calibrated and applied to permafrost conditions.
2. A similar approach will be used to develop mechanistic indices quantifying the transfer and the retention of heat caused by water flow and snow accumulation.
3. The design indices developed using thermal modelling will be validated using thermal data from the Tasiujaq and Beaver Creek test sites.

The mechanistic indices developed as part of this project will then be integrated in pavement design procedures in the research projects proposed as part of theme 3.

Theme 2: Identification and characterization of thaw sensitive soils (2 Msc projects)

Areas of terrain that is unstable due to poor soil conditions pose a risk to the integrity of transportation infrastructures and must be identified and characterized. Ice-rich permafrost at shallow depths is the most challenging terrain condition to manage for construction and maintenance of transportation infrastructure. The spatial distribution of massive ice bodies and ice-rich soil structures is very difficult to predict, especially where surficial materials or soil types are highly variable. This represents a major challenge for the planning and preparation of new transportation projects and for the management of existing transportation infrastructure. The capacities of existing investigation methods are limited considering the lack of precision of some methods and the high cost of others. along existing roads, it is expected that advanced analysis of surface profile and condition can help identifying and characterizing thaw-sensitive zones. A better knowledge on the distribution and the characteristics of ice-rich soils is needed for routing of new transportation facilities and for the effective management of existing ones. In addition of detailed literature reviews on these topics, proposed work will include:

a) Geophysical and thermal analysis methods

The focus of this research will be on methods and technologies used in permafrost monitoring and ground ice detection. From an engineering standpoint, the most important questions are the location and ice content of ice-rich permafrost. This can either be in a local area such as a proposed building site or a linear corridor such as a railroad or highway. The combination of several geophysical techniques and the cross-referencing of indications of ice-rich materials is the most promising technique for delineating ice-rich zones [Kneisel et al., 2008]. The primary research goal will be to utilize geophysical and direct measurement techniques to detect the presence and characterize the engineering properties of ice-rich, fine-grained permafrost and buried massive ground ice. The technologies under consideration will focus on DC electrical resistivity geophysical imaging, ground penetrating radar, micro-gravimetry and thermal profiling. Studies in the literature generally used one and two dimensional resistivity and GPR. Three-dimensional studies are being initiated; however, they are often in a rectilinear Cartesian grid. Recent studies indicate that using a radial array pattern around a central point produces much less noisy data and results in clearer images. In the high-resistance permafrost environment, this could result in a much greater reliability of results. Several authors (Saarenketo and Scullion, 2000; Moorman et al., 2003) describe a “fingerprinting” technique for identifying different soil types by their GPR signature. This has been done visually, but the process could be digitized. Using a combination of statistical software and 3D modeling software, a fuzzy logic system could easily be developed to correlate “fingerprint” features to a probability of ground ice. The project involves:

1. The use DC resistivity, GPR, gravimetric and thermal readings to define “fingerprints” of ice-rich materials through the examination of a large number of ground-truthed tomograms throughout the Yukon and examination of tomograms in the literature.
2. The development of a radial 3D methodology for the rapid three dimensional site assessment.
3. Develop a software framework for interpreting multiple geophysics data sets in order to pick out ice-rich signatures. Use Surfer and SigmaPlot 3D statistical plotting software. Make use

of cloud-computing techniques to handle the large amount of data generated. Assign a qualitative description of quantitative data indicating ice-rich terrain and use a fuzzy-logic system to assign degrees of probability to the presence of ground ice similar to that used by Hauck and Wagner (2003) or potentially a permutation of a remote sensing pattern recognition program.

4. Develop a methodology for taking linear GPR, resistivity, gravimetric and thermal readings simultaneously from a moving vehicle for corridor mapping. This technique would output a probability of ground ice map for the upper 10.0 m of soil.

The evaluation of the effectiveness of the detection technologies will be conducted at several sites in Yukon and North-west Territories. The presence of ice-rich soils and massive ground ice has been well documented at most of these sites.

b) Analysis of longitudinal profiles of existing pavements

Early detection of permafrost degradation under existing roadways and airfields is a key component of a good decision making process for maintenance and rehabilitation of embankments built in permafrost areas. Profile analysis techniques have proven to be good tools for the detection and the characterization of frost effects on roads in seasonal frost areas [Fradette et al., 2005; Vaillancourt et al., 2003; Doré et al., 2001]. The same techniques, based on signal filtering and wave-length analysis, are likely to prove to be very effective in early-detection of permafrost degradation and selecting the appropriate mitigation strategy. The project involves the following research activities:

1. Longitudinal and transverse profile measurements will be collected along the Alaska Highway and on the Kuujjuaq airstrip in Nunavik. Profiles will be collected at the end of summer (maximum thaw penetration) using the SURPRO profilometer available at Laval University. The manual profilometer is however slow and only allows data collection on short sections of highway. The data will be supplemented by profile data collected by private firms mandated by Yukon highways and Transport Canada (Kuujjuaq Airstrip in Nunavik).

2. The profiles will be analyzed using PROVAL, ROADRUF and/or PROFAN softwares in order to identify the “signature” of permafrost degradation in terms of wavelength and amplitude for different contexts. Power spectral density analysis and wavelength content analysis techniques developed by Flamand [Doré et al., 2001] will be used to compare road and airstrip sections in thaw sensitive and non thaw sensitive contexts.

3. Based on the analysis described in activity 2, an algorithm will be developed to help detect profile anomalies likely to be associated to permafrost degradation along a road or an airstrip.

The research products from this project will help locating thaw sensitive zones along a transportation corridor, diagnose the causes of degradation and select proper mitigation strategy.

c) In-situ œdometric tests

When ice-rich permafrost is identified and located using geophysical, thermal or profiling techniques, the main challenge is to characterize thaw-sensitive soils in order to assess the risk of building a new transportation embankment or maintaining an existing one. This is currently only possible through drilling and sampling frozen soils. The recuperation of undisturbed frozen samples during drilling operation is very difficult and expensive in remote northern locations. The objective of this project is to develop an œdometric core barrel to measure in-situ, consolidation properties of permafrost. Instead of trying to recuperate frozen samples, the testing system would allow to thaw permafrost within the core barrel and to measure its consolidation properties under selected levels of vertical stress. This would allow producing thaw-consolidation profiles of soils with depth which would support risk analysis under different warming and thawing scenarios. The project involves the following activities:

1. Designing the œdometric core barrel in cooperation with the design office of the mechanical engineering department of Laval University
2. Building a prototype for laboratory and field testing
3. Validation of the performance of the core barrel in a ice rich soil sample reconstituted in a cold room of the civil engineering department
4. Adjustments to the design of the core barrel and modification of the prototype if required
5. Field testing of the performance of the core barrel using light-weight drilling equipment available at Laval University and in the Yukon (Cryotek inc)

If the tests are conclusive, a fully operational core barrel will be constructed and used for site characterization for the Arquluk program as well as for other permafrost research projects.

Theme 3: Development of adaptation techniques for transportation infrastructures built on unstable permafrost (1 PhD project, 2 Msc projects)

In addition to different maintenance strategies, many methods have been proposed and tested to counter the effects of permafrost degradation. These methods can be classified into three main categories:

- methods based on limiting heat intake underneath the embankment during summer,
- methods based on maximizing heat extraction from the embankment during winter, and,
- methods based on the reinforcement of the embankment in order to resist permafrost degradation problems.

The main objective of this theme is to optimize preservation strategies by assessing their field of application, their performance and by documenting associated costs and implementation barriers. The research activities within this theme will also focus on the improvement of design features and on the development of thermal stabilisation methods including adapted maintenance and rehabilitation activities. These strategies will be integrated in a transportation infrastructure management framework that will allow for the identification and the assessment of realistic adaptation scenarios required for stabilizing vital transportation infrastructure in remote northern communities. In addition to a full review of the literature on the subject, the following research activities will be included:

a) Laboratory and numerical modelling

Small scale laboratory testing has been performed on protection techniques in a controlled environment at Laval University. These tests have proved to be very useful in providing engineering parameters (thermal conductivities, convective properties, and other) to be used for the optimization and the design of those techniques. A more detailed study will be required to assess engineering properties over a range of conditions (temperature, moisture, etc.) and to improve design features of existing and new protection techniques. The proposed research project will support development and performance assessment of selected protection techniques. It will include the following activities:

1. Testing of air convection embankments (ACE), heat drains and half-pipe systems in small scale embankments in a cold room. In addition to the benefits identified in the previous paragraph, these studies will also be used to determine a minimum operating temperature of these systems in order to explain poor performance observed in the field on some of these systems during mild winters.
2. Testing of high albedo surfacing materials on the Laval University road experimental site (SERUL) located 75km north of Quebec City.

Thermal numerical modelling will build upon the results of tasks 1b. Engineering properties obtained from the literature, from the small scale experiments and from test sections will be used to feed the thermal model. The effectiveness of the proposed protection techniques will be evaluated by comparing a protected embankment with an unprotected embankment. Models calibrated using test site thermal data will be used for the following analysis:

1. Variation of thermal boundary conditions in order to document the field of application of the techniques
2. Variation of design features of the protection systems in order to maximize their effectiveness.

The effectiveness of the protective techniques will be assessed on a short-term basis (one full seasonal cycle) and on a long-term basis (15-20 years) based on realistic warming scenarios. Permafrost temperature, active layer thickness and their evolution with time (and climate warming) will be used to assess the effectiveness of the protection techniques considered relative to an unprotected embankment.

b) Development of maintenance materials and techniques for embankments affected by permafrost degradation

Road and airfield pavements affected by permafrost degradation are rapidly losing functional capacity due to embankment distortion and cracking. Commonly used maintenance techniques and materials include surface grading and filling with granular materials for gravel surfaced structures, ripping, grading and resurfacing surface treated roads and cold-mix filling for asphalt surfaced structures. Despite the fact that these maintenance treatments are adequately addressing the functional capacity problems, they often exacerbate thermal degradation due to the dark color of maintenance materials making these treatments ineffective for medium to long-term stabilisation. This research project will focus on the development of maintenance strategies based on the use of clear colour materials and thermal stabilisation approaches. It will include the following research tasks:

1. Identify and document the properties of a range of maintenance materials having the following basic properties: High albedo (for reduction of solar radiation); adapted to cold environments (ability to adhere to existing gravel and asphalt surfaces, to cure and to perform adequately in cold temperatures); easy to transport and to lay down in remote locations with available construction equipment.

2. Test in controlled environments (on asphalt or gravel slabs in laboratory and Laval University Road Experimental Site; activity done as part of project 3a) to document engineering properties (skid resistance, adherence and albedo)
3. Develop a comprehensive maintenance strategy for the thermal stabilization of embankment sections affected by permafrost degradation. The strategy is likely to involve reprofiling of the pavement surface, raising the grade of the surface and application of a high albedo surfacing material
4. Experiment the maintenance strategies and materials on sections of roads on the Alaska Highway in Yukon as well as on the Akulivik and on the Salluit access roads in Nunavik. The experimentation involves documenting the practical problems occurring during the maintenance operations, monitoring the thermal profile within the treated section in comparison to an adjacent untreated reference section and short term (2 years) monitoring of surface condition after application

c) Development of a framework for the management of transportation infrastructure built on degrading permafrost

This research activity will consist in the development of integrated tools to support the management of road and/or airstrip networks in permafrost regions considering the local context as well as climate change. The management framework will rest on the widely documented basic principles of asset management [Cowe Falls et al., 2001] and risk management [van Staveren M., 2007]. Pavement asset management is a combination of integrated activities allowing for the maximization of value of the transportation assets. It involves the following main activities:

1. Inventory of the assets and of their conditions: In a northern transportation infrastructure context, this activity involves mainly the development of a methodology for the characterization of the value and the condition of roads and airstrips as well as for the identification and the characterization of vulnerable sections. A procedure has been developed and used by Transports Quebec [Boucher et al., 2010] for the monitoring of airstrips and access roads in Nunavik. This activity will build on this experience and on the existing state of the art in pavement asset management to develop a practical and easy to implement methodology adapted for remote transportation infrastructure in permafrost environments.
2. Analysis of investment scenarios: This key activity involves two types of analysis. <u>a) Cost benefit analysis</u>: This type of analysis requires a good knowledge on the feasibility and the cost of different investments applicable to roads and airfields in permafrost environments (maintenance, thermal stabilization, relocation, etc.). It also involves a good knowledge on the probable evolution of a given pavement section with or without investment. The analysis then relies on a life-cycle cost-benefit assessment of the different strategies considered. The cost, the feasibility and the performance of different strategies for roads and airstrips will be documented as part of this research activity. The information will be mainly obtained from existing files with the cooperation of Yukon Highways and Public Works, Transports Québec and Kativik Regional Government. If needed, additional information will be gathered as part of this project.

   <u>b) Risk analysis</u>: In addition to cost and service level which are the two factors dominating most decision making processes, risk must also be taken into consideration for remote northern communities where alternative access routes are often inexistent. The likelihood

of a failure causing road or airstrip closure and the possible consequence on local communities must be taken into consideration in the decision making process. Based on state of the art risk analysis methods, a procedure will be developed as part of this activity to adequately weight the risk of failure in addition to cost-benefit analysis in the decision making process.

This research activity will result in the development of a transportation infrastructure management framework. The method will be validated at the end of the research project through two pilot projects done on a road and on an airstrip in Yukon and in Nunavik. These projects will be done in cooperation with the local administrations.

PROGRAM DELIVERABLES

The proposed research will lead to the development of expertise, procedures and techniques for the detection and the characterization of thaw sensitive permafrost, for the mitigation of permafrost degradation and for the management of transportation infrastructures in permafrost environments. More specifically, the following deliverables will be produced as a result of the research initiative:

- A discussion document describing and discussing adaptation strategies to support transportation infrastructure development planning at upper management levels of transportation and local administrations. The document will examine the appropriateness of different scenarios such as permafrost protection and forced permafrost thawing in different contexts of Northern Canada in order to achieve economic long-term stable transportation services.
- Technical guidelines for the preparation of transportation projects, for the preservation of existing facilities and for the management of roads and airstrips networks in a changing climate context. Site characterization for project planning and preparation as well as design, construction and maintenance of transportation infrastructure will be addressed in a practical guideline compendium.
- An important part of the project will be the production of course material for engineering courses. This will support regular engineering programs, online graduate courses and continuous education courses for practicing engineers. Material produced will include presentation material and practical work assignments based on case histories built as part of the project.
- The project will also produce several high-level scientific publications presented at specialty conferences and proposed to scientific journals.

The products of the proposed program should support the analysis of different adaptation scenarios by providing tools to assess condition of transportation infrastructure and by providing valuable information on the performance of different protective techniques.

EXPERTISE OF THE RESEARCH TEAM

The researchers and practitioners involved in the project have a strong knowledge and understanding of permafrost related processes and permafrost-embankment interaction from both a practical and theoretical perspective. The multi-disciplinary team involves a specialist in permafrost engineering, a specialist in heat transfer and thermal modelling and a specialist in periglacial geomorphology and permafrost science.

The team will be under the direction of Professor Guy Doré who has a strong background on transportation infrastructure engineering in seasonal frost and permafrost contexts. Amongst other activities, Guy Doré has worked on the design and construction of transportation infrastructures in Nunavik. In the past ten years, he has developed an important research program on the performance and on the protection of roads, railways and airfields on thaw sensitive permafrost. Amongst several other publications on the topic, he has coauthored the books "Cold regions pavement engineering" (McGraw-Hill/ ASCE press) and "Guidelines for development and management of transportation infrastructure in permafrost regions" recently published by The Transportation Association of Canada.

Louis Gosselin is a professor of mechanical engineering (Université Laval), with a recognized expertise in the modeling of heat transfer mechanisms and thermal systems optimization. His recent interests include, among other topics, work related to solid-liquid phase change problems, heat transfer and fluid flow in porous media, permafrost, and geothermal energy.

Daniel Fortier is professor of geomorphology at Université de Montréal, associate research professor at the Institute of Northern Engineering (University of Alaska Fairbanks), and director of the Cold Regions Geomorphology and Geotechnics Laboratory at Université de Montréal. Since the early 2000s, his research has been focusing on the geodynamics of permafrost regions. In Yukon and Nunavik, he manages research projects dealing with the impact of permafrost degradation on infrastructure stability in a global warming context. He has been involved in the choice of the site and the permafrost characterization, as well as in the design, the construction and the monitoring of the experimental road section at Beaver Creek (Yukon), to test mitigation techniques of permafrost degradation. The team efforts will be supported by a group of collaborators from the industry (program partners). These collaborators are pavement engineering experts involved in soil investigation, pavement design, construction and maintenance of roads and airfields in permafrost areas. They will provide a practical engineering perspective and an intimate knowledge of problems related to the management of transportation infrastructure in permafrost environment.

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