Science to Technology—The importance of understanding the fundamentals of permafrost science for engineers practicing in the north

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
The author met J. Ross Mackay in 1972 after requesting his assistance to prepare for a pipeline data collection program in the Mackenzie Valley. Mackay provided selflessly of his time to transfer basic knowledge of permafrost and ground ice with advice on what to look for in the field. That relationship carried on to the end of his life with exchange of information useful for engineering purposes. He was outstanding in his dedication to his research and to those who worked with him and then went on to carve out their own niche in this important region of Canada. The paper looks at the importance of understanding the genesis of ground ice and its importance to engineering. Polygonal ground formed by ice wedges is identified as a high-risk terrain unit. The paper relates this knowledge to decisions that had to be made when routing a new highway from Inuvik to Tuktoyaktuk. The route crosses 140 km of some of the most difficult terrain for road building in Canada.

RÉSUMÉ
L'auteur a rencontré J. Ross Mackay en 1972 lors des études du projet d'un couloir de gazoduc dans la vallée du Mackenzie. Mackay lui a transmis ses connaissances en pergélisol et en glace de sol ainsi que ce qu'il faudrait chercher sur le terrain. Cette relation a continué tout au long de sa vie avec des échanges d'informations utiles en ingénierie. C'était un chercheur dédié à ses travaux et à ceux qui travaillaient avec lui et qui ont ensuite fait carrière dans cette importante région du Canada. Cet article démontre l'intérêt de comprendre la naissance des glaces de sol et leur importance en ingénierie. La structure polygonale formée par les coins de glace est identifiée comme très dangereuse. Cette information est ensuite liée aux décisions prises lors de la création de l'itinéraire de la nouvelle autoroute entre Inuvik et Tuktoyaktuk, route qui traverse 140 km de terrain le plus difficile pour la construction d'une route au Canada.

1 INTRODUCTION

It is an unfortunate reality today that civil engineers graduating from Canada's Universities learn little about the permafrost that underlies fifty percent of our country. Even graduate students in civil/geotechnical are fortunate if they can get more than a lecture or two on how to recognize and accommodate the unique challenges posed by design and construction for permafrost regions. Those that choose to practice engineering in Canada's North must learn the tools by working with a mentor and by self-study. That self-study component must include a grasp of the fundamental properties of permafrost that affect its distribution and its ability to support the infrastructure that northern Canada needs. We frequently turn to an active scientific group of permafrost geographers currently working in Canada, many of whom can link their mentorship and motivation to the work of Professor J. Ross Mackay.

This paper examines how Mackay's work helped shape engineering practice in the North through the 1970's and 80's. In 1972, the author was assigned a task of planning and executing a helicopter supported, geotechnical drilling program that was required for early feasibility assessment of an Arctic gas pipeline (Gas Arctic Systems). That program covered the lower Mackenzie Valley and northern Yukon to the Alaska border. Dr. Mackay took an entire day to educate this neophyte engineer on how to recognize terrain features that are indicative of an active ground ice environment. From that time forward, we became friends and shared experiences through his many published papers and at the International Permafrost Conferences. His dedication to the science and genuine desire to help others was an enormous benefit to all those who chose to practice engineering in regions where permafrost is present.

2 GEOTECHNICAL ENGINEERING PRACTICE EVOLVES FROM GOOD SCIENCE

There is nothing more effective at bringing science to engineering practice than a natural impediment to proposed new infrastructure to which there seems to be no practical solution. In the early 1970's, following discovery of oil at Atkinson Point on Tuktoyaktuk Peninsula, it was recognized that permafrost was a serious impediment to either a warm oil pipeline south from the Mackenzie Delta or a cold gas pipeline in discontinuous permafrost of the upper Mackenzie Valley. There was a clear need to put the engineers who were looking for information together with the scientists who had been studying permafrost in order to look for solutions. That process was initiated at a conference in Ottawa in 1972, organized by the National Research Council and referred to as the Canadian Northern Pipeline Research Conference. As a recent graduate with a strong desire to better understand the hidden perils of northern terrain, I had the opportunity to attend that conference. Ross Mackay presented a lengthy paper simply entitled “Permafrost and Ground Ice” (Mackay, 1972) in which he wisely told the engineers that:

“The most important engineering element in permafrost construction is the distribution and behaviour of ground ice in permafrost. If such high ice content permafrost can be mapped and thus avoided or designed for, the engineering problems in permafrost will be substantially minimized.”

This seemingly simple message was right for the time as it helped to establish a solid user group for Ross’s research into the world of underground ice. At the same conference, Dr. Jack Mollard introduced us to the new science of terrain classification and mapping using airphotos and Dr R.M. Hardy, then Dean of Engineering at University of Alberta provided an overview of the engineering challenges. We went away from that conference with at least two new tools to work with; the importance of identifying terrain with a prevalence of ground ice and stereo airphotos that can provide a tool for identification of surface indicators along any proposed route.

3 IMPORTANCE OF GROUND ICE

The realization that ground ice should be treated as a stratum within our geotechnical logs brought about a need to understand how it got there. Not unlike classifying a sand or gravel as alluvium or moraine, we needed to know more about ground ice origins. Ross Mackay’s work on the origin of ground ice in key papers published in the early 1970’s, such as: “The Origin of Massive Icy Beds in Permafrost , Western Arctic Coast, Canada” (Mackay, 1971a), “The World of Underground Ice” (Mackay, 1972b) and “The Growth of Pingos, Western Arctic Coast, Canada” (Mackay, 1973) gave us the basics we needed. Engineers practicing in permafrost regions learned to use that information to make rational judgements on the probable nature of ground ice from terrain features. The effective use of stereo airphoto interpretation with appropriate ground reconnaissance quickly became an essential component of northern geotechnical practice.

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3.1 Quaternary History

It became clear from Mackay’s early work in the Mackenzie Delta Region that some knowledge of Quaternary history for the particular terrain provides a valuable insight from which to evaluate ground ice distribution and risk. He reminded us that the age of permafrost is directly related to regional glacial episodes. We think of permafrost in the Western Canadian Arctic as Late Pleistocene in age, some 13,000 years old. Mackay showed us the significance of understanding the different phases of Laurentide glaciation that left behind permafrost in the Mackenzie Delta region with ages ranging from 44,000 to 13,000 years. The most recent permafrost of the modern Mackenzie Delta was formed by “open system”, downward freezing of unfrozen soils. Mackay refers to this common form of ground ice as; “aggradational segregated ice” or epigenetic ice, as the soil formation predates the ground ice that is now found in it. This ice type gives rise to extensive and sometimes near continuous ground ice just below the current active layer in Mackenzie Valley permafrost. This is in contrast to older permafrost soils of the Tuktoyaktuk Peninsula and Yukon Coast that have a much longer permafrost history with periods of closed system freezing following interglacial periods that produces massive icy beds exposed on the coast of the Tuktoyaktuk Peninsula as shown in Figure 1 (Mackay 1971a, 1971b).

The distribution of ground ice can be even more complex in regions of central Yukon where relict permafrost, believed to be as old as 700,000 years, has been found at substantial depths in placer mine exposures (Froese et al., 2008). Ground ice, believed to have formed in early glacial times, was also encountered in a deep clay horizon shown in Figure 2. These unexpected events prove to be challenging for engineers working on resource projects where stability of pit walls and waste material embankments often control operations.

Figure 1. Exposure of massive Icy beds, near Tuktoyaktuk, June 2012

The continuing possibility that some massive ice features may be remnants from past glaciers that have been preserved by granular cover has been a source of debate among permafrost scientists in Canada for some time. Mackay was not a strong proponent of this potential ground ice source because he was able to otherwise rationalize ground ice origin within his research sphere of the Mackenzie Delta environs. Ground ice features found at the base of large eskers within the Canadian Shield Region of Northwest Territories and Nunavut do not fit any of Mackay’s ground ice description. A typical exposure of clear blue ice, shown in Figure 3, exposed at the contact between a dense impermeable till sheet below and a clean sandy gravel esker above are common occurrences in that region. Inspection of an ice exposure at Ekati Diamond Mine by a group of permafrost scientists is shown in Figure 3. That site visit conducted in conjunction with the Seventh International Conference on Permafrost, Yellowknife, 1998, resulted in consensus that the ice must be a glacial remnant. Buried glacial ice, embedded in moraines and below eskers, has now been accepted as ground ice features that also pose risk for roads and foundation infrastructure.

Figure 2. Ice lenses up to 1 m thick exposed in a deep clay horizon believed to be relict permafrost, Minto Copper Mine, Yukon

Figure 3. Massive ice exposure at the base of an esker, Ekati Diamond Mine, 1998

3.2 Ice Wedges and Frost Effects

Near surface ice wedges that form polygonal ground are evident to most who work and build in permafrost regions. The explanation for ice wedge polygon formation is usually attributed to Lachenbruch (1962) based on his assessment of the massive polygon fields on the Alaska North Slope. Ground surface cracking at the onset of winter in response to rapidly cooled ground initiates ice wedge growth. The presence of these near surface linear ground ice features poses a substantial risk to all forms of transportation infrastructure in regions of continuous permafrost. The near surface ice can become a seepage corridor that will erode the core of a linear ice wedge that is supporting an embankment resulting in near instantaneous sinkhole formation. Road collapse caused by thermal erosion of ice wedges has been a direct cause of at least one traffic fatality on the Dempster Highway (Hayley et al, 1987).

Route selection tries to avoid or at least minimize regions of active ice wedge polygons. Not all ice wedges are directly visible as polygonal patterned ground as they also occur on slopes where soilifluction processes can obliterate the surface expression we look for with aerial photography (Mackay 1995). Where ice wedge polygon fields can't be avoided then the risk of thermal erosion followed by road collapse must be assessed and the embankment design modified to protect the shoulders from pond formation and retrogressive slumping. This usually goes along with a clear expectation that maintenance activities will escalate where ice wedges are included in the foundation soils.

Ross Mackay devoted much of his research effort toward understanding the freezing and cracking that initiates ice wedges, how they develop and change over time (Mackay, 2000). His long-term research on Garry Island has provided the source of knowledge that engineers need to evaluate the risk whenever ice wedge polygon fields must be crossed.

4 THE INUVIK TO TUKTOYAKTUK HIGHWAY (ITH)

An all-weather road to Tuktoyaktuk, NT that is under construction in 2015 incorporates many of the practical applications of lessons learned by engineers who have benefitted from the research of Ross Mackay. There were initiatives dating back to the 1960's to construct an overland highway that would connect Inuvik to Tuktoyaktuk on the Beaufort Sea. That would be a logical completion of the Dempster highway system that would provide road access to an Arctic seaport and service the community of Tuktoyaktuk. A route, approximately 140 km in length, has been studied and refined a number of times but was always considered too difficult because of the nature of the permafrost terrain and therefore too costly.

The Federal Government completed construction of the Dempster Highway in 1978 but there was a long follow-up period of contract litigation that showed a need for better terrain knowledge. Design and contracting methods also needed fine tuning to the Arctic environment before another major highway project was initiated over difficult permafrost terrain. Permafrost conditions on the Dempster highway have been described elsewhere in the proceedings by Burn et al (2015).

The most troublesome terrain on the Dempster highway has been where it crosses the Richardson Mountains at the border between Yukon and Northwest Territories. The eastern foothills of the mountains, commonly known as the Peel Plateau, have clearly demonstrated to highway engineers the risks that shallow ground ice, both massive ice and wedge ice, poses to embankment stability. The site of the embankment collapse at NT-km 8.5 in 1985, shown in a current photograph, Figure 4, remains a persistent challenge.

Figure 4. Long-term embankment instability over shallow ice wedges, Dempster Highway, NT-km 8.5, June 2015 photo

The Project Description Report for the new highway was submitted in 2010 (Kiggiak-EBA 2010), and the environmental hearings were complete in spring of 2013 with a positive endorsement of the project. Construction began during the 2013-2014 winter season after a cost-sharing agreement was signed between the federal and territorial governments. It was anticipated that construction would occur over four successive winter seasons, two of which have passed at the time of this conference. Embankment construction is on schedule and about half complete as of June, 2015.

Figure 5. The ITH road alignment had segments with a challenging choice between fields of ice wedge polygons and unstable thermokarst lakeshores. June 2015, photo

The technical challenges that had to be dealt with for this project included:

- Route optimization to avoid obvious terrain features indicative of ice wedge polygon fields and thaw flow slides (Figures 6 and 7).
- Recognition that a particularly ice rich zone occurs virtually everywhere below the active layer and can extend to depths of several metres. This concentration of ground ice is so prevalent that it must be assumed to be continuous
- The embankment fill must be continuous with a minimum thickness that can vary somewhat with active layer properties and ground ice type.
- The tundra surface is highly sensitive to disturbance everywhere therefore the construction plan must preclude any operation over tundra that was not protected by a fill structure or winter road. All fill placement must occur when the active layer is fully frozen
- Material sources are scarce and usually contained excess ice. It was recognized that winter fill placement followed by grading, shaping and compaction of the embankment in summer would be a requirement. Techniques for material sorting to minimize ice content would have to be developed within the individual borrow pits.

Figure 6. Thermokarst lake with active thaw-flow slide a few km south of ITH route near Inuvik. June, 2012 photo.

Figure 7. Material source access road over ice-wedge polygons just south of Tuktoyaktuk.

A number of options were examined at the final design stage to maintain the original active layer beneath the embankment in a fully frozen condition. Embankment thicknesses were optimized with 2D geothermal analyses based on four general terrain types. Options that included insulation with sideslope berms for high risk terrain, such as ice wedge polygon fields, were developed as an alternative to simply increasing embankment fill thickness. However, the design-build contractor had a strong preference for thicker fills rather than address the complexities associated with multi-layered embankment systems. There was a strong but understandable pull to keep construction simple given the winter conditions.

The behavior of winter-constructed thick fills required to achieve design vertical grades were a concern as experience has shown that the sideslopes will creep on an ice-rich foundation resulting in longitudinal cracking. A test section was constructed with sideslopes that included geotextile layers as reinforcement in April 2015. A description of the test site and how it was constructed is included in these proceedings (De Gusman et al, 2015)

5 CONCLUSIONS

The legacy of Ross Mackay has been permanently embedded in permafrost science in Canada and has also shaped the evolution of engineering practice for our northern environment. Engineers learn by experience from each project they undertake. In order for it not to be the same experience repeated again and again, we must collectively build upon an accumulation of knowledge that contributes to a better understanding of our natural environment. That is particularly true in the North where permafrost terrain continually challenges us to produce reliable yet cost-effective infrastructure.

I was fortunate to deliver a presentation at a special celebration for Ross Mackay's 90th birthday on February 17, 2006. Several days later I received mail from Ross thanking me for the presentation. The message was hand-written on the back of a photograph taken near Inuvik. That photograph showed a snow fence he installed in 1978 to study the effects of snow cover on active layer thickness and his message to me included an update on what 10 years of enhanced snow cover could do to the active layer. It is truly hard to comprehend the passion he had for his work and his joy at spreading the knowledge. May we all take a message of inspiration from a life so well lived.

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