Considering Permafrost in the Design of Linear Infrastructure through Mountainous Terrain

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Traditionally, only a 500 - 2000 meter corridor width is considered and assessed when linear infrastructure, such as a road, pipeline or transmission line is planned. As such, hazards that originate from the periglacial belt at high elevations outside the corridor, which are often controlled by climatic parameters, may not be considered. Rapid climate change and variations in climate extremes can have a significant impact on the permafrost degradation and deglaciation in mountainous terrains of the Canadian Rockies and the Coast Mountain Range and change the geohazard potential with time. In order to assess such potential hazards for linear infrastructure projects through northern British Columbia, the role of permafrost must be addressed. This is best carried out in a systematic way, where direct and indirect hazards are assessed by using a scenario based approach that may also consider future climate change.

RÉSUMÉ
Lors de l'implantation d'une infrastructure linéaire telle une route, un pipeline ou une ligne de transmission, une largeur de corridor de 500 à 2000 mètres est traditionnellement examinée et évaluée. Les dangers provenant de la zone périglaciaire à haute altitude située à l'extérieur du corridor, souvent contrôlée par des paramètres climatiques, peuvent donc ne pas être pris en considération lors des analyses. Les changements climatiques rapides et les variations climatiques extrêmes peuvent avoir un impact significatif sur la dégradation du pergélisol dans les Rocheuses canadiennes et la chaîne de Montagnes Côtières modifiant ainsi le potentiel de géorisques dans les années à venir. Afin d'évaluer ces risques potentiels sur les projets d'infrastructures linéaires dans le nord de la Colombie-Britannique, le rôle du pergélisol se doit d'être analysé. La meilleure manière d'y arriver est d'identifier les zones à risques directs et indirects et de réaliser de manière systématique des analyses selon une approche considérant les changements climatiques futurs.

1 INTRODUCTION

Identifying geohazards is a critical task during early stages when developing the route for new linear infrastructure or when assessing risks to existing transportation, communication and energy networks. Often, a 500 m to 2000 m wide corridor is selected in which the infrastructure route is considered, and geohazards are identified that occur within or have historically impacted this corridor. A geohazards inventory then evolves as project specific knowledge is gained through successive stages of air photo or satellite image review, assessment of high resolution, bare earth topography (e.g., from LiDAR), helicopter and ground reconnaissance, and if possible, subsurface investigations.

The types of geohazards can vary significantly along the total extent of the linear infrastructure and often chains of events occur, such as a rock fall or ice fall into a proglacial lake that can cause a flood or debris flow downstream (Quinn et al., 2014). In particular in mountainous terrain, where gravity driven mass movements are the most common geohazards, such chains must be assessed. An overview of typical geohazard types in mountainous terrain is presented in Table 1.

Water plays an important role for triggering mass movements and controlling travel distances. When affected by frost adding the attributes *frozen* and *thawed* to the water conditions, as suggested by Couture and Cruden (2010) and Couture 2011, is considered particularly useful for the classification of landslides in permafrost terrain in northern Canada as well as mountainous environments.

Table 1. Potential range of geohazard types to be considered for linear infrastructure in mountainous terrain.

Bedrock slump	Soil creep
Rock creep	Soil slump
Rock fall	Slow earth flow
Rock slide	Rapid earth flow
Rock avalanche	Debris flow / flood
Debris slide / avalanche	Snow avalanche
Ice fall / avalanche	Glacial lake outburst flood

Once the hazard type has been identified, the magnitude and annual probability (or frequency) of a particular event is required in order to carry out a geohazard risk assessment. Often, a geoprofessional relies on historic events in order to estimate the frequency of an event with a specific magnitude to occur. However, historic events and past processes may not represent current and future conditions, if the pre-conditioning factors or triggers are non-stationary in time. As such, the frequency magnitude relationship may either be over- or underestimated from past events.

In glaciated mountainous environments rapid changes are currently noted (WGMS, 2008, Gardner et al., 2013). In particular glacier retreat and permafrost degradation, which occur at unprecedented rates (Deline et al., 2015), result is the formation of new hazards or the elimination of old ones (Haeberli et al., 1997). Fischer et al. (2012) show that changes in atmospheric temperatures and related changes in surface ice covers can induce slope destabilization. However, they further found that once triggered, mass movement activity can proceed in a self-reinforcing cycle. A single mass movement event might be strongly influenced by short-term extreme temperature events.

To account for the dynamics in mountain environments Huggel et al. (2004) presented a procedure for a first-order assessment of glacial hazards. The authors note that the probability of occurrence for glacial hazards is difficult to estimate because of rapid changes in the nature of glacial systems, the low frequency of such events, and the high complexity of the involved processes.

While changes in the glacial environment are striking and easily noted by the general public (e.g., Athabasca Glacier: CBC, 2014), changes also occur in the permafrost environment. Haeberli et al. (submitted) highlight the climate change related changes in the dynamics between the glacial and the periglacial environment. Ground temperatures and ground ice conditions change at a significantly slower rate than surface ice, because of the thermal protection. Haeberli et al. (submitted) estimate for the European Alps that the volume of subsurface ice will exceed the volume of surface ice in about 40 years. With regards to assessing geohazards in a mountainous environment this means that glacial hazards, such as ice falls, may no longer exist whereas new rock fall hazards will form from newly exposed rock faces. Haeberli et al. (submitted) further highlight the increased hazards related to the increasing potential for destructive flood waves from new lakes in deglaciated mountainous regions. Such new lakes can become multipliers for geohazards and affect regions far beyond historical conditions (Carey et al. 2012; Haeberli 2013).

In this paper we describe the challenges in identifying potential hazards related to permafrost and how these may affect linear infrastructure.

2 LINEAR INFRASTRUCTURE AND PERMAFROST

While the potential presence of permafrost in non-mountainous northern latitudes is relatively straightforward to evaluate using existing maps (Brown, 1960; NRCan, 1993), this is much more difficult within mountainous terrain. In the arctic regions, elevation and topography has a secondary impact on the presence and characteristics of permafrost compared to the mountainous terrain of the Rocky Mountains and the Coast Mountains, where the existence of permafrost is largely driven by the topography, i.e., elevation and aspect. In addition, gravity driven mass movements, including snow avalanches, as well as snowpack thickness that will change with aspect and wind exposure, further affect whether permafrost conditions prevail or not, where ground ice may form, and the ground thermal regime. Therefore, spatial permafrost distributions in mountainous environments should be described relative to a probability and not in terms of continuity as it is known from Arctic regions.

The high spatial variability in the existence and characteristics of permafrost together with the non-stationarity of mass movements' triggering mechanisms from within the periglacial belt requires the consideration of all potential processes that can potentially affect the infrastructure. As such, permafrost that exist at slopes to the height of land outside a narrow design corridor (e.g., 500 m wide) must be included in a proper hazard assessment.

Different permafrost distribution models have been developed in recent years. Some are global with a very coarse spatial resolution (e.g., Gruber, 2012), regional at higher spatial resolution (Arenson and Jakob, 2010; Bonnaventure and Lewkowicz, 2012; Bonnaventure et al. 2012; Quinn, 2013), or even local. Unlike glaciers, permafrost is not visible at the surface and therefore it is often only possible to infer the presence of permafrost and use periglacial landforms, such as rock glaciers (Figure 1), or solifluction slopes for the calibration and/or validation of a particular model.

Figure 1. Rock glacier in the Rock Mountains near Banff, AB (Photo: L. Arenson, 2014)

While it is important to understand current conditions, risks also need to be evaluated for the future. The existence of ground ice together with the variability and heterogeneity in the distribution of mountain permafrost complicates the use of climate projections in order to estimate future permafrost distributions. While attempts using atmospheric changes to project permafrost warming and changes in the spatial distribution (e.g., Bonnaventure and Lewkowicz, 2013) have been presented, such results have to be used with caution. Ground temperatures, in particular when ice-rich, have different response times to atmospheric changes depending on their depth (e.g., Lachenbruch and Marshall, 1986). Therefore, it is possible that atmospheric driven projections of future permafrost behaviour may overestimate the permafrost degradation rates and hence, future hazard potential from the periglacial environment.

The effect of topography on the presence of permafrost in Western Canada is visualized in Figures 2 and 3. Figure 2 shows the distribution of slopes and Figure 3 presents the permafrost zonation index after Gruber (2012), which is an indicator for the presence of permafrost, but not necessarily ground ice. Within two important mountain ranges for western Canada (Coast Mountains and Rocky Mountains) permafrost could be encountered at all latitudes, given adequate altitude, aspect, slope angle, geology and drainage. The probability decreases towards the south and with lower elevation (Harris and Brown, 1982; Harris, 1986).

Figure 2. Mountain topography of western Canada. Dark shades indicate steep slopes, white, flat (DEM based on ASTER GDEM data).

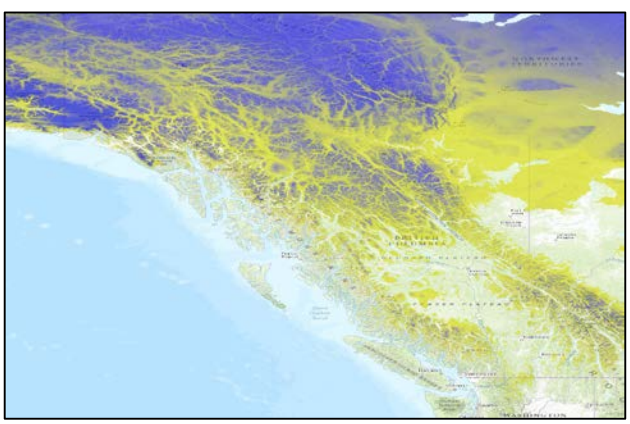

Figure 3. Permafrost zonation indes for western Canada. Color indicates likelihood for permafrost to exist: Yellow: low; Blue: high (based on Gruber, 2012).

A recent focus on the interaction between permafrost and linear infrastructure in Western Canada has been mainly concerned with proposed pipelines. Figure 4 shows a series of proposed gas pipelines to serve proposed LNG plants in coastal BC. When comparing the pipeline routes to Figures 2 and 3, they fall into the ranges where permafrost may exist. Permafrost may not be present within the narrow right-of-way, particularly if it runs along valley bottoms (i.e., there may be no direct impact on the permafrost or from the permafrost conditions on the pipeline), but it may be present at higher elevation and cause a hazard if degrading.

Pipelines are not the only type of linear infrastructure that must be assessed. There are various other types of linear infrastructure where geohazards related to permafrost must be addressed. An overview of existing linear infrastructure in British Columbia is shown in Figure 5.

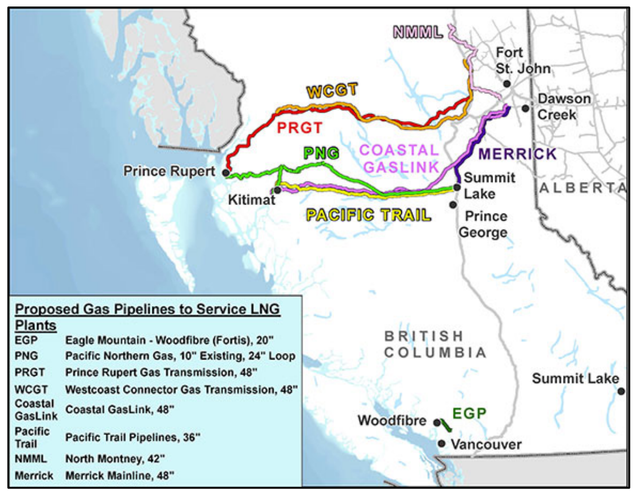

Figure 4. Proposed and existing pipelines in British Columbia. This map illustrates the various pipelines that have been proposed in British Columbia to deliver natural gas to potential LNG liquefaction facilities for export to overseas markets.

3 POTENTIAL HAZARDS AND ASSESSMENTS

The effects of permafrost interaction with linear infrastructure can be direct, such a road embankment built on a permafrost foundation, or indirect, where rock fall originating from the periglacial belt can trigger a flood, which affects the foundation of a transmission line tower. These two types of geohazards are discussed in this section, and some considerations related to climate change are discussed.

3.1 Direct hazards

Direct hazards are considered those that are related to the presence of permafrost under or directly adjacent to the linear infrastructure, i.e., where permafrost is present within the right-of-way. Changes in the surface ground thermal regimes and the surficial hydrology, which will always occur independent on the type of infrastructure, are herein considered to cause direct hazards. Direct hazards therefore include existing hazards that may impact the infrastructure, or hazards initiated due to changes that are caused by the construction of and the infrastructure itself.

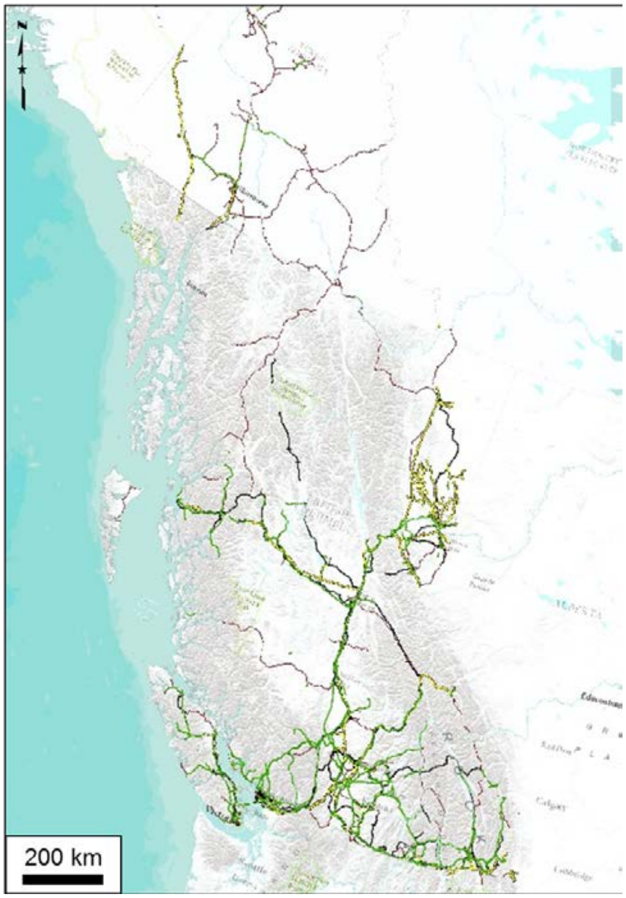

Figure 5. Network of linear infrastructure in Western Canada: Transmission lines (green), pipelines (yellow), Railways (black); Major roads (brown).

The evaluation of direct hazards is typically easier than evaluation of indirect hazards since, assuming the location, extent and characteristics of the permafrost are known, the impact on a structure or its foundation and the related hazards are evident while carrying out any foundation design. For example, hazards to a structure triggered by thermokarst formation or thaw settlements can be calculated based on an understanding of the geotechnical properties of the foundation.

3.2 Indirect hazards

Indirect hazards are those where the permafrost is not present at the location of the infrastructure, but where the hazard originates from it. Some of those hazards may have manifested themselves at the location of the infrastructure and indicators from past events, such as mass movement deposits (debris fan) or abandoned river channels, may be visible. Others may not yet have occurred because the environmental conditions have changed. Indirect hazards can only be identified if a thorough terrain assessment is carried out that expands past a narrow corridor and typically includes an evaluation of all slopes to the height of land, or a sufficiently wide corridor.

The hazard assessment is therefore best to be carried out scenario-based by anticipating conditions that reach well beyond a historical understanding. This involves a compilation of various failure scenarios and event-chains that can be envisioned along the linear infrastructure even if it is obvious that such an event has never occur in the past, or may not yet be possible, e.g., formation a flood wave from a proglacial lake, despite the lake has not yet formed. Professional knowledge and experience of mountain permafrost, and an understanding of how changes in ground thermal regimes can influence hazards from the permafrost, are required. Physical and numerical modelling, such as rock fall, debris flow and/or thermal modelling can support the quantification of the various hazard scenarios developed during an initial stage. It is further recommended that the hazard scenarios are discussed amongst various experts in order to evaluate potential event magnitude and annual probabilities.

3.3 Climate change

As indicated above, ongoing climate change results in unprecedented rates in glacier retreat and permafrost degradation. These two processes occur at different rates and it is possible that for the Canadian mountain ranges, the volume of surficial ice may eventually be smaller than the volume of ground ice in the permafrost. Where no permafrost hazards or only glacier hazards exist today, permafrost related geohazards may form in the future and must be considered.

To evaluate future hazard potential considering climate change, a time horizon must first be selected, for which the hazard is to be evaluated. In the short-term, climate change may have no impact on the geohazards, but this may be different in the long-term when glaciers have receded and new proglacial lakes have formed. The evaluation should be scenario-based, but also requires a good understanding of the current conditions.

General trends in future climate can reasonably be projected (IPCC, 2013). However, in order to evaluate hazards from permafrost, extreme events are often controlling and result in significant increase in a hazard (e.g., 2003 heat wave in the European Alps, Huggel et al., 2010; Allen and Huggel, 2013). This is related to the important role of the active layer in the triggering of mass movements, since large instabilities mainly occur if the underlying permafrost is affected. However, during an extreme warm year, and potentially in combination with change in precipitation, the active layer can penetrate significantly, thereby triggering unprecedented slope instabilities. It is therefore not sufficient to only consider long-term changes in air temperatures when assessing changes in hazards from permafrost, but also to assess the changes in the probability of extreme events to occur. For mountainous environments this is an extremely challenging task and there is no approach that would work for all situations. Therefore, such an assessment must be carried out on a case-by-case basis.

While developing the various hazard scenarios considering potential changes in climate conditions it is important to recognise if events have the potential for reoccurrence or not. For example, a rock avalanche cannot reoccur if the single event resulted in complete removal of the hazard source zone.

3.4 Systematic assessment

In a systematic approach, the potential presence and the mechanical and thermal characteristics of the permafrost must be evaluated. Coarse permafrost distribution models (e.g., Gruber 2012; Figure 3) can help initially, but local, high-resolution models that are calibrated for the local conditions should be used during subsequent steps (Figure 6). Since the temperature conditions and the ground ice characteristics of permafrost are not directly visible at the surface (Figure 7), detailed site investigations are often needed. However, such investigations are often expensive and time consuming and therefore an iterative process is recommended.

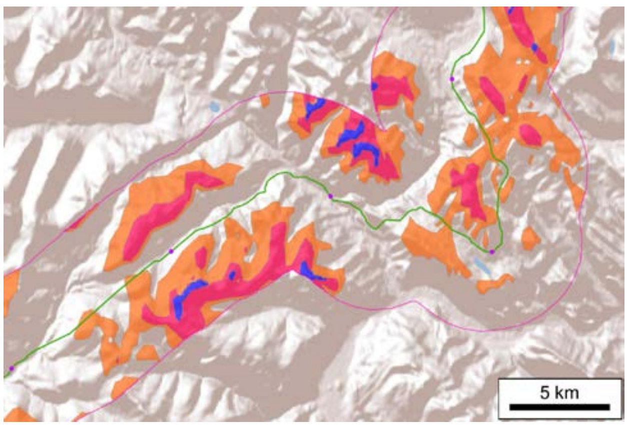

Figure 6. Permafrost probability distribution for an 8 km wide corridor along a proposed linear infrastructure.

Figure 7. Area of low permafrost probability. Site investigations may be required to understand where permafrost and ground ice may exist.

Figure 8 is a simplified attempt to illustrate an approach for evaluating geohazards in a permafrost environment, considering the potential for future change of the permafrost regime. The major challenge in such an assessment is the uncertainty related to the soil and ground temperature conditions, which includes future variability of permafrost and ground temperatures. It is therefore recommended to evaluate key hazards and risks in an iterative approach. This can be done by starting with a high-level identification of major risks on a qualitative basis, followed by a quantification of the risks in a next iteration using site specific data that were collected in the field.

Data from remote sensing, supported by local field calibration may be sufficient to evaluate risks at a high level. However, it is important that the assessment corridor is not defined in such a way that hazards originating from higher elevations are ignored, even though there may be no evidence of past events at the location of the proposed infrastructure.

Using the initial hazard and risk evaluation, more detailed investigations, and physical or numerical modelling can be carried out that primarily focus on high risk zones. Insights from these further investigations will then support improved hazard and risk assessment. At the end of the updated assessment it is important that the initial hazard assessment is revisited in order to calibrate the overall hazard classification and to ascertain that the hazard evaluation has been carried out uniformly.

4 CONCLUSIONS

Rapid changes in mountain permafrost can create geohazards that have not occurred in the past or change the frequency and/or magnitude of existing geohazards. An approach has been introduced that can help in evaluating direct and indirect hazards related to permafrost when designing and routing linear infrastructure through mountainous terrain. The major challenges related to the identification and quantification of such hazards are:

- Permafrost is not visible at the surface;
- Glaciers are receding at a fast rate, changing the mountain landscape by creating new hazard potential, e.g., proglacial lakes with outburst flood potential;
- Permafrost-related hazards often react to extreme climate events and not to average changes; and
- Hazards triggered from high mountain permafrost can cause impacts at significant distances downslope.

An iterative assessment of hazards, using a scenario-based approach to evaluation of potential direct and indirect permafrost geohazards has been presented. While the lack of site specific data often limits the quantification of a hazard, the proposed approach can support the identification of sites where more detailed study is required.

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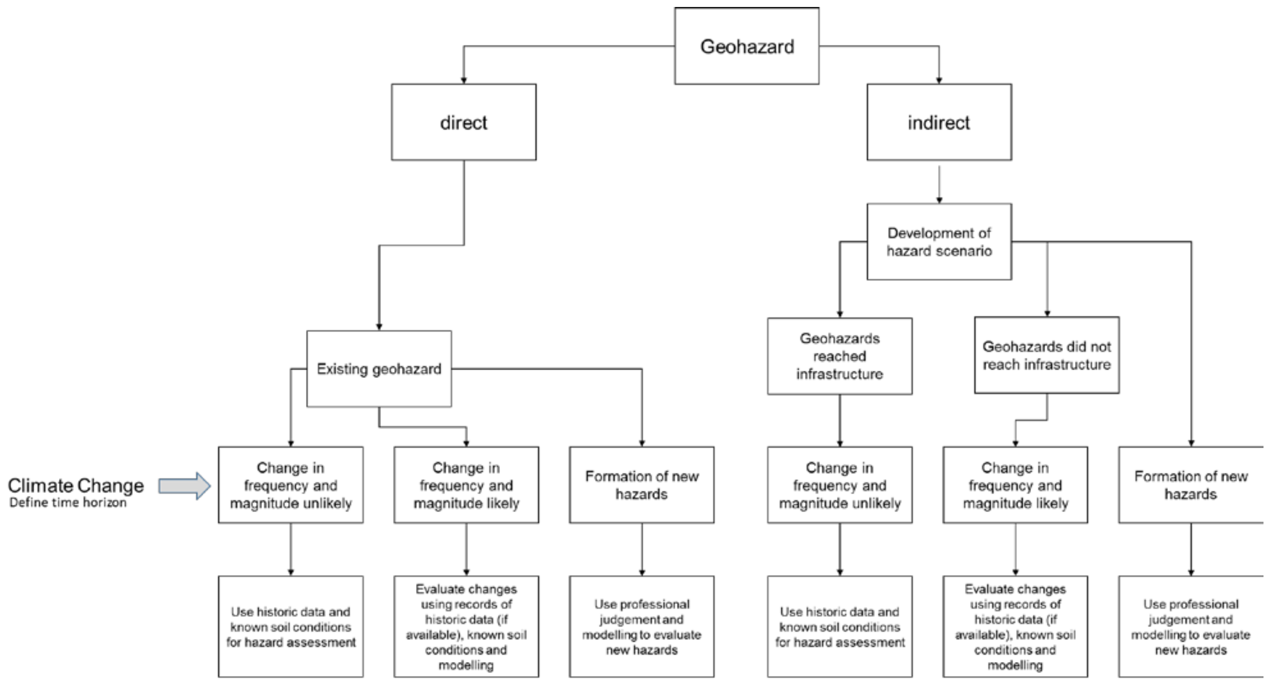

Figure 8. Schematic approach in evaluating direct and indirect geohazards from permafrost.

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