Quantitative Risk Analysis of Linear Infrastructure: State of the Practice and Research Plan

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Abstract: Qualitative analysis processes are currently used to design and allocate maintenance monies for linear infrastructure on permafrost. The routing and maintenance locations are generally selected using a qualitative process, with probabilities and consequences of each potential failure mode evaluated using a scalar rating system. A quantitative risk assessment utilizes calculated values of failure probability and consequence. In either analysis method, the values of probability and consequence are multiplied to determine a risk importance factor, which is used to rank and analyze each risk. While qualitative analysis methods have been used for many years, there is a push within the engineering community towards probability-based methodologies, quantifying the analysis process. This paper presents a review of probabilistic methods used to analyze geotechnical properties and calculation uncertainty, problems and failure modes of embankment-supported infrastructure on permafrost, and risk analysis methods. This review is an initial step in the development of a tool and methodology for quantitative risk assessment of linear infrastructure on permafrost; a brief discussion of the research plan is also included.

Keywords: Embankment; Infrastructure; Permafrost; Risk analysis; Uncertainty.

1 INTRODUCTION

Continuous and discontinuous permafrost areas are ubiquitous in circumpolar regions. In the arctic regions of Alaska and Canada, communities with rural and business interests (oil and gas exploration, mining activity) are increasing (Allard et al. 2012). These business interests and communities require transportation of goods and people to and from these areas, thus roadways, railways, or airports are necessary. Additionally, pipelines and power lines are needed within these communities and industrial regions.

In rural Alaska and Canada, a significant number of rural communities are solely connected to major population centers via air travel for people and perishable goods and via waterways for durable goods (Allard et al. 2012; Beaulac and Doré 2006). Only a few North American communities in permafrost areas are connected via year-round roadways supported by embankments. These include, for example, Prudhoe Bay, Alaska, via the Dalton Highway (Hwy), Yellowknife via Northwest Territories (NWT) Hwy 3, and Inuvik, NWT from Dawson City, Yukon, via the Dempster Hwy. Railways on permafrost have been constructed in Alaska, Canada, Russia, and China (Kondratiev 2013). Since these transportation infrastructure systems are often the sole method of transport for goods, services, and people, these infrastructures are critical and necessary, and the consequences of their poor performance or failure can be significant economically, politically, socially, and culturally.

In order for communities and industry to make informed, unbiased assessments of their infrastructure vulnerabilities, an objective analysis method is needed. This paper reviews risk analysis methods, statistical methods used in geotechnical engineering, and problems and failure modes of embankment-supported infrastructure on permafrost.

2 REVIEW OF RISK ANALYSIS AND SELECT METHODOLOGIES

Risk analysis is the combination of the probability of an adverse event (failure) occurring multiplied by the consequence of the event's occurrence, as shown in equation [1]:

$$R = P \cdot C \qquad [1]$$

where P = the probability of failure, C = the consequence of failure, and R = the risk or risk importance factor.

In the planning and design of linear infrastructure systems, qualitative or quantitative risk analysis methods are and can be used as a decision tool to analyze the costs and benefits of alignments or to prioritize maintenance activities. In a qualitative analysis method, P and C are assigned a scalar value from a previously specified range, usually a rubric, where the higher the value, the greater the probability of failure or consequence (PIEVC 2009). For a quantitative analysis, P and C are both calculated for each failure mode with P calculated from the failure mode uncertainties and C determined from the direct and indirect consequences associated with the failure mode. The resulting risk factor is used to rank the possible failure modes.

The process of risk assessment is best outlined in the All Hazards Risk Assessment Methodology created by Public Safety Canada (2011). While not specifically an engineering risk analysis, the steps presented for risk analysis are apt and include the following: 1) identifying the risks by defining internal and external parameters for consideration; 2) describing each identified risk; 3) analyzing the risk by calculating P and C for each risk and determining R; 4) evaluating the risks by ranking and sorting risks based on R; and 5) determining which risks require action or are acceptable. Acceptable risk benchmarks, as suggested for slope stability, are "established by balancing the costs of achieving a degree of safety with the costs associated with failure, multiplied by the probability of failure" (Christian et al. 1994).

Public Safety Canada's (2011) broad analysis method serves as a basis for other risk analysis methods. The United States Army Corps of Engineers (USACE) uses a risk-based quantitative analysis to improve financial decisions associated with dam and levee infrastructure by creating an unbiased decision tool in support of planning studies. In order to characterize and identify the risk events, the method utilizes an event tree, in which each node is an event with two or more mutually exclusive branches. The probability of an event's occurrence is determined by multiplying the probability of the preceding events along the path of the event tree (Baecher and Christian 2003, USACE 1999). Since this guide is largely used to analyze dam and levee infrastructure, probabilities of failure have been determined based on documented past occurrence. However, the method recommends First Order Second Moment (FOSM) Methods or Monte Carlo simulation for P calculations when there is insufficient data for a frequency analysis (USACE 1999).

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) has created, and validated via case studies, a standardized protocol for use by engineering professionals in Canada to assess infrastructure vulnerability to climate change (PIEVC 2009). The infrastructure elements are combined with climate change elements, and then each combination is analyzed using standardized tables of P and C values. The protocol can be either qualitative or quantitative depending on the assessor's engineering judgment of the available data (PIEVC 2009). Note this method is the intellectual property of Engineers Canada and a user agreement is required to utilize this analysis method.

A case study to test the PIEVC methodology was completed to analyze the vulnerability of a section of Hwy 3 near Yellowknife, NWT. The focus of the project was to determine how climate change may impact the highway (BGC Engineering, Inc. 2011). Using the protocol, the analysis team assessed "more than 1,100 highway infrastructure element-climate change combinations" using the qualitative analysis procedure because of insufficient information. Due to the large number of analysis combinations, the qualitative analysis used 5 broad categories to represent the subgrade soil conditions. Maintenance data were not sufficiently detailed for use in the analysis and a detailed historical and projected climate analysis was completed (BGC Engineering, Inc. 2011).

Based on the analysis, the highest risks generally included the following climate conditions: thermally sensitive (temperatures near 0°C) ice-rich subgrade soils, and drainage systems sensitive to changing rainfall conditions. Additionally, five climate properties were generally associated with the highest risks; these include ground and water temperature, average daily air temperature, thawing index and the number of freeze/thaw cycles" (BGC Engineering, Inc. 2011). Additional action was suggested to gather further climate data, investigate subgrade soil conditions, project infrastructure capacity, and analyze operation and maintenance records (BGC Engineering, Inc. 2011).

One of the assessors noted that this two dimensional analysis method (climate change condition, infrastructure element) is challenging to use for linear infrastructure (Arenson 2013). Arenson (2013) suggests the addition of subsurface conditions (soil and thermal) as a third dimension to the analysis.

3 REVIEW OF UNCERTAINTY AND PROBABILITY OF FAILURE (P) CALCULATION METHODS

To complete a quantitative risk assessment, one must calculate P and C. The probability of failure may be determined from reliability analysis methods, which aggregate the uncertainty from input parameters (Vick 2002).

Uncertainty, in some form, is inevitable in geotechnical engineering; these uncertainties must be reduced, faced and dealt with in a logical manner (Einstein and Baecher 1983). For geotechnical engineering, there are two types: natural variation (aleatory uncertainty) and systematic error (epistemic uncertainty). Aleatory uncertainty "reflects the underlying physical randomness" (Baecher and Christian 2003). The error due to sample disturbance, and the bias between the actual and model conditions are epistemic uncertainties (Baecher and Christian 2003).

3.1 Uncertainty in Soil Properties

Soil property determination includes both forms of uncertainty as conditions are naturally random and sampling methods introduce disturbance error. To account for these uncertainties, the designer must incorporate not only the data but also take into account the data's quality, the site geology, and applicable engineering judgment (Lacasse and Nadim 1996). Additionally, if a statistical analysis is performed, the evaluation of the data, the selection of a model to represent the data, and the difference between the model and reality combine to form additional epistemic uncertainty in the analysis. Further uncertainty or bias may be present due to the location, selection criteria and number of boreholes, samples, and laboratory tests (Vick 2002).

The most common probability density functions (PDFs) for soil properties and model uncertainty discussed in the literature include beta, normal, and lognormal distributions (Lacasse and Nadim 1996, Vita 1984).

In permafrost and non-permafrost areas, Vita (1984) proposed a method using Bayesian statistical methodologies to quantify and rationally augment site-specific data with that from other sites of the same landform. A landform is an element of the landscape formed by a single geologic process or a combination of associated processes, generally identified using aerial photographic interpretation and refined with further investigation. The end result is a method for supplementing sparse data to "probabilistically predict" geotechnical behavior (Vita 1984). This method was used to analyze soil and permafrost properties along the Dalton Hwy (R&M Consultants, Inc. 1984).

3.2 Reliability Analysis Methods

The uncertainties within geotechnical analyses, from the data and calculations, are taken into account within factors of safety (FOS), thus these FOS “act, to some extent, as correction factors” (Mortensen 1983). Analysis methods have been developed to determine the reliability of FOS to help determine the extent to which FOS are used as correction factors. The first utilizes the uncertainty within the input parameters to calculate the reliability of FOS (Duncan 2000). The second uses a more in-depth statistical analysis to determine the probability of failure in relation to a critical value (Banerjee and Datta 1991). The third, limit state design, also known as load and resistance factor design (LRFD), applies separate factors to the loading and resistance sides of a calculation to provide a consistent reliability of design (Goble 1999).

Reliability is defined as the probability of success or unity minus the probability of failure (Duncan 2000). In some engineering calculations, reliability index, β, is used as a measure of reliability, where reliability index is the mean value of FOS divided by their standard deviation (Baecher and Christian 2003, Christian et al. 1994).

Duncan (2000) proposes utilizing a Taylor series calculation method to determine FOS reliability. In this method, each input parameter within the engineering calculation requires a most likely value (mean) and a standard deviation. The most likely and highest and lowest likely values are calculated using the standard deviation. The FOS is evaluated at all possible combinations of high, low and most likely values and using these data the FOS variation can be determined. The FOS variation from each parameter is used to calculate β, from which a probability of failure is determined using a common PDF. Large amounts of data can be required to accurately calculate the mean and standard deviation of any parameter, and some parameters may be estimated from judgment or published sources (Duncan 2000). Thus, Duncan (2000) presents four methods to estimate the standard deviation. However, Duncan’s method only accounts for the aleatory uncertainty within the calculation; the epistemic uncertainty is not addressed nor calculated. Additionally, each parameter is considered an independent random variable that is not correlated with other input parameters (conditional probability).

In order to include both aleatory and epistemic uncertainty, Banerjee and Datta (1991) analyzed the reliability of thaw induced pore pressure calculations using Morgenstern and Nixon’s Theory (1971). First-order uncertainty analysis of the calculation method was used to mathematically determine the functions of the total, epistemic, and aleatory uncertainty in the calculation of the excess pore water pressure. Once a total uncertainty function is determined, the Taylor series expansions using the partial derivatives of the dimensionless pore pressure equation are evaluated with respect to each random variable, and then each equation evaluated at the mean value for each variable. In order to determine the probability of failure due to thaw induced pore pressure, the calculated value needs to be compared to a critical value. In this theory, R denotes the relationship between the rate of generation and expulsion of pore water; a value greater than one represents possible instability and is used as the critical value. Thus the calculated probability of failure is the probability that R exceeds one, given the epistemic and aleatory uncertainty. The mathematical analysis method was validated using a Monte Carlo simulation with 5,000 points for each parameter. The coefficients of correlation between dependent parameters were assumed and did not largely impact the final reliability calculation.

However, the determination of the uncertainty or reliability cannot be complete until the relationships between the properties are identified. If the properties are dependent, the conditional probabilities between the two dependent variables need to be determined (Baecher and Christian 2003). Correlation parameters between dependent variables are accounted for in Banerjee and Datta's analysis method.

Load and Resistance Factor Design (LRFD) is a design methodology combining statistical methods with traditional Allowable Stress Design (ASD) calculation methods. In ASD, the design engineer determines the driving forces (load) causing failure and the resistance forces against failure. The ratio of the resistance forces to the loading forces is the FOS for the analyzed failure mode; the FOS must be above a value based on engineering judgment and situation specific risk for the site (author experience). FOS calculation is a strength-based analysis (strength limit state), but the serviceability (deflection requirements) of an engineering analysis also needs to be considered (serviceability limit states).

In LRFD, the uncertainty in the loads and resistances are treated separately using different factors, as shown in equations [2] and [3] for strength and serviceability limit states in structural engineering, respectively. The load and resistance factors need to be determined through a calibration process, either to past practice (typical or codified factors of safety) or to a specific reliability index value (Goble 1999).

$$R_r = \phi R_n \geq \eta \sum \gamma_i Q_i \qquad [2]$$

$$\eta \sum \gamma_i \delta_i \leq \phi \cdot \delta_n \qquad [3]$$

where R_r = factored resistance; φ = resistance factor; R_n = unfactored resistance; η = dimensionless factors from the structural engineering code; γ_i = load factor; Q_i = load, stress or stress resultant; δ_i = estimated displacement; and δ_n = tolerable displacement.

Currently, the primary use of LRFD, in geotechnical engineering, is in the design of foundations, initially highway bridges, to match the practices of structural engineers (Baecher and Christian 2003, Goble 1999). Work is being done to extend the use of LRFD methods to other forms of geotechnical engineering.

The strength limit states of slope and retaining wall analyses are being analyzed to develop LRFD codes (Kim and Salgado 2008). Probabilistic analysis methods (Gaussian random field theory, first order reliability methods, and Monte Carlo simulations) were used by Kim and Salgado (2008) to determine the resistance factors at two probabilities of failure and three reliabilities using load factors from the AASHTO design code. However, given that the load and resistance force calculations rely upon mutual soil properties and the complex and varied geometry of slopes and retaining walls, the resistance factors vary on a case-by-case basis (Kim and Salgado 2008).

4 INFRASTRUCTURE SUPPORTED ON PERMAFROST

Permafrost is defined as a soil state, a mixture of mineral particles, unfrozen water, ice and/or air, where ground temperatures are below 0°C (32°F) for at least 2 years. The active layer is a surface soil layer that freezes and thaws on a yearly basis. However, the depth of freezing and thawing in the active layer varies depending on the winter and summer conditions (temperature, sun exposure, precipitation, and surface conditions, for example). Due to local thermal variations, a subsurface region with temperatures above 0°C can be present in an area surrounded (vertically or horizontally) by permafrost; this unfrozen area is known as a talik (Andersland and Ladanyi 2004).

Permafrost can be bonded or unbonded. Unbonded permafrost meets the definition of permafrost but due to a lack of moisture or a depressed freezing point the material exhibits behavioral characteristics of unfrozen soil. Bonded permafrost can be classified into three categories: massive ice, ice-rich permafrost and ice-poor permafrost. Massive ice is a term describing large subsurface ice features, including ice wedges, segregated ice, and buried ice. Ice-rich permafrost describes permafrost where the volume of ice is greater than the available soil pore volume in a thawed state. When the volume of ice is less than the available thawed soil pore volume, the permafrost is ice-poor. Further information on the definition and classification of permafrost can be found in any textbook on the topic.

4.1 Embankments on Permafrost

Embankment-supported linear infrastructure on permafrost is constructed by placing and compacting available fill materials on the ground surface in either winter or summer, thus compressing the active layer in subsequent years or after placement, respectively. In order to preserve the permafrost, the embankment is thermally designed in a manner preserving or raising the permafrost elevation (TCCRE 1996). However, the embankment itself changes the surface conditions, thus changing the localized thermal regime. Common embankment problems largely stem from this change in topography, such as lateral embankment spreading, which is triggered and exacerbated by snow drifting and ponded water adjacent to embankments (Andersland and Ladanyi 2004, Baecher and Christian 2003).

Observations of Hwy 3 and the Dempster Hwy were completed for a climate change vulnerability assessment by BGC Engineering, Inc. (2011) and a Master's thesis by Lingnau (1985), respectively. The observed infrastructure problems consist of: 1) differential movement in areas of subsurface soil transition (bedrock to ice-rich permafrost) or areas of previous construction; 2) settlement and transverse cracking at culvert locations leading to altered culvert gradients or culvert collapse; and 3) embankment and road surface instabilities in areas adjacent to water features (ponds, creeks, rivers) (BGC Engineering, Inc. 2011, Lingnau 1985).

In 1984, R&M Consultants, Inc. of Anchorage, Alaska was tasked with assessing the geotechnical characteristics of the Dalton Hwy, an un-surfaced haul road. The report notes "roadway surface conditions along the route vary substantially and are, to a large degree, dependent upon the characteristics of the imported embankment material." Potholes, rutting and soft spots were also noted. Additional problems may have been present; however, they may be masked by roadway maintenance activities (R&M Consultants, Inc. 1984).

The problems discussed previously are located within or adjacent to the embankment structure itself; additional problems or conditions that may impact performance are due to the surrounding geologic conditions. Creep settlement (due to warm permafrost temperature), thermal erosion (due to drainage conditions), thermal karsting (due to thawing buried glacier ice), and retrogressive thaw slumps have been observed on or threaten sections of the Alaska Hwy (M-Lepage et al. 2014). Poor drainage induced karsting and active layer detachment landslides have also threatened infrastructure at the Iqaluit Airport and along the Salluit Airport access road, respectively (Allard 2013, Boucher et al. 2012, Hawkins 2013, Trimble 2013). A collection of photographs illustrating a few of the problems discussed previously is presented below in Figure 1.

Figure 1. A collection of photographs showing the possible failure modes of a roadway on permafrost taken by the author in Summer 2014 on the Alaska and Dempster Hwys, Yukon Territory, Canada.

4.2 Additional Statistical Analysis in Permafrost Areas

A spatially distributed permafrost probability model has been created to determine the probability of permafrost in a region (Zhang et al. 2013, Zhang et al. 2014). The model was developed because “mapping the distribution of permafrost and its possible changes with climate are important for land use planning, infrastructure development, ecological and environmental assessments and modeling the climate system” (Zhang et al. 2014). The model consists of a transient thermal analysis in one dimension “considering the effects of climate, vegetation, snow and soil conditions” (Zhang et al., 2013). This model is known as the Northern Ecosystem Soil Temperature (NEST) model and was used to determine the probability of permafrost in a region near Yellowknife, NWT with respect to climate change. The model was successfully validated using field data of active layer thickness (Zhang et al. 2014).

5 KNOWLEDGE GAPS AND RESEARCH PROJECT OBJECTIVE

As discussed above, methods for the quantification of geotechnical uncertainty have been created (Baecher and Christian 2003, Duncan 2000, Goble 1999; Kim and Salgado 2008, Lacasse and Nadim 1996, Whitman 1984) and some quantification of engineering calculations has been done for permafrost analyses (Banerjee and Datta, 1991). Additional work is needed to further quantify uncertainty in permafrost engineering calculations and apply these calculations to a risk analysis framework.

Where risk assessments have been completed in permafrost areas, a qualitative analysis was used and only generally included subsurface conditions (BGC Engineering, Inc. 2011). As noted by Allard et al. (2012), “further applied research should include developing a better understanding of permafrost-processes and climate system, and producing risk assessments based on climate conditions.”

The project goal is to create a quantitative risk analysis methodology and tool for analyzing embankment-supported linear infrastructure on permafrost utilizing site conditions (geotechnical properties and climate conditions), physical or empirical engineering calculations, and economic consequences on a landform basis. Since in the early stages of a route analysis, aerial photography, geotechnical investigations and surficial geology maps are often used to create and/or verify a landform map of the route, these maps may be available for most infrastructures. Additionally, by focusing on a single area, risk can be evaluated using landform or site-specific parameters (for example, permafrost temperature and material haul costs), and recalculated for additional landforms or sections. From the landform maps and the calculated landform risk, a risk plot can be generated along the length of the infrastructure and/or a distance based weighted average can be used to determine a risk value for the route.

In order to accomplish this project, the necessary research will be conducted in a manner similar to the risk analysis process presented by Public Safety Canada (2011). The project will begin by identifying the possible failure modes for the infrastructure in the form of a fault tree. A preliminary fault tree is presented below in Figure 2. Once identified, the failure modes need to be described by defining a calculation method for each failure mode. P and C will be evaluated for each failure mode, where P will be calculated from the aleatory and epistemic uncertainty of the calculation method, and C from the direct and indirect impact of the associated failure. The next step will be to create the risk analysis tool. The tool will be validated by conducting risk assessments on existing research sites where failure modes and hazards have already been identified, such as the Salluit Airport access road, Iqaluit Airport, and Dempster Hwy. The research will be guided by a group of stakeholders, the resulting tool's end users.

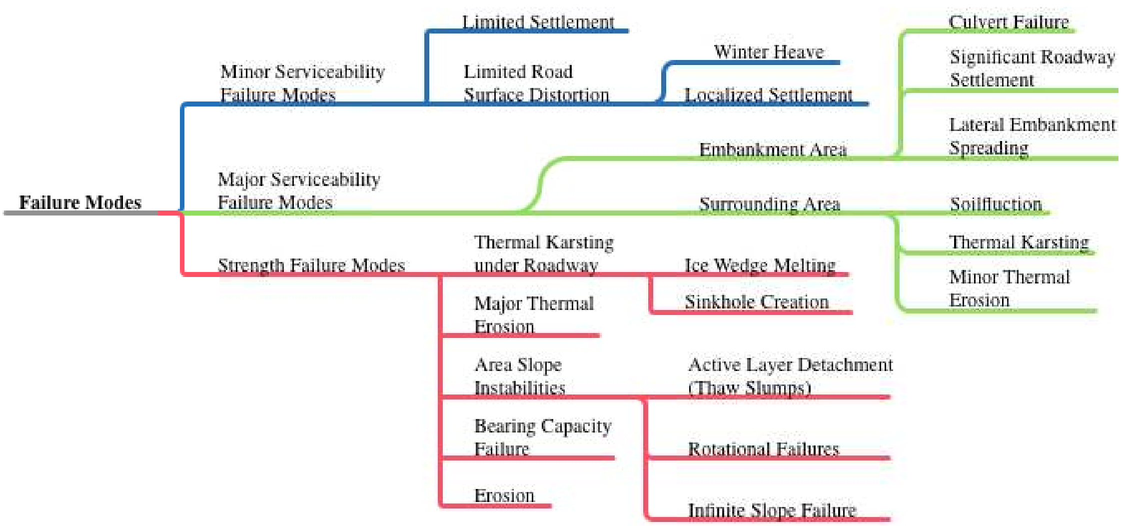

Figure 2. Preliminary fault tree showing possible failure modes of embankment supported infrastructure on permafrost.

6 CONCLUSIONS

There is a need for an unbiased quantitative risk analysis tool that can take into account aleatory and epistemic uncertainty in probability of failure analysis. Currently, no such tool exists. Given the scope and the variation of permafrost conditions, the analysis tool will be calculated on a landform basis, as subsurface conditions within a landform are, by definition, similar. The model will be validated in varied geotechnical conditions with sites exhibiting a range of failure modes and associated consequences to test the breadth of the tool.

The final tool will be an asset to practicing engineers analyzing new and existing infrastructure and will also provide a method for risk calculation, where climate conditions can be varied, the analysis repeated, and the results used for a predictive risk assessment.

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