PERMAFROST-SUPPORTED LINEAR INFRASTRUCTURE RISK ANALYSIS SOFTWARE: DESIGN & GOALS

Permafrost engineering research program
Programme de recherche en ingénierie du pergélisol

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Salluit, Nunavik, Québec

Project Objective

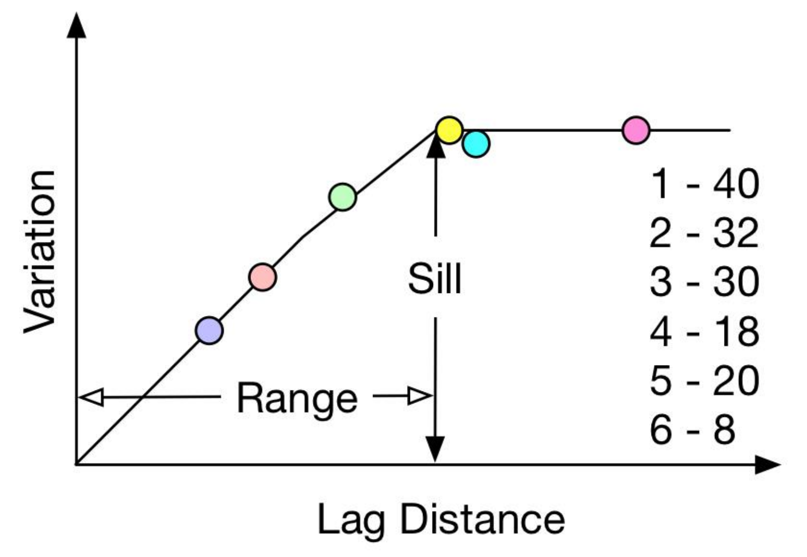
To **create** a quantitative risk analysis **methodology** and **tool** for embankment-supported infrastructure on permafrost **utilizing** site conditions, physical and/or empirical engineering calculations and consequences.

Definitions and Terminology

- **Danger** – an event or process causing damage
- **Hazard** – probability of a danger's occurrence within a time frame
- **Random Variable** – uncertain input parameter
- **Probability Density Function** – mathematical distribution of probable values
    - Defined by the average and standard deviation

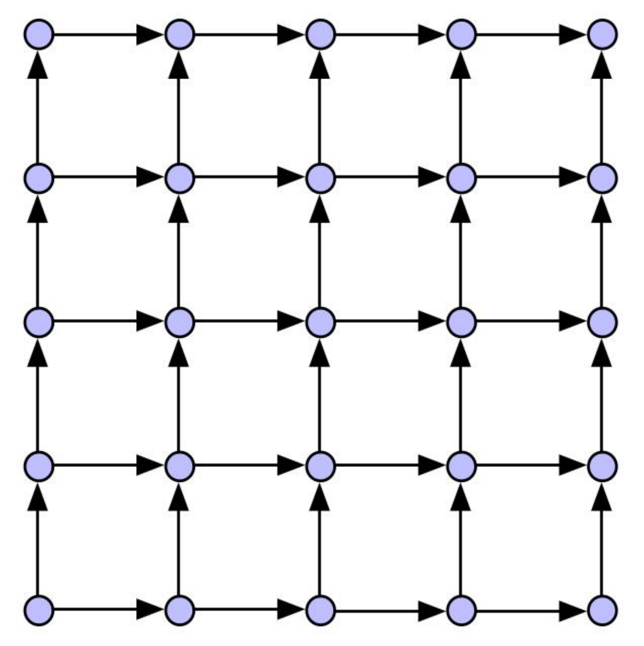
Statistical Variation in Geotechnics

SPATIAL VARIATION - VARIOGRAM



1 - 40
2 - 32
3 - 30
4 - 18
5 - 20
6 - 8

$$\hat{\gamma}(h) = \frac{1}{2n}\sum_{i}^{n}(Z_i - Z_{i+h})^2$$



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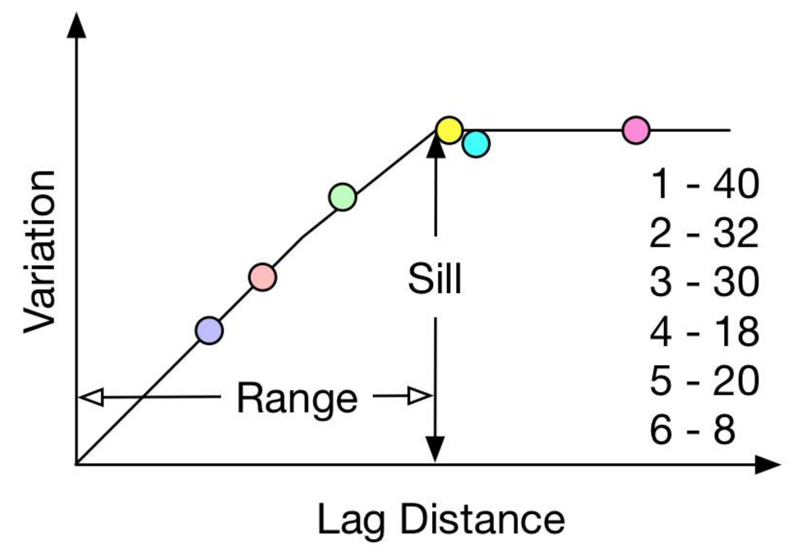

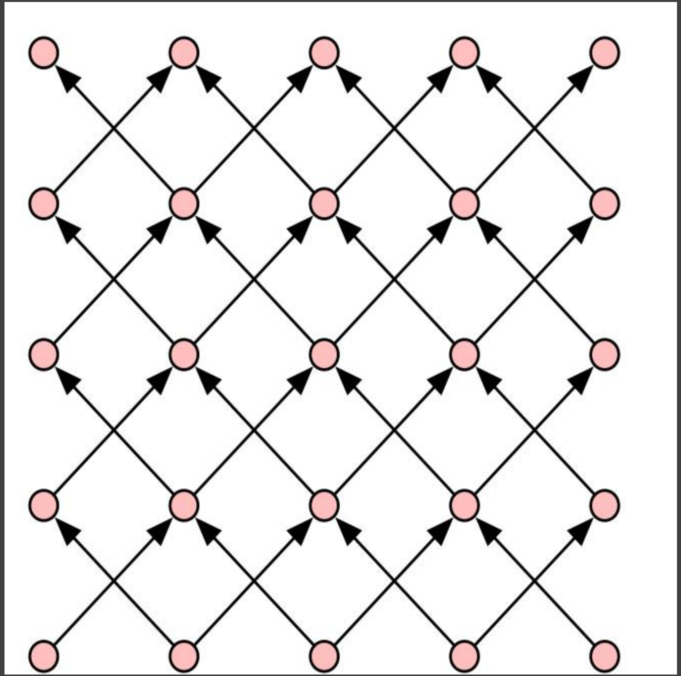

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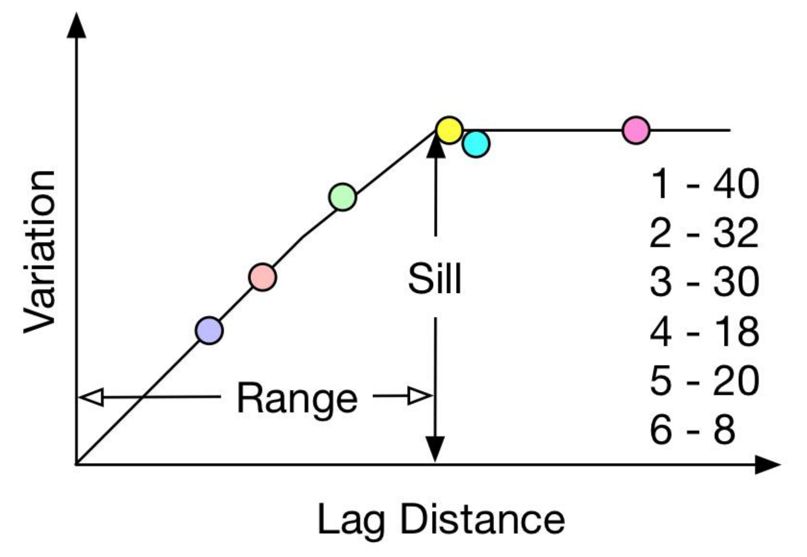

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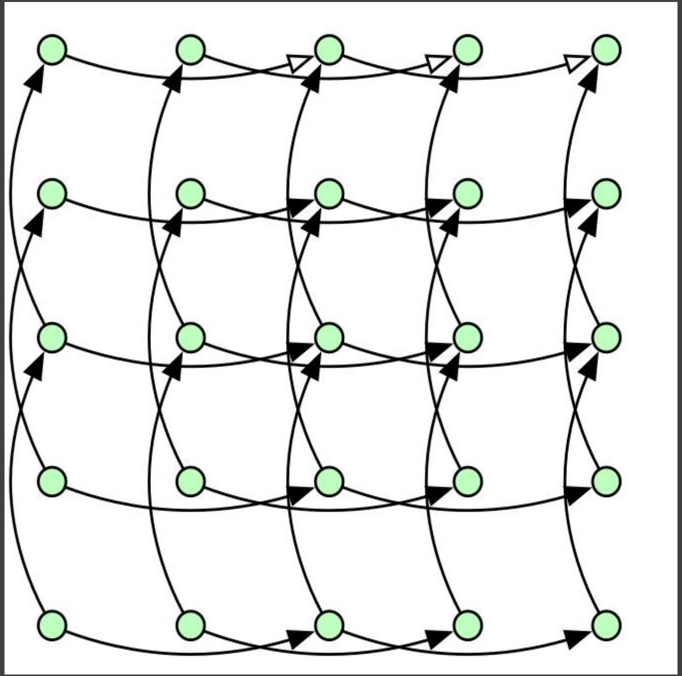

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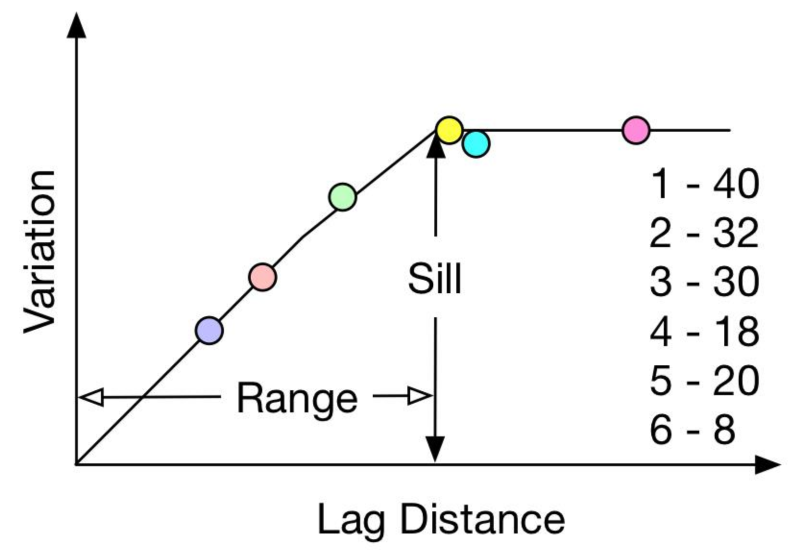

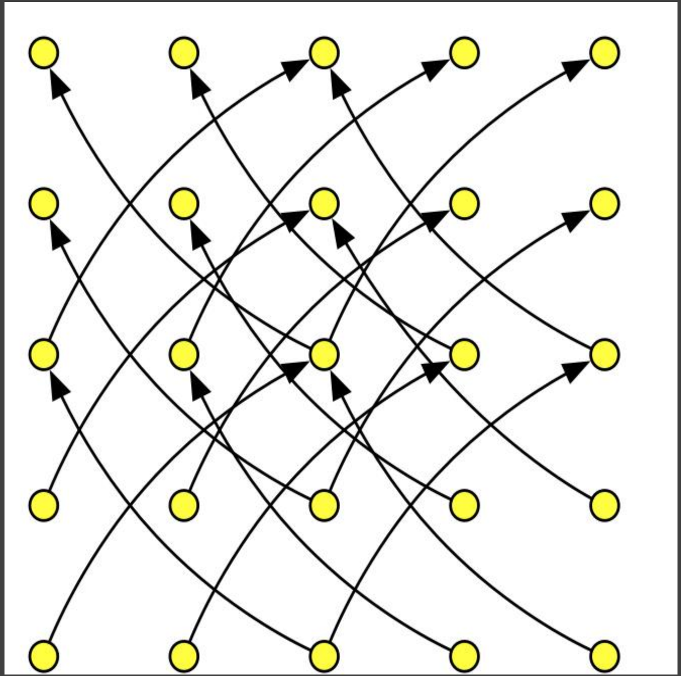

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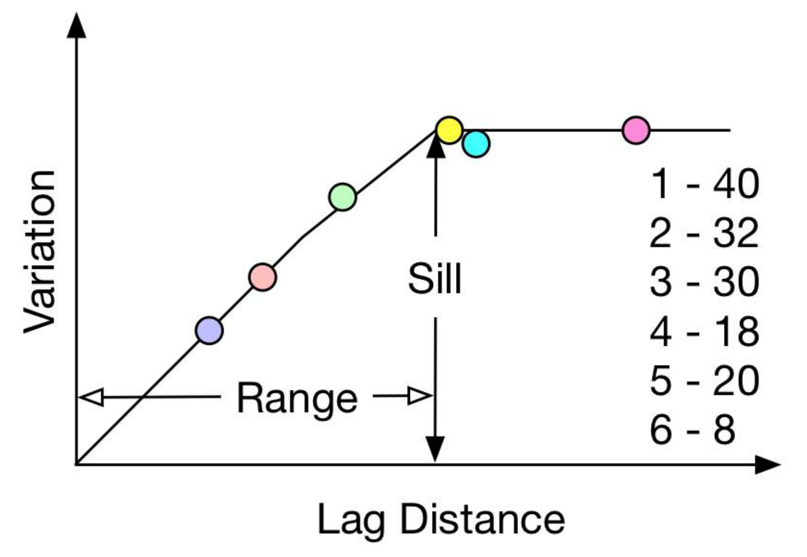

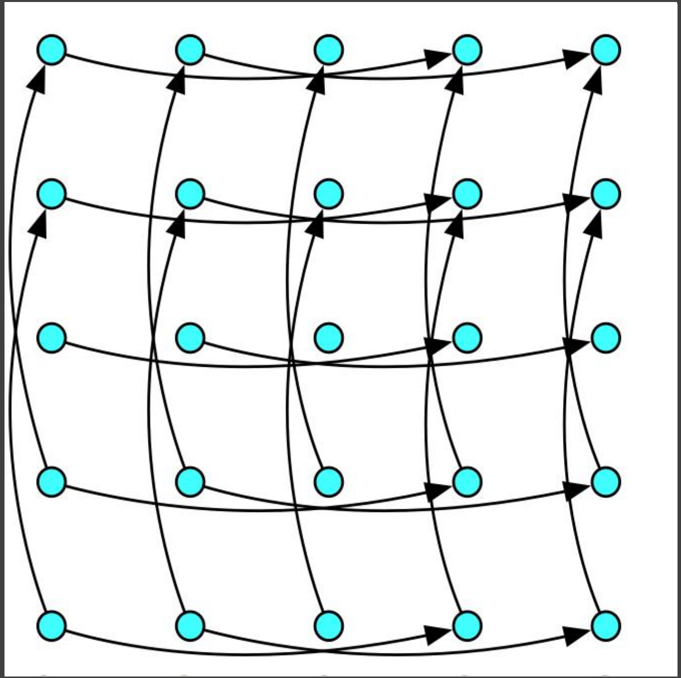

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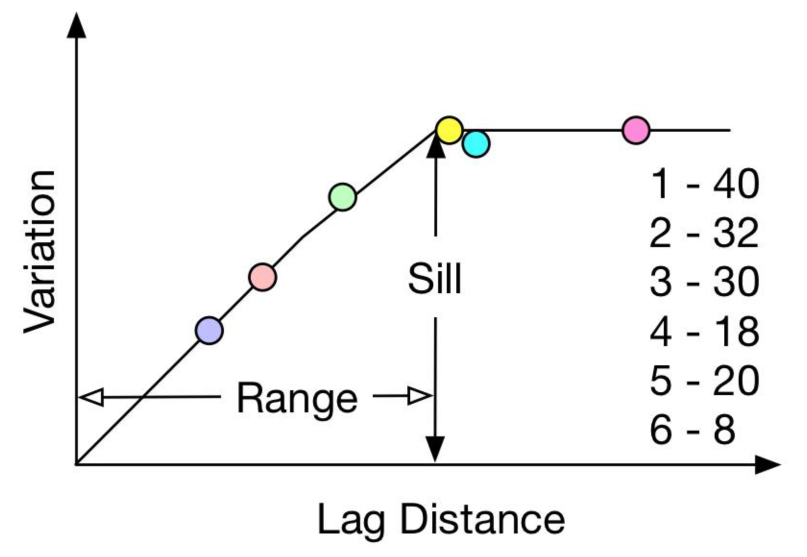
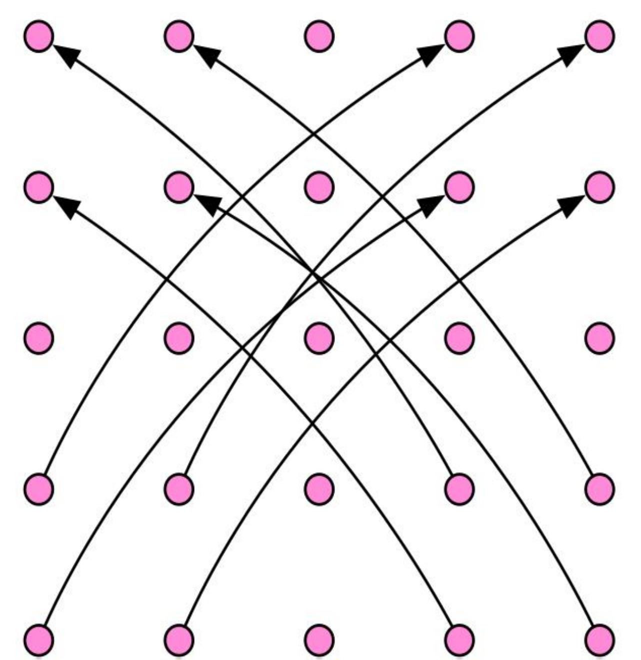




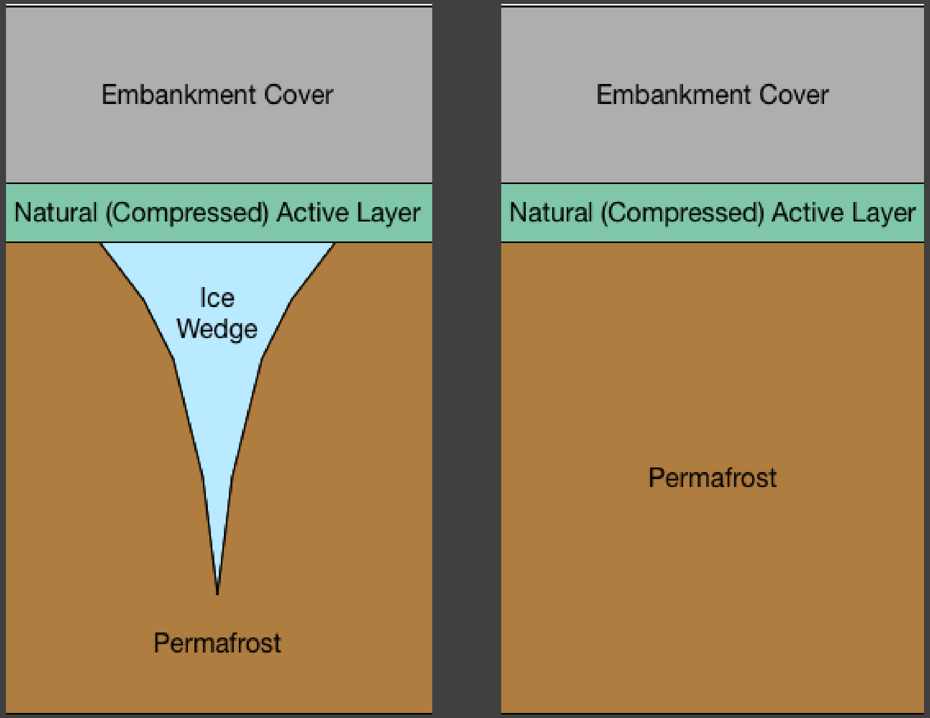
$$\hat{\gamma}(h) = \frac{1}{2n}\sum_{i}^{n}(Z_i - Z_{i+h})^2$$

PERMAFROST ACTIVE LAYER DEPTH VARIABILITY

- General Spatial Variability Analysis (Nelson et al 1999)
  - Coastal Plain – 100-300m lag
  - Foothills – 60% uncertainty in <100m lag
- CALM Data Sets (Nelson & Hinkel)
  - measurement spacing site dependent
  - spatial – range = 400 – 660m at 2 Alaska sites
  - time – strong inter-annual correlation; Markovian response
- Active Layer Moisture Spatial Variation (Yang et al 2011)
  - range = 50-85m from 10m spacing

Photo: permafrost.gi.alaska.edu/photos/image/84#image-load

SPATIAL VARIATION HAZARD CALCULATION



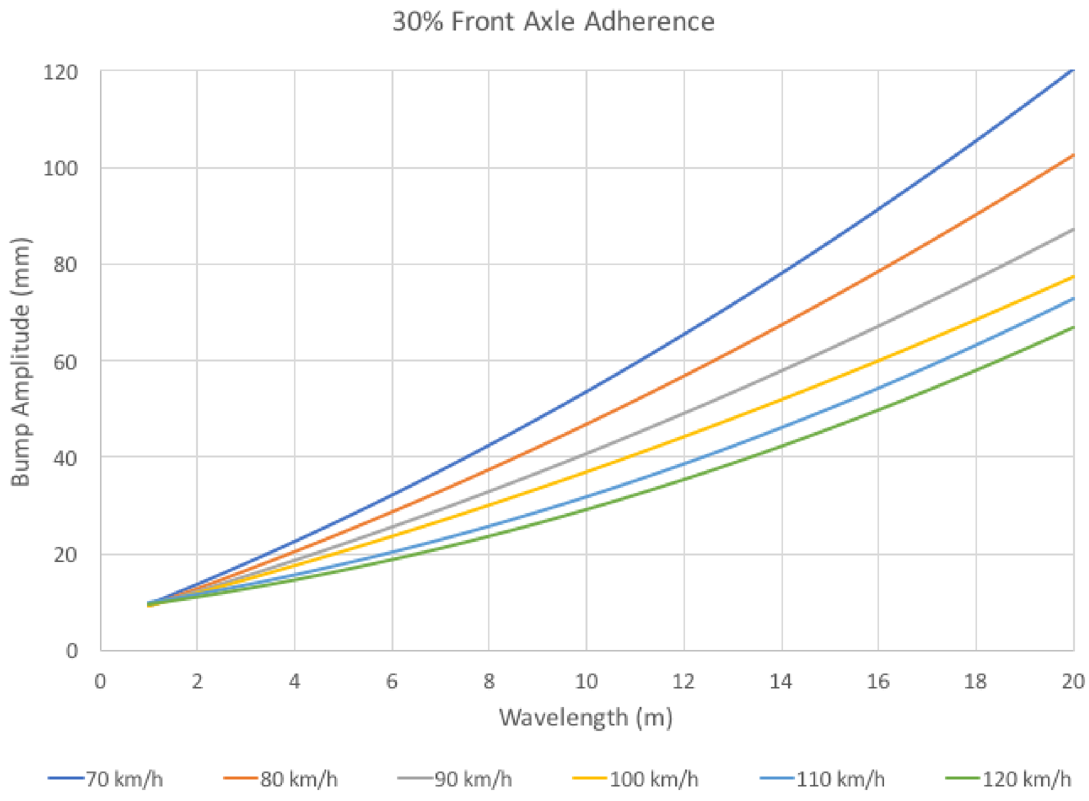
- Variation in Active Layer
  - Little published information
  - Site specific
  - Aggregate uncertainty of many factors

- Options for Program without Spatial Variation
  - Ice-wedge specific case
  - Assume uniform parameter variation

- Need serviceability or failure limits

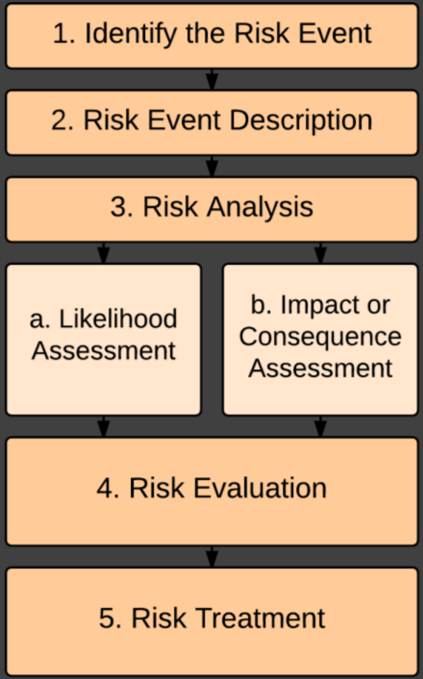
SETTLEMENT FAILURE LIMITS

- Roadways
  - Quarter car surface adherence criteria (Fradette 2005)
- Runways (Emery et al. 2015)
  - Boeing bump index
  - Isolated irregularity criteria
    - > 8 cm in 45 m
- Railways
  - Federal Railway Administration or Transport Canada criteria



Quantitative Risk Analysis Program

Risk Analysis Process



1. Identify the Risk Event

2. Risk Event Description

3. Risk Analysis

a. Likelihood Assessment

b. Impact or Consequence Assessment

4. Risk Evaluation

5. Risk Treatment

Similar to descriptions from
Public Safety Canada 2011

R = H x C x V

- R = Risk
- H = Hazard
- C = Consequence

Quantitative

- H from past experience or uncertainty calculation
- C calculated from expected damage

Hazard Identification & Description

Subsurface Massive Ice – Ice Wedge

Tension Cracking from Lateral Embankment Spreading

Subsurface Embankment Voids

Localized Thaw Settlement

Thermal Erosion Induced Karsting

Drainage Ditch Thermal Erosion

Hazard Calculation Methods

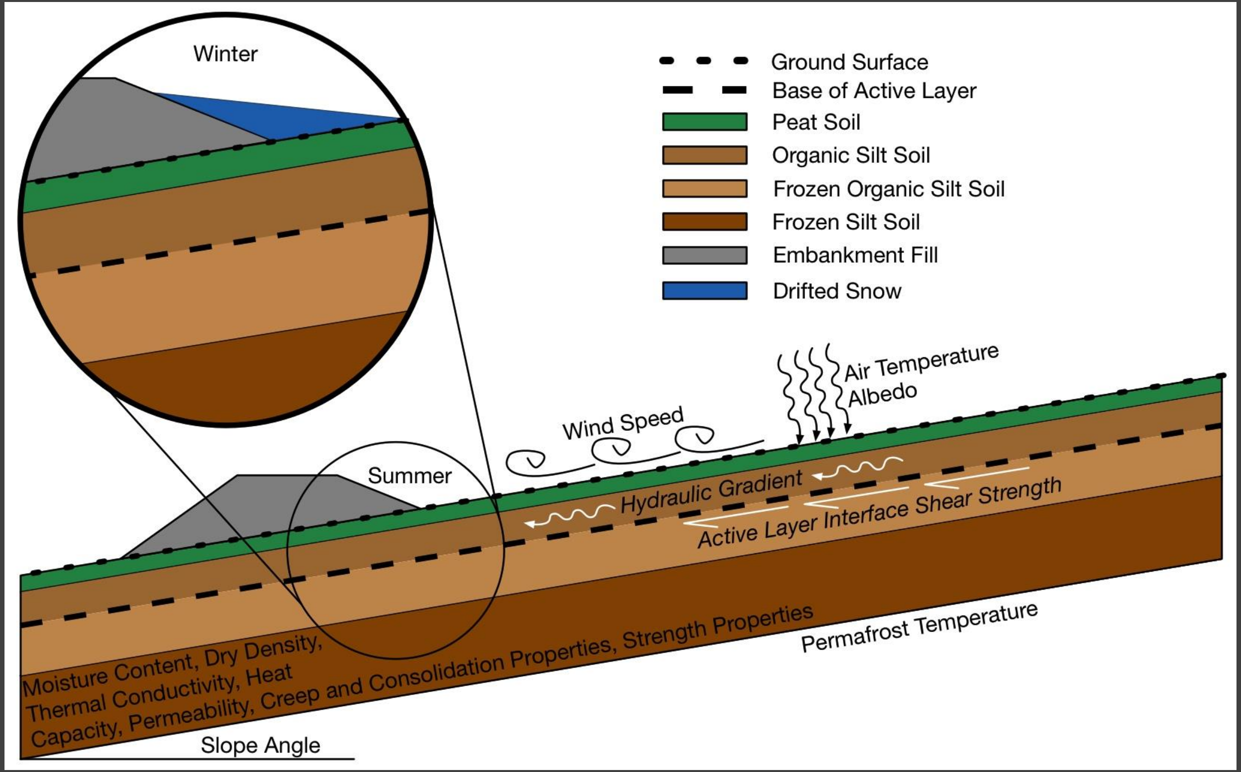
First Order Second Moment (FOSM)

- Taylor Series Expansion of the Limit State Equation
    - partial derivatives for each input variable
- Result Average
    - calculated from input parameter averages
- Result Variation
    - summation of evaluated partial derivatives
- Outlined in Duncan 2000

Monte Carlo Simulation

- Simultaneously varies all random variables
    - o PDFs characterize parameter variation
- 1 Calculation = 1 Simulation
- Repeated Simulations Result in Output Statistics
    - o average
    - o standard deviation
- Accuracy Dependent on Quantity of Simulations

Input Parameters



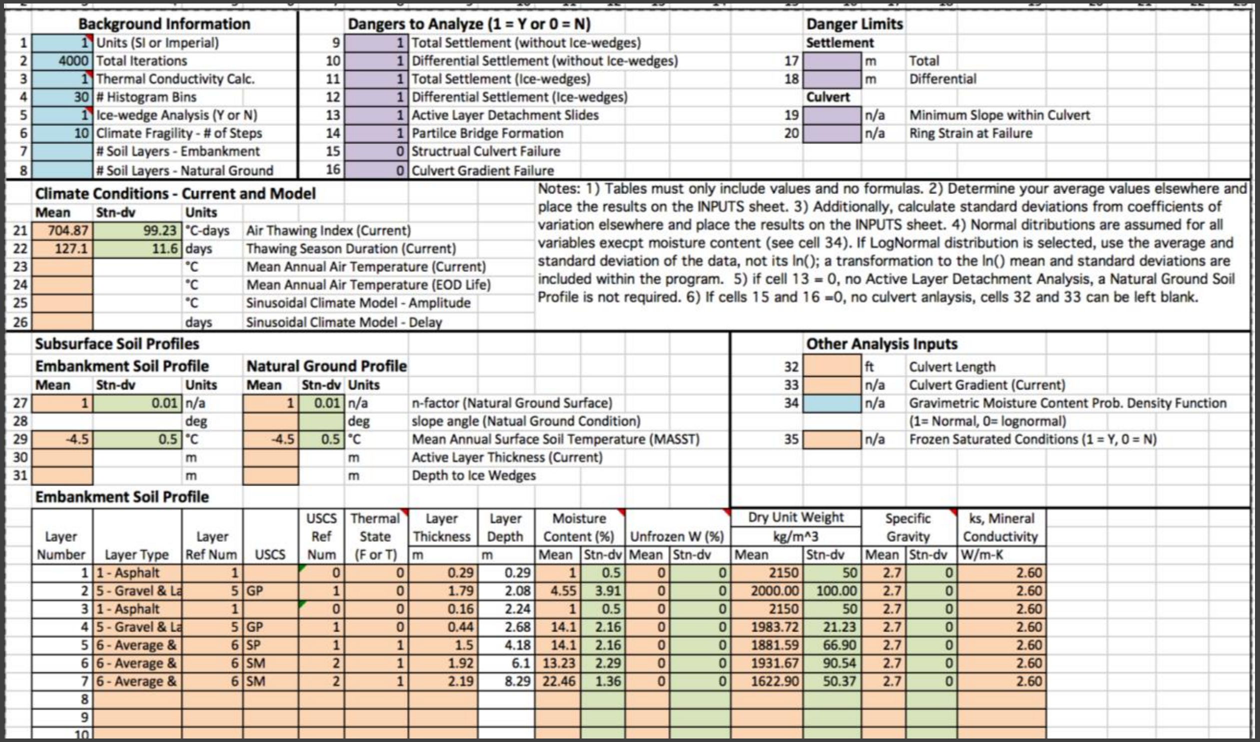
Excel Spreadsheet Tool

- Thaw Depth Calculation
  - Monte Carlo Analysis
  - Climate & Soil Property Variation
- PDFs (Normal & Lognormal)
- VBA Marco in Excel

Input Parameters

Climate - ATI, n, MASST, t

Soil (each layer) - w, w_u, γ_d, SpG, k_s



Background Information

1	1	Units (SI or Imperial)
2	4000	Total Iterations
3	1	Thermal Conductivity Calc.
4	30	# Histogram Bins
5	1	Ice-wedge Analysis (Y or N)
6	10	Climate Fragility - # of Steps
7		# Soil Layers - Embankment
8		# Soil Layers - Natural Ground

Dangers to Analyze (1 = Y or 0 = N)

9	1	Total Settlement (without Ice-wedges)
10	1	Differential Settlement (without Ice-wedges)
11	1	Total Settlement (Ice-wedges)
12	1	Differential Settlement (Ice-wedges)
13	1	Active Layer Detachment Slides
14	1	Partilce Bridge Formation
15	0	Structrual Culvert Failure
16	0	Culvert Gradient Failure

Danger Limits

Settlement

17		m	Total
18		m	Differential

Culvert

19		n/a	Minimum Slope within Culvert
20		n/a	Ring Strain at Failure

Climate Conditions - Current and Model

	Mean	Stn-dv	Units	
21	704.87	99.23	°C-days	Air Thawing Index (Current)
22	127.1	11.6	days	Thawing Season Duration (Current)
23			°C	Mean Annual Air Temperature (Current)
24			°C	Mean Annual Air Temperature (EOD Life)
25			°C	Sinusoidal Climate Model - Amplitude
26			days	Sinusoidal Climate Model - Delay

Notes: 1) Tables must only include values and no formulas. 2) Determine your average values elsewhere and place the results on the INPUTS sheet. 3) Additionally, calculate standard deviations from coefficients of variation elsewhere and place the results on the INPUTS sheet. 4) Normal ditributions are assumed for all variables execpt moisture content (see cell 34). If LogNormal distribution is selected, use the average and standard deviation of the data, not its ln(); a transformation to the ln() mean and standard deviations are included within the program. 5) if cell 13 = 0, no Active Layer Detachment Analysis, a Natural Ground Soil Profile is not required. 6) If cells 15 and 16 =0, no culvert anlaysis, cells 32 and 33 can be left blank.

Subsurface Soil Profiles

	Embankment Soil Profile			Natural Ground Profile			
	Mean	Stn-dv	Units	Mean	Stn-dv	Units	
27	1	0.01	n/a	1	0.01	n/a	n-factor (Natural Ground Surface)
28			deg			deg	slope angle (Natual Ground Condition)
29	-4.5	0.5	°C	-4.5	0.5	°C	Mean Annual Surface Soil Temperature (MASST)
30			m			m	Active Layer Thickness (Current)
31			m			m	Depth to Ice Wedges

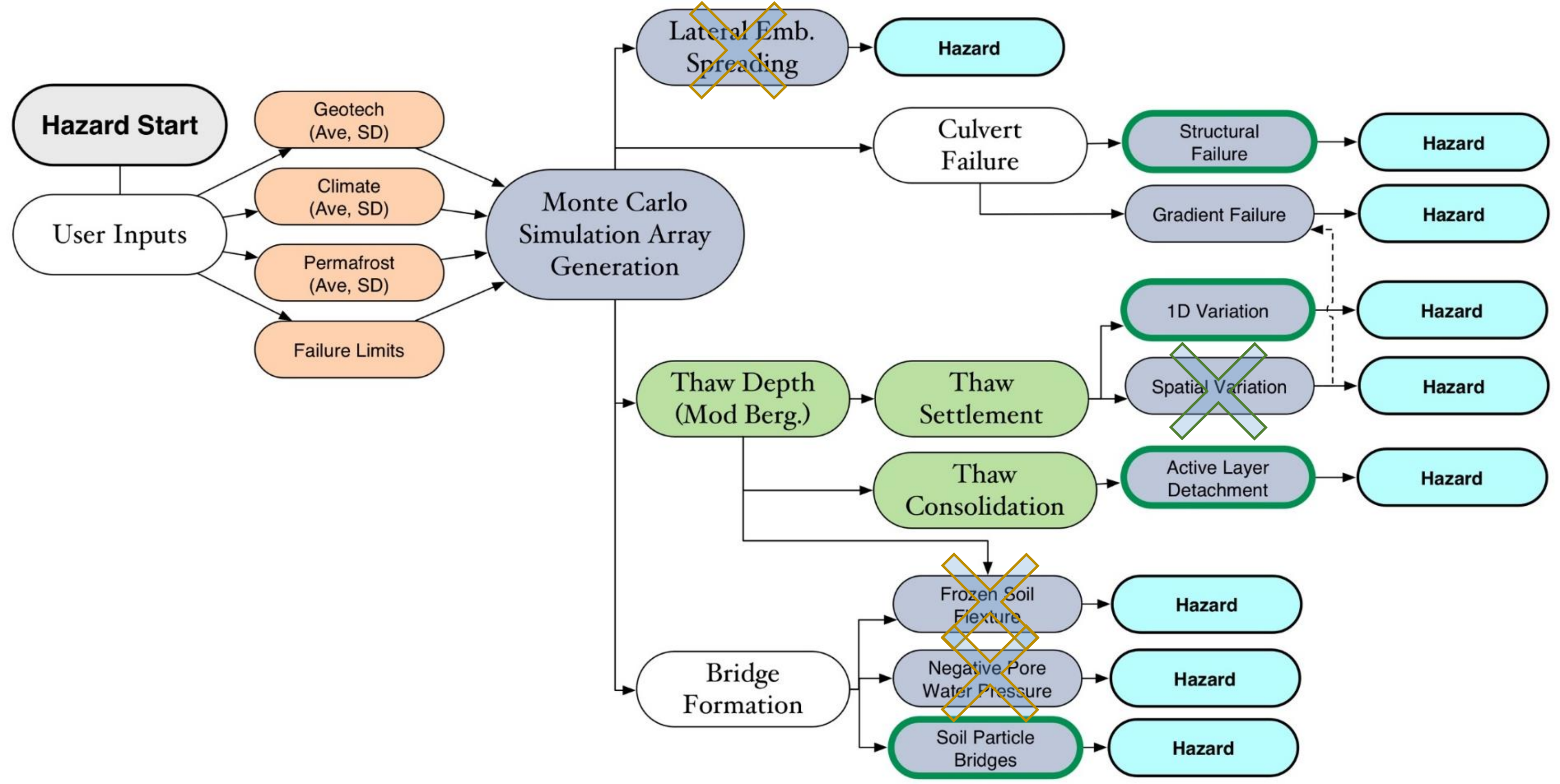
Other Analysis Inputs

32		ft	Culvert Length
33		n/a	Culvert Gradient (Current)
34		n/a	Gravimetric Moisture Content Prob. Density Function
			(1= Normal, 0= lognormal)
35		n/a	Frozen Saturated Conditions (1 = Y, 0 = N)

Embankment Soil Profile

Layer Number	Layer Type	Layer Ref Num	USCS	USCS Ref Num	Thermal State (F or T)	Layer Thickness	Layer Depth	Moisture Content (%)		Unfrozen W (%)		Dry Unit Weight kg/m^3		Specific Gravity		ks, Mineral Conductivity
						m	m	Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv	W/m-K
1	1 - Asphalt	1		0	0	0.29	0.29	1	0.5	0	0	2150	50	2.7	0	2.60
2	5 - Gravel & La	5	GP	1	0	1.79	2.08	4.55	3.91	0	0	2000.00	100.00	2.7	0	2.60
3	1 - Asphalt	1		0	0	0.16	2.24	1	0.5	0	0	2150	50	2.7	0	2.60
4	5 - Gravel & La	5	GP	1	0	0.44	2.68	14.1	2.16	0	0	1983.72	21.23	2.7	0	2.60
5	6 - Average &	6	SP	1	1	1.5	4.18	14.1	2.16	0	0	1881.59	66.90	2.7	0	2.60
6	6 - Average &	6	SM	2	1	1.92	6.1	13.23	2.29	0	0	1931.67	90.54	2.7	0	2.60
7	6 - Average &	6	SM	2	1	2.19	8.29	22.46	1.36	0	0	1622.90	50.37	2.7	0	2.60
8																
9																
10																

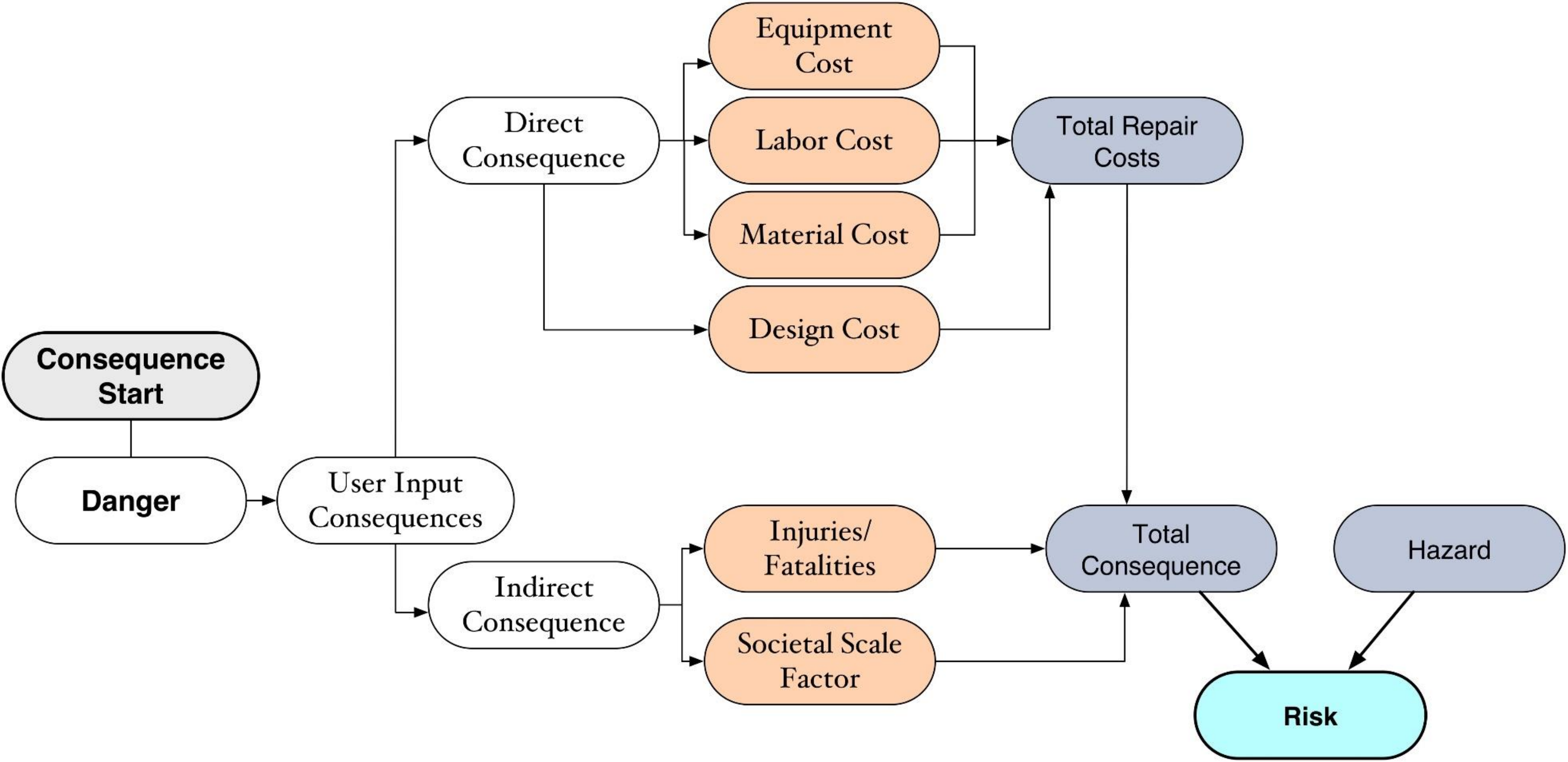
PROGRAM DESIGN - HAZARD



Monte Carlo Calculation Example

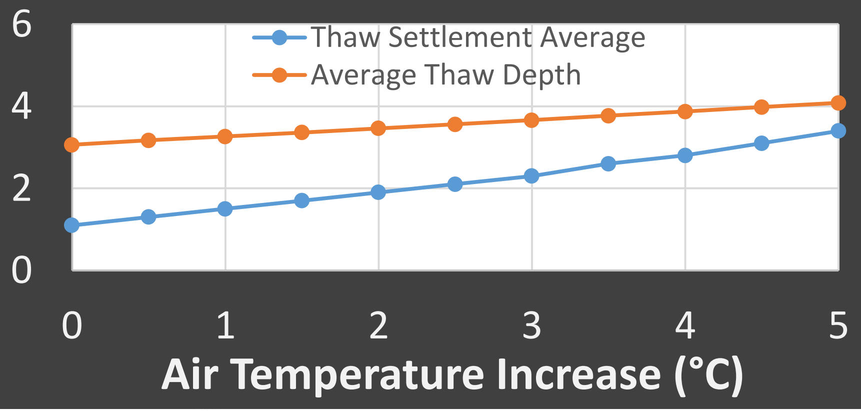
Sim #	Initial Inputs	Intermediate Calculations				Final Results		
1	$w_{(x,1)}$, $\gamma_{d(x,1)}$	Thermal Property Calculations	$K_{f,t(x,1)}$, $C_{f,t(x,1)}$, $L_{(x,1)}$, $\varepsilon_{thaw(x,1)}$	+	ATI_1, n_1, t_1, $MASST_1$	Thaw Depth & Settlement	ALD_1, TS_1	P_f[TS>Settlement Limit]
2	$w_{(x,2)}$, $\gamma_{d(x,2)}$		$K_{f,t(x,2)}$, $C_{f,t(x,2)}$, $L_{(x,2)}$, $\varepsilon_{thaw(x,2)}$		ATI_2, n_2, t_2, $MASST_2$		ALD_2, TS_2	
3…	$w_{(x,3)}$, $\gamma_{d(x,3)}$		$K_{f,t(x,3)}$, $C_{f,t(x,3)}$, $L_{(x,3)}$, $\varepsilon_{thaw(x,3)}$		ATI_3, n_3, t_3, $MASST_3$		ALD_3, TS_3	
n	$w_{(x,n)}$, $\gamma_{d(x,n)}$		$K_{f,t(x,n)}$, $C_{f,t(x,n)}$, $L_{(x,n),}$ $\varepsilon_{thaw(x,n)}$		ATI_n, n_n, t_n, $MASST_n$		ALD_n, TS_n	

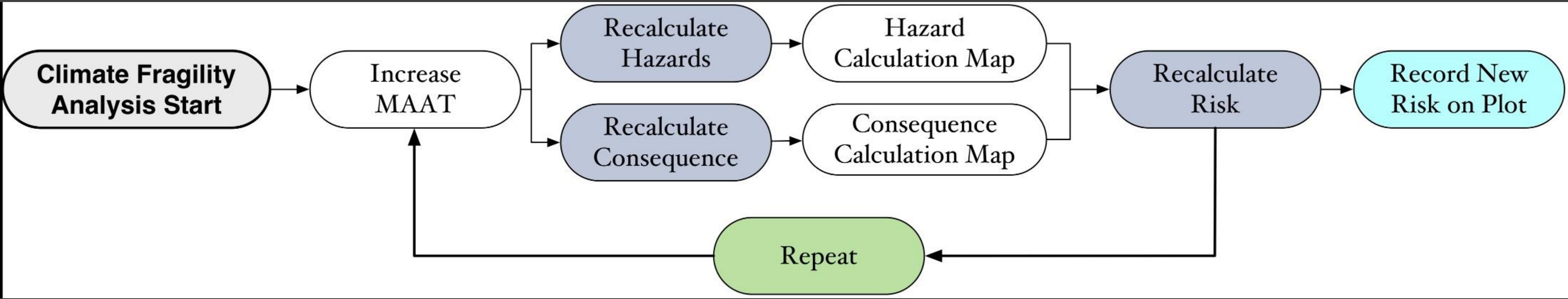
PROGRAMMING DESIGN - CONSEQUENCES



Climate Warming Fragility Assessment

- Sinusoidal Annual Temperature Model
- Increase Mean Annual Air Temperature (MAAT)
  - Thawing index
  - Thaw season duration





PRESENTATIONS AND PUBLICATIONS

- ICOP XI – Presentation (Award Winning)
- ArcticNet 2016 – 2 Presentations, Poster

- Permafrost and Periglacial Processes – Co-author on ICOP XI Plenary Paper

- Submitted Journal Article
  - Permafrost Geotechnical Property Variability

- Article under internal review
  - Void Bridging Mechanics within Embankments in Cold Regions

IN COLLABORATION WITH AND WITH SUPPORT FROM:

- Iqaluit Airport
  - Prof. Michel Allard
  - Valérie Mathon-Dufour
  - John Hawkins, eng.
- Bridging Mechanics
  - Christina Ponniah
  - Marielle Fauteux
  - Prof. Serge Leroueil
- Permafrost Property Statistics
  - Sharon Smith, PhD
- Others
  - Janice Festa, Duane Miller, Richard Mitchells

QUESTIONS

?

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Cold Climate Innovation
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