UNIVERSITÉ LAVAL

Quantitative Risk Analysis for Linear Infrastructure Supported by Permafrost: Methodology and Computer Program

Thèse

Heather Brooks

Doctorat en génie civil
Philosophiæ doctor (Ph. D.)

Québec, Canada

Appendix C Arquluk-RISK User Guide

Arquluk-RISK(SS) and (LI) have been developed for the analysis of hazard and risk to permafrost embankment infrastructure using a one dimensional conductive heat transfer thermal calculation (Modified Berggren equation), empirical thaw strain calculations (Luscher and Afifi 1973), limit state functions for the dangers analyzed (total and ice wedge differential thaw settlement, active layer detachment landslides, bridging voids from particle position, and culvert gradient and structural failure) and Monte Carlo Simulation. This appendix will provide guidance to users of Arquluk-RISK including outlining the input screens, the calculation process and the results reporting available in both versions. The equations used in the program and its engineering background are presented as the main text of this thesis.

C.1 Dangers Available for Calculation

The dangers included in the program versions are the same as are their calculation processes. The dangers available for analysis are the following:

- Total Thaw Settlement,
- Differential Thaw Settlement (only available with the ice wedge analysis),
- Culvert Structural Failure,
- Culvert Gradient Failure,
- Active Layer Detachment Landslides and
- Particle Bridge Formation,

and an optional ice wedge analysis of all of the above. The abbreviations for the dangers are presented in Table C.1 and are used in the output results. These dangers, their calculation, their input parameters, and parametric study results are presented and discussed in section 4.2.5. The soil profile for the ice wedge analysis is automatically created based on the depth to ice wedges input by the user (Figure C.1).

Table C.1. Danger Abbreviations

Danger	**Abbreviations**	
	Regular Analysis	**Ice Wedge Analysis**
Total Thaw Settlement	TS-Emb	TS-IWEmb
Differential Thaw Settlement	DS-Emb	
Culvert Structural Failure	CFS-Emb	CFS-IWEmb
Culvert Gradient Failure	CFG-Emb	CFG-IWEmb
Particle Bridge Formation	PBF	
Active Layer Detachment Landslides	ALDS-NG	ALDS-IWNG

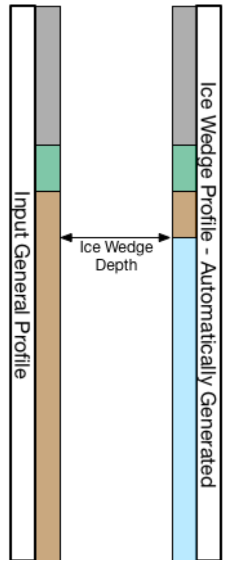

Figure C.1. The user's soil profile and the automatically generated ice wedge soil profile.

C.2 Characterize Climate and Site Random Variables

Before completing any analyses with Arquluk-RISK, it is necessary to characterize the random variables used in the analysis. Each variable requires an average and standard deviation. Further guidance on the characterization of input variables is discussed in section 4.6.2. Start by compiling the existing geotechnical and climate data and creating the site or section idealized soil profile. Note the program functions best the active layer is used as a division between soil layers.

The climate data average and standard deviation (air thawing index and thaw season duration) should be calculated for the current climate using the previous 30-years of data. If a warming climate fragility assessment is to be conducted, use the sinusoidal climate model discussed in Appendix A to determine the amplitude of the sinusoidal air temperature model. The user will also need the current and end-of-design-life mean annual air temperatures (MAAT).

The soil index property data should be determined for each soil layer by separating data by layer and random variable. These random variables can include moisture content, unfrozen moisture content, dry density, and specific gravity for most dangers, and coefficient of consolidation, and the effective cohesion and friction angle for the active layer detachment landslide (ALDS) danger.

The site variables required include n-factor, and permafrost temperature for most dangers and the slope angle is required for the ALDS danger.

C.3 Choose Arquluk-RISK Version

The two versions of the program focus on a single site location and a multiple section analysis along the length of the user's embankment infrastructure. The major differences and features of the two programs are presented in Table C.2.

Table C.2. Differences between (SS) and (LI) Arquluk-RISK versions.

Arquluk-RISK (SS)	**Arquluk-RISK (LI)**
• Single site location • Hazard calculation only (current and future air temperatures) • Automatic histogram outputs (optional) • Fragility assessment hazard vs. mean annual air temperature chart • Text file output of Monte Carlo values and intermediate calculation values	• Multiple infrastructure sections (each on a new sheet) • Hazard and/or risk calculation (current and future air temperatures) • Direct cost data for each section • Indirect factors for the infrastructure under analysis • Reporting of hazard and/or risk by marker post graphically (current air temperatures) and tabularly (current and future air temperatures) • Tabular reporting highlights high, medium and low risk

Once a program version is selected, open the appropriate version of the program.

C.4 Arquluk-RISK(SS) Analysis Steps

To complete a hazard analysis using Arquluk-RISK(SS), follow the steps outlined below.

C.4.1 Input Data

The inputs necessary to within the program are outlined below. Note any available random variable within the program can be changed to a constant when the standard deviation is set to zero. The input tab is shown in Figure C.2 where the white, blue, purple, orange and green cells represent sheet calculations, program conditions, danger selection and limits, averages or constant variables, and variable standard deviations, respectively. The inputs are divided into boxes and each box is discussed individually and cell is discussed below.

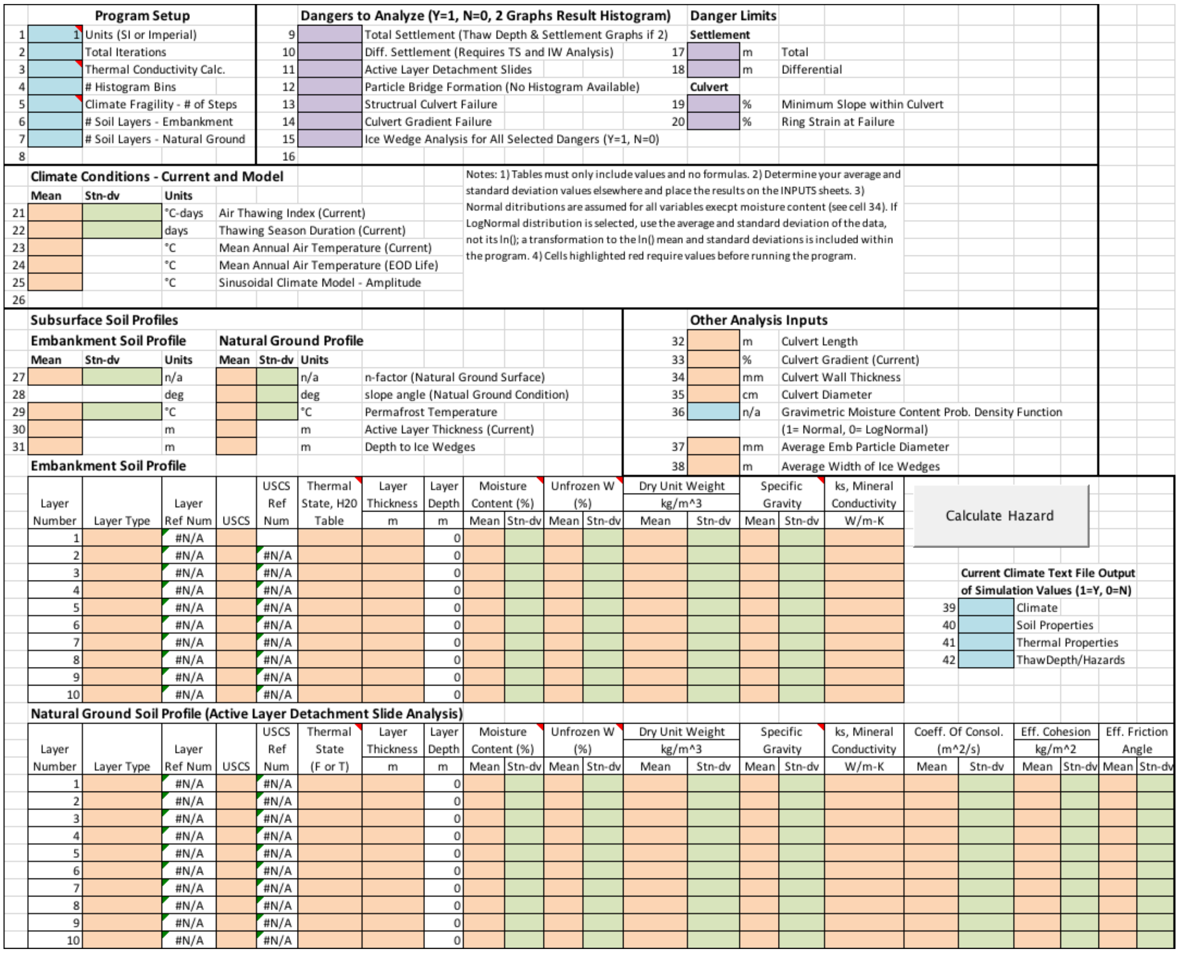

Figure C.2. Input tab of Arquluk-RISK(SS)

The program setup box outlines the program conditions (Figure C.3) to setup the analysis and allow the program to upload the soil profile values. The values for each cell are explained in Table C.3.

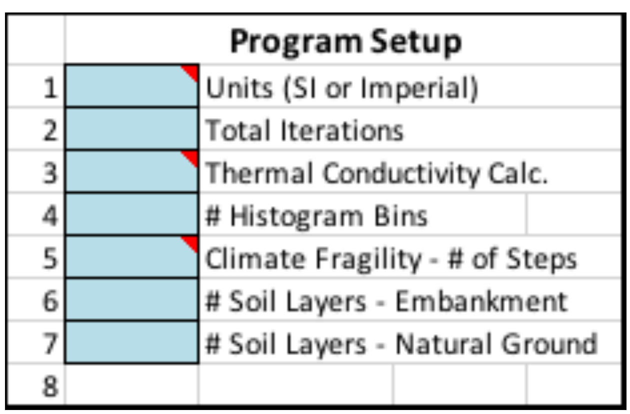

Figure C.3. (SS) Program Setup Box

Table C.3. (SS) Program Setup Variable Values

Variable	Values
Units	0 = Imperial Units 1 = SI Units
Total Iterations	Number of Monte Carlo simulations (See section 4.3 or use 20,000 as default)
Thermal Conductivity Calculation	0 = Kersten (1949) 1 = Côté and Konrad (2005)
Histogram Bins	Number of bins within the histogram outputs
Climate Fragility - # of Steps	0 = No Climate Fragility Assessment Number of steps in the Fragility Assessment
#Soil Layers – Embankment	Number of soil layers in the Embankment soil profile (all dangers except ALDS)
#Soil Layers – Natural Ground	Number of soil layers in the Natural Ground soil profile (ALDS danger)

The dangers to analyze box defines the dangers analyzed by Arquluk-RISK(SS) and which are graphed using a histogram. Cells 9 to 14 select the dangers, while cell 15 determines if an ice wedge danger analysis is completed. In cells 9 to 14, a value of 1 will trigger the danger's hazard analysis while a value of 2 will complete the hazard analysis and graph a histogram of the output. A value of 1 in call 15 triggers the hazard analysis of all selected dangers using the ice wedge soil profile outlined in Figure C.1. Note the differential settlement danger requires both the total settlement danger and an ice wedge analysis be selected.

		Dangers to Analyze (Y=1, N=0, 2 Graphs Result Histogram)
9		Total Settlement (Thaw Depth & Settlement Graphs if 2)
10		Diff. Settlement (Requires TS and IW Analysis)
11		Active Layer Detachment Slides
12		Particle Bridge Formation (No Histogram Available)
13		Structrual Culvert Failure
14		Culvert Gradient Failure
15		Ice Wedge Analysis for All Selected Dangers (Y=1, N=0)
16		

Figure C.4. (SS) Dangers to Analyze Box

The danger limits box defines the danger limits of the selected dangers. Guidance for the danger limits is discussed in section 4.2.5.

	Danger Limits		
	Settlement		
17		m	Total
18		m	Differential
	Culvert		
19		%	Minimum Slope within Culvert
20		%	Ring Strain at Failure

Figure C.5. (SS) Danger Limits Box

The climate conditions box defines the climate conditions used in the one-dimensional thaw depth calculation (Figure C.6). Line 21 and 22 are the average and standard deviation of the air thawing index (ATI) and the thaw season duration (ts), respectively. Cells 23 and 24 are the current and end-of-design-life mean annual air temperatures for the site. The amplitude of the sinusoidal air temperature model is in cell 25. These are necessary to calculate the mean annual air temperature steps used in the climate fragility analysis.

	Climate Conditions - Current and Model			
	Mean	**Stn-dv**	**Units**	
21			°C-days	Air Thawing Index (Current)
22			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				

Figure C.6. (SS) Climate Conditions – Current and Model Box

The other analysis inputs box contains the constant variable inputs for other danger analyses (Figure C.7). Cell 32 is the culvert length used in culvert gradient and structural failure dangers. The current culvert gradient is the existing slope of the culvert under analysis and its value is input in cell 33. The culvert wall thickness and culvert diameter are used in the culvert structural failure danger are input in cells 34 and 35, respectively. Cell 36 gives the user the choice between using normal (1) and lognormal (0) probability density functions for moisture content. Cells 37 and 38 are inputs for the particle bridging danger, which are the average particle size and average ice wedge width, respectively.

	Other Analysis Inputs		
32		m	Culvert Length
33		%	Culvert Gradient (Current)
34		mm	Culvert Wall Thickness
35		cm	Culvert Diameter
36		n/a	Gravimetric Moisture Content Prob. Density Function
			(1= Normal, 0= LogNormal)
37		mm	Average Emb Particle Diameter
38		m	Average Width of Ice Wedges

Figure C.7. (SS) Other Analysis Inputs Box

The last box, which includes analysis options, is shown below in Figure C.8. If a value of one is placed in cells 39 to 42, the program will automatically generate a text file presenting the simulation values for each simulation. If the ALDS danger is selected, then the soil properties and thermal properties will be reported in two text files the embankment profile and the natural ground profile. Table C.4 presents the variables output in each text file. The text file is set to save in the same location as the program's Excel file.

	Current Climate Text File Output of Simulation Values (1=Y, 0=N)	
39		Climate
40		Soil Properties
41		Thermal Properties
42		ThawDepth/Hazards

Figure C.8. (SS) Text File Output Box

Table C.4. (SS) Variables Output in Each Text File.

Text File Title	Variables
Climate	Air Thawing Index, Thaw Season Duration, n-factor, Permafrost Temperature
Soil Properties	Moisture Content, Unfrozen Moisture Content, Dry Density, Specific Gravity (Coefficient of Consolidation, Effective Cohesion and Friction Angle)
Thermal Properties	Frozen and thawed thermal conductivity and heat capacity, latent heat
Thaw Depth/ Hazard	Thaw Depth, Thaw Settlement, Limit State Function Results (All Dangers except Total and Differential Thaw Settlement)

The next section reviews the soil and site random variables. The input of site conditions is shown in Figure C.9. The embankment soil profile data is required unless only the ALDS danger is selected. If ALDS is selected with other dangers, both profiles are required. Row 27 includes the input average (orange) and standard deviation (green) for n-factor. The average and standard deviation of the infrastructure site's slope is input on row 28 for the natural ground profile. The temperature of the permafrost is input in row 29. Rows 30 and 31 are the thickness of the active layer and the depth to the ice wedges, respectively.

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

Figure C.9. (SS) Site Condition Variables Inputs

The final necessary inputs to the program are the random variables of the soil profile (Figure C.10). The layer type is the layer's material, which includes the following options: asphalt, ice, insulation, crushed gravel, gravel and large sand, average and fine sand, silts and clays, and peat. USCS is selected from a dropdown menu. The layer and USCS reference numbers are lookups for a value used in the program to signify the material type and soil classifications, respectively, and are only used in thermal conductivity and thaw strain equation selection. The thermal state of the soil defines the dry density calculation equation used to verify the soil's mass/volume conditions are not exceeding saturation; if the values are 1 or 0, the pore water is assumed to be frozen or unfrozen, respectively. The total and unfrozen moisture content are input in percentage by their average and standard deviation. The average and standard deviation of a layer's dry unit weight or density are input following the moisture content variables. The soil layer's specific gravity properties are next. The final column in the thermal conductivity of the soil particles (only used with the Côté and Konrad (2005) option to calculate thermal conductivity). The above described soil profile defines the conditions for the embankment profile.

If an ALDS analysis is selected, an additional soil profile is needed for the surrounding area, the natural ground profile. This profile requires all of the data necessary for the embankment profile plus some additional variables. The other soil properties (Figure C.10C) are used in the ALDS hazard analysis for the natural ground profile and includes the coefficient of consolidation and the effective cohesion and friction angle.

A)

Layer Number	Layer Type	Layer Ref Num	USCS	USCS Ref Num	Thermal State
1		#N/A			
2		#N/A		#N/A	
3		#N/A		#N/A	
4		#N/A		#N/A	

B)

Moisture Content (%)		Unfrozen W (%)		Dry Unit Weight kg/m^3		Specific Gravity		ks, Mineral Conductivity
Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv	W/m-K

C)

Coeff. Of Consol. (m^2/s)		Eff. Cohesion kg/m^2		Eff. Friction Angle	
Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv

Figure C.10. (SS) Soil Profile Inputs for the embankment (A and B) and extra variables for the natural ground profile (C).

C.4.2 Calculate Hazard

Once all the data has been input, click the calculate hazard button on the inputs sheet to run the program. The results will be output automatically depending on the users program choices. The tab "HazardcOutput" presents the tabular results for the current climate conditions while the tabs "FragA_Hazard" and "HazardFAOutput" present the results graphically and tabularly, respectively. If the user elects to include histograms, graphs appear on the "Histogram" tab.

C.5 Arquluk-RISK(LI) Analysis Steps

The analysis of a linear infrastructure using Arquluk-RISK(LI) must be completed in sections. This program version is organized such that setup macro is run to setup the reporting sheets, this automatically opens and labels the first section sheet, and running the hazard/risk analysis program will report the values for the section and open and label the next section for analysis. At any point these can be rerun so long as the section marker posts do not change. The following section outlines the process to run the program.

C.5.1 Initial Program Inputs

The initial input sheet (Figure C.11) defines the dangers analysis, the programing details, the hazard limits and the indirect consequence factors for each danger chosen. The cells' shading denotes what the cell's value is used for; blue, purple and yellow signify program variables, danger variables, and consequence variables, respectively.

	Program Setup			**Dangers to Analyze (Yes=1, No=0)**		
1	1	Units (SI=1, Imperial=0)	8	1	Total Thaw Settlement	
2	10000	Monte Carlo Simulations	9	1	Differential Thaw Settlement	
3	1	Thermal Conductivity Calc	10	1	Culvert Failure - Structural	
		(Côté & Konrad=1, Kersten=0)	11	1	Culvert Failure - Gradient	
4	0	Moisture Content PDF	12	1	Active Layer Detachment Landslides	
		(Normal=1, LogNormal=0)	13	0	Particle Bridge Formation	
5	10	Climate Fragility - # of Steps	14	1	Ice Wedge Analysis for All Selected Dangers	
		(if 0, no climate fragility analysis)		**Infrastructure Analysis Data**		
6	0	Hazard & Risk Reporting	15	0	km	Beginning Length
		(Both=0, Hazard=1, Risk=2)	16	10	km	Ending Length
7	0	Graph Hazardc & Riskc Profile	17	0.5	km	Graph Unit Length
		(Both=0, Hazard=1, Risk=2, No=3)				

	Indirect Consequence Factors				
	Ih		Is		Casualty (Ih) and Social (Is) Factors
18	2 - Minor Imp	2	2 - Minor Impa	2	Total Thaw Settlement
19	1 - No Impact	1	2 - Minor Impa	2	Differential Thaw Settlement
20	2 - Minor Imp	2	5 - Major Impa	5	Culvert Failure
21	2 - Minor Imp	2	2 - Minor Impa	2	Active Layer Detachment Landslides
22	5 - Major Imp	5	5 - Major Impa	5	Particle Bridge Formation

Notes: 1) Fill out this sheet (Inputs), then hit "1) Setup Excel File" button. 2) Complete analyses for all sections. 3) Hit "3) Graph Charts" if you want the graphical presentation of the current data analyses. DO NOT CHANGE THE NAMES OF SHEETS!!

	Hazard Analysis Limits						
	Settlement				1) Setup Excel File		
23	0.05	m	Total				
24	0.03	m	Differential				
	Culvert			30	2	km	Kilometer Post Ending 1st Section
25	2	%	Minimum Culvert Slope		**Qualitative Shading of Reporting Sheets**		
26	15	%	Culvert Collapse Ring Strain		**Hazard**		
				31	0.25	Max Percentage in Green (values in decimals)	
	Climate Data			32	0.75	Max Percentage in Yellow (values in decimals)	
27	-5	°C	Current MAAT		**Risk**		
28	0	°C	End of Design Life MAAT	33	$ 50,000	Max $ in Green	3) Graph Charts
29	10	°F	Climate Curve Amplitude	34	#########	Max $ in Yellow	

Figure C.11. Inputs sheet for Arquluk-RISK(LI).

The program setup box (Figure C.12) is similar to that of the Arquluk-RISK(SS) program. The inputs for each cell are further discussed in Table C.5.

	Program Setup	
1	1	Units (SI=1, Imperial=0)
2	10000	Monte Carlo Simulations
3	1	Thermal Conductivity Calc
		(Côté & Konrad=1, Kersten=0)
4	0	Moisture Content PDF
		(Normal=1, LogNormal=0)
5	10	Climate Fragility - # of Steps
		(if 0, no climate fragility analysis)
6	0	Hazard & Risk Reporting
		(Both=0, Hazard=1, Risk=2)
7	0	Graph Hazardc & Riskc Profile
		(Both=0, Hazard=1, Risk=2, No=3)

Figure C.12. (LI) Program Setup Box

Table C.5. (LI) Program Setup Variable Values

Variable	**Values**
Units	0 = Imperial Units 1 = SI Units
Monte Carlo Simulation	Number of Monte Carlo simulations (See Section 4.3 or use 20,000 as default)
Thermal Conductivity Calculation	0 = Kersten (1949) 1 = Côté and Konrad (2005)
Moisture Content Probability Density Function	0 = Lognormal Distribution 1 = Normal Distribution
Climate Fragility - # of Steps	0 = No Climate Fragility Assessment Number of steps in the Fragility Assessment
Hazard and Risk Reporting (Tabularly)	0 = Both Hazard and Risk 1 = Only Hazard 2 = Only Risk
Graph Hazardc and Riskc Profile (Current climate conditions)	0 = Both Hazard and Risk 1 = Only Hazard 2 = Only Risk 3 = No Graphs

The following inputs section includes the Dangers to Analyze and the Infrastructure analysis data (Figure C.13). Cells 8 to 13 select the dangers, while cell 14 determines if an ice wedge danger analysis is completed. In cells 8 to 13, a value of 1 will trigger the danger's hazard analysis. A value of 1 in call 14 triggers the hazard analysis of all selected dangers using the ice wedge soil profile outlined in Figure C.1, above. Note the differential settlement danger requires both the total settlement danger and an ice wedge analysis be selected. The Infrastructure Analysis Data box defines the length of the infrastructure under analysis with its beginning and ending marker posts (cell 15 and 16, respectively) and spacing between reporting points (Graph Unit Length, call 17). These variables define the starting and ending points of the sections. The Graph Unit Length is the length between the reported sections. For example, if a the beginning and ending lengths are 10 and 20 km, 10 km of infrastructure will be analyzed. With a graph unit length of 0.5, the data will be reported at 10, 10.5, 11 km … etc. for a total of twenty points.

	Dangers to Analyze (Yes=1, No=0)		
8	1	Total Thaw Settlement	
9	1	Differential Thaw Settlement	
10	1	Culvert Failure - Structural	
11	1	Culvert Failure - Gradient	
12	1	Active Layer Detachment Landslides	
13	0	Particle Bridge Formation	
14	1	Ice Wedge Analysis for All Selected Dangers	
	Infrastructure Analysis Data		
15	0	km	Beginning Length
16	10	km	Ending Length
17	0.5	km	Graph Unit Length

Figure C.13. (LI) Dangers to Analyze and Infrastructure Analysis Data

The Indirect Consequences box (Figure C.14) defines the casualty and social impact factors for each of the dangers. The values are chosen in the yellow cells for each danger from a dropdown menu or are input at the discretion of the user into the white cells adjacent. These factors are discussed in greater detail in section 4.4.2.

	Indirect Consequence Factors				
	Ih		Is		Casualty (Ih) and Social (Is) Factors
18	2 - Minor Imp	2	2 - Minor Impa	2	Total Thaw Settlement
19	1 - No Impact	1	2 - Minor Impa	2	Differential Thaw Settlement
20	2 - Minor Imp	2	5 - Major Impa	5	Culvert Failure
21	2 - Minor Imp	2	2 - Minor Impa	2	Active Layer Detachment Landslides
22	5 - Major Imp	5	5 - Major Impa	5	Particle Bridge Formation

Figure C.14. (LI) Indirect Consequences Box

The Hazard Analysis Limits box (Figure C.15) defines the settlement and culvert hazard limits. Further discussion on the choice of these limits is available in section 4.2.5.

	Hazard Analysis Limits		
	Settlement		
23	0.05	m	Total
24	0.03	m	Differential
	Culvert		
25	2	%	Minimum Culvert Slope
26	15	%	Culvert Collapse Ring Strain
	Climate Data		
27	-5	°C	Current MAAT
28	0	°C	End of Design Life MAAT
29	10	°F	Climate Curve Amplitude

Figure C.15. (LI) Hazard Analysis Limits and Climate Data in the Fragility Assessment

The following inputs setup the initial section sheet and define the colors used in reporting the hazard and risk data (Figure C.16). Cell 30 is the ending marker post of the 1st analysis section. Continuing the example from above, if this value is 11 the initial section will be 1 km long extending from marker post 10 to 11. Cells 21 and 32 define the maximum hazard probabilities in the green (low) and yellow (medium) hazard cells, respectively. The same values in dollars are used for risk for cells 33 and 34. Any values greater than those in cells 32 and 34 are highlighted red.

30	2	km	Kilometer Post Ending 1st Section
	Qualitative Shading of Reporting Sheets		
	Hazard		
31	0.25	Max Percentage in Green (values in decimals)	
32	0.75	Max Percentage in Yellow (values in decimals)	
	Risk		
33	$ 50,000	Max $ in Green	
34	$500,000	Max $ in Yellow	

Figure C.16. (LI) Initial Section Sheet, and Shading for Hazard and Risk Reporting

C.5.2 Run Setup Excel Macro

Once all of the data is on the input sheet, click on the “1) Setup Excel File” button. This will open and create tabs depending on choices on the inputs sheets and the initial section sheet. These tabs include “Hazardc,” “Riskc,” HazardFA,” and “RiskFA” which present the current climate condition (c) and fragility assessment (FA) results for hazard and risk.

C.5.3 Input Section Conditions

The inputs for a section include the soil profile inputs and the variable inputs from these other boxes. Note the orange and green cells denote the average and standard deviation of the variable, respectively. The climate condition box (Figure C.17) includes the air thawing index and thaw season duration for the section.

Climate Conditions - Current and Model			
Mean	Stn-dv	Units	
		°F-days	Air Thawing Index (Current)
		days	Thawing Season Duration (Current)

Figure C.17. (LI) Climate Conditions Box

The section’s direct consequence inputs (Figure C.18) for each of the dangers; the culvert gradient and structural failure direct consequences have been combined, as the if either occurs, the entire culvert will require replacement. These costs should include the material (including shipping and trucking), labor, equipment and consulting fees to repair the infrastructure should the danger occur.

Section Direct Consequence	
	Total Thaw Settlement
	Differential Thaw Settlement
	Culvert Failure
	Active Layer Detachment Landslides
	Particle Bridge Formation

Figure C.18. (LI) Section Direct Consequence Data

The other analysis inputs box (Figure C.19) defines other parameters necessary for the program to function and to calculate the dangers. The number of soil layers in the embankment and natural ground profile are used to input data into the program. The section’s culvert length, current gradient, wall thickness and diameter are used in the analysis of the culvert dangers. The average embankment particle diameter and width of ice wedges are used in the calculation of the particle bridging hazard. Only the cells necessary for the selected dangers are required to be filled.

Other Analysis Inputs		
		# Soil Layers in Embankment Profile
		# Soil Layers in Natural Ground profile
	ft	Culvert Length
	%	Culvert Gradient (Current)
	in	Culvert Wall Thickness
	in	Culvert Diameter
	in	Average Emb Particle Diameter
	ft	Average Width of Ice Wedges

Figure C.19. (LI) Other Analysis Inputs

The Other Analysis Inputs 2 box (Figure C.20) is used to define the current section and the next section to conduct and report the hazard and risk analysis results. The upper two cells are the starting and ending marker posts for the section currently under analysis. The lowermost cell defines the ending point of the next section under analysis.

Other Analysis Inputs 2		
	km	Section Starting Post
	km	Section Ending Post
	km	End Point of Next Section

Figure C.20. (LI) Other Analysis Inputs 2 – Data for Next Section

The final inputs for the analysis of a section are the soil profile parameters. The next section reviews the soil and site random variables. The input of site conditions is shown in Figure C.21. The embankment soil profile data is required unless only the ALDS danger is selected. Note in this version of the program, all references and cells relating to the natural soil profile are deleted if an ALDS danger analysis has not been selected. If ALDS is selected with other dangers, both profiles are required. The uppermost row includes the input average (orange) and standard deviation (green) for n-factor. The average and standard deviation of the infrastructure site's slope is input on the row below for the natural ground profile. The temperature of the permafrost is input below the site slope for the two profiles. The two lowermost cells in each profile are the thickness of the active layer and the depth to the ice wedges, respectively.

Embankment Soil Profile			Natural Ground Profile			
Mean	Stn-dv	Units	Mean	Stn-dv	Units	
		n/a			n/a	n-factor (Natural Ground Surface)
		deg			deg	slope angle (Natual Ground Condition)
		°C			°C	Permafrost Temperature
		m			m	Active Layer Thickness (Current)
		m			m	Depth to Ice Wedges

Figure C.21. (LI) Site Condition Variables Inputs

The random variables of the soil profile (Figure C.22) are the final values necessary to run the program. The layer type is the layer's material, which includes the following options: asphalt, ice, insulation, crushed gravel, gravel and large sand, average and fine sand, silts and clays, and peat. USCS is selected from a dropdown menu of the common soil classifications[6]. The layer and USCS reference numbers are lookups for a value used in the program to signify the material type and soil classifications, respectively, and are only used in thermal conductivity and thaw strain equation selection. The thermal state of the soil defines the dry density calculation equation used to verify the soil's mass/volume conditions are not exceeding saturation; if the values are 1 or 0, the pore water is assumed to be frozen or unfrozen, respectively. The total and unfrozen moisture content are input in percentage by their average and standard deviation. The average and standard deviation of a layer's dry unit weight or density are input following the moisture content variables. The soil layer's specific gravity properties are next. The final column in the thermal conductivity of the soil particles (only used with the Côté and Konrad (2005) option to calculate thermal conductivity). The above described soil profile defines the conditions for the embankment profile.

If an ALDS analysis is selected, its analysis profile requires all of the data necessary for the embankment profile plus some additional variables. The other soil properties (Figure C.22C) are used in the ALDS hazard analysis for the natural ground profile and includes the coefficient of consolidation and the effective cohesion and friction angle.

[6] Peat is not included on this list. Please select organic silt.

A)

Layer Number	Layer Type	Layer Ref Num	USCS	USCS Ref Num	Thermal State
1		#N/A			
2		#N/A		#N/A	
3		#N/A		#N/A	
4		#N/A		#N/A	

B)

Moisture Content (%)		Unfrozen W (%)		Dry Unit Weight kg/m^3		Specific Gravity		ks, Mineral Conductivity
Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv	W/m-K

C)

Coeff. Of Consol. (m^2/s)		Eff. Cohesion kg/m^2		Eff. Friction Angle	
Mean	Stn-dv	Mean	Stn-dv	Mean	Stn-dv

Figure C.22. (LI) Soil Profile Inputs for the embankment (A and B) and extra variables for the natural ground profile (C).

C.5.4 Run Section Analysis and Repeat

Once all of the data necessary to complete the section's analysis has been input, click on the "Calculate Section Results" button on the section sheet. This will run the risk and hazard analysis program and report the requested results to the spreadsheets automatically filling the cells of the section. Running this program will also open the next section's input sheet if it doesn't already exist in the Excel file. Repeating the input and calculation of all of the sections along the infrastructure will complete its hazard and risk profile.

C.5.5 Interpreting and graphing the Reported Results

The reported results are automatically output in tabular form on the sheets "Hazardc," "Riskc," "HazardFA," and "RiskFA" depending on the user's choices. The initial two sheets present the current climate condition results and the later show the fragility assessment results. The current climate conditions hazard and risk results are presented with each column being a danger and each row a marker post along the infrastructure (Figure C.23). The fragility assessment results are presented by danger and mean annual air temperature for each row and by marker post for each column (Figure C.24). While Figure C.23 and Figure C.24 present the hazard results, the presentation of the risk results is similar. If the user desires to graph the current climate condition results, click the “3) Graph Charts” button.

MarkerPost	TS-Emb	TS-IWEmb	DS-Emb
0	51.7%	55.9%	4.9%
0.5	51.7%	55.9%	4.9%
1	51.7%	55.9%	4.9%
1.5	51.7%	55.9%	4.9%
2	51.7%	55.9%	4.9%
2.5	51.7%	55.9%	4.9%
3	51.7%	55.9%	4.9%

Figure C.23. (LI) Current Climate Condition Hazard Result Reporting

	MAAT	Marker Post	km					
Danger	°C	0	0.5	1	1.5	2	2.5	3
TS-Emb	-4.5	83.9%	83.9%	83.9%	83.9%	83.9%	83.9%	83.9%
TS-Emb	-4.0	85.4%	85.4%	85.4%	85.4%	85.4%	85.4%	85.4%
TS-Emb	-3.5	86.7%	86.7%	86.7%	86.7%	86.7%	86.7%	86.7%
TS-Emb	-3.0	87.8%	87.8%	87.8%	87.8%	87.8%	87.8%	87.8%
TS-IWEmb	-4.5	92.4%	92.4%	92.4%	92.4%	92.4%	92.4%	92.4%
TS-IWEmb	-4.0	93.0%	93.0%	93.0%	93.0%	93.0%	93.0%	93.0%
TS-IWEmb	-3.5	96.0%	96.0%	96.0%	96.0%	96.0%	96.0%	96.0%
TS-IWEmb	-3.0	92.9%	92.9%	92.9%	92.9%	92.9%	92.9%	92.9%
DS-Emb	-4.5	6.3%	6.3%	6.3%	6.3%	6.3%	6.3%	6.3%
DS-Emb	-4.0	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%
DS-Emb	-3.5	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%	4.4%
DS-Emb	-3.0	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%	4.2%

Figure C.24. (LI) Fragility Assessment Hazard