Probabilistic Slope Stability Analysis of an Earth-filled Embankment Dam – Case Study

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Outline

- Motivation
- Background – Summary of Analysis Techniques
- Case Study – Methodology
- Case Study – Analysis Results

Motivation

- Determine the feasibility of implementing probabilistic based design with data from existing projects
- Validate results from probabilistic based design with observed performance

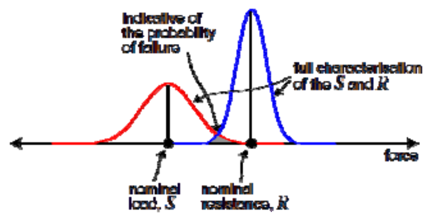
Background

Deterministic	Probabilistic
Traditional Standard Based	Non-traditional probability based
$FS = \frac{Resisting\ Forces}{Driving\ Forces}$	$\beta = -\Phi^{-1}[p_f]$

Background

Deterministic	Probabilistic
Traditional Standard Based	Non-traditional probability based

$$FS = \frac{Resisting\ Forces}{Driving\ Forces}$$

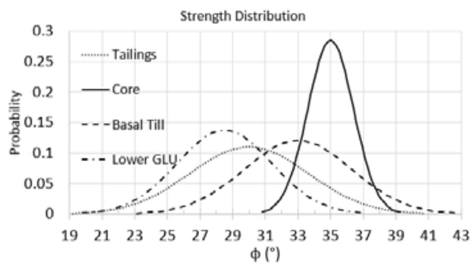


Background

Deterministic

Material Name	Unit Weight (lb/ft^3)	Cohesion (kPa)	Phi (deg)
Core	131	0	35.0
Tailings	115	0	30.0
Hard Glaciolacustrine	127	0	28.0
Basal Till	134	0	33.0

Probabilistic



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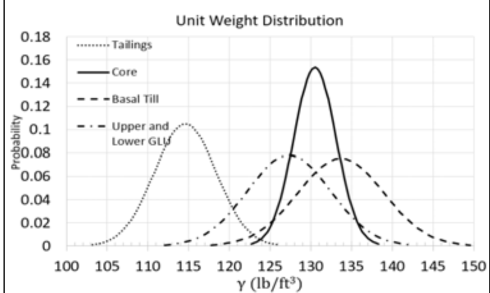


Background

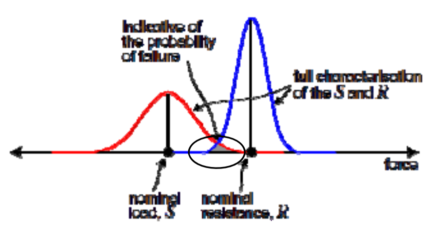
Deterministic

Traditional Standard Based

$$FS = \frac{Resisting\ Forces}{Driving\ Forces}$$

Probabilistic

Non-traditional probability based



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Deterministic	Probabilistic
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$FS = \frac{Resisting\ Forces}{Driving\ Forces}$	$\beta = -\Phi^{-1}[p_f]$

Background

Deterministic	Probabilistic
Traditional Standard Based	Non-traditional probability based
$FS = 1.2$	$\beta = 2.3$

Background

Deterministic	Probabilistic
Uncertainty handled discretely through the use of "most likely scenarios", "worst case scenarios", etc.	The combined effects of various scenarios and their probability of occurrence considered holistically.
Most Likely Case FoS = 1.5	P_f = 0.5%
Worst Case FoS = 1.2	

Background

Deterministic

Analytical

$$FOS = \frac{\tan\phi}{\tan\alpha}$$

Iteration
- Limit Equilibrium

Approximation
- Finite element analysis
- Tables and charts

Probabilistic

Analytical

$$P_f = \int_{g(\phi)\leq 1} f_\phi(\phi)\,d\phi$$

Simulation
- Monte Carlo simulation

Approximation
- Tables and charts
- Uncertainty propagation
- Other reliability methods

Background

Deterministic

Analytical

$$FOS = \frac{\tan \phi}{\tan \alpha}$$

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Simulation

- Monte Carlo simulation

Approximation

- Tables and charts
- Uncertainty propagation
- Other reliability methods

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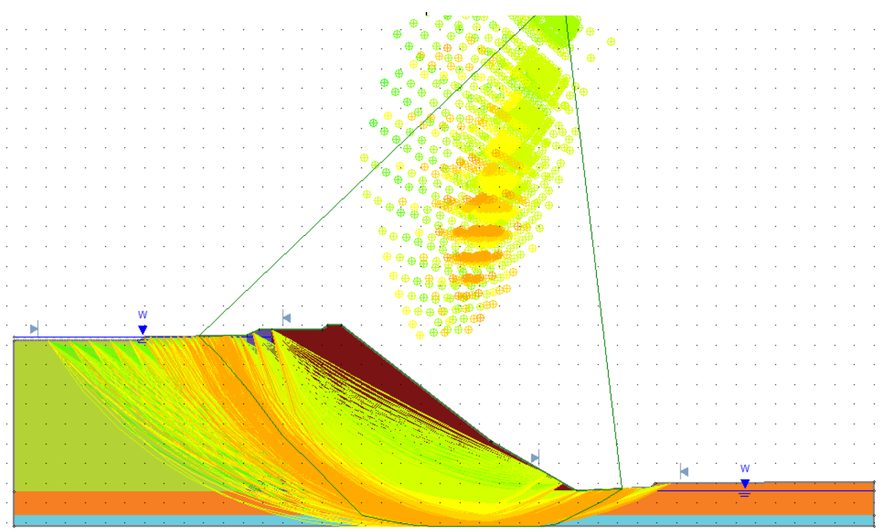
Background



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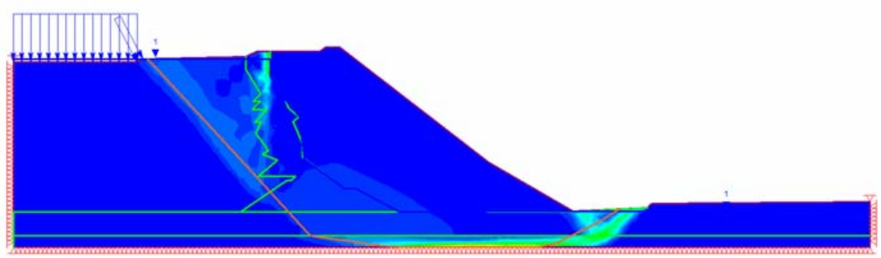
Background



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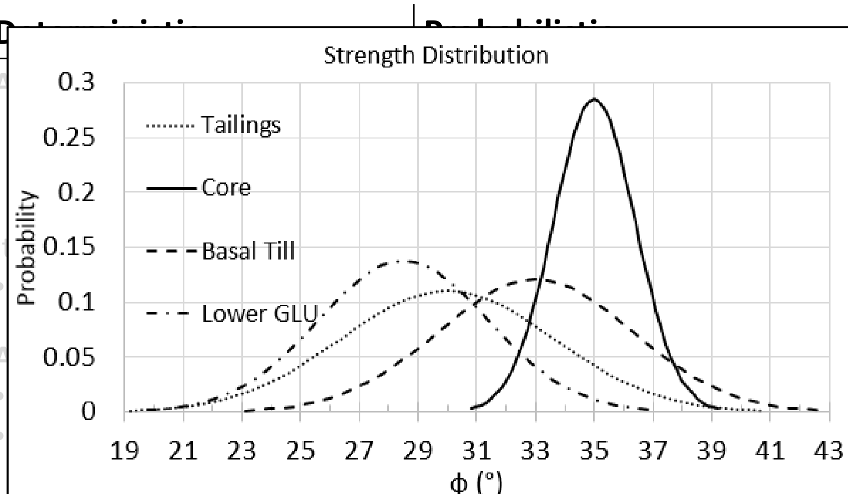

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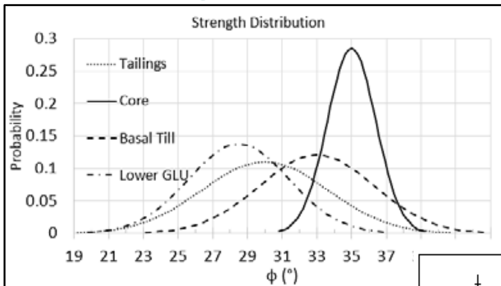

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alytical

$$P_f = \int_{g(\phi)\leq 1} f_\phi(\phi)d\phi$$

- Limit Equilibrium

Approximation

- Finite element analysis
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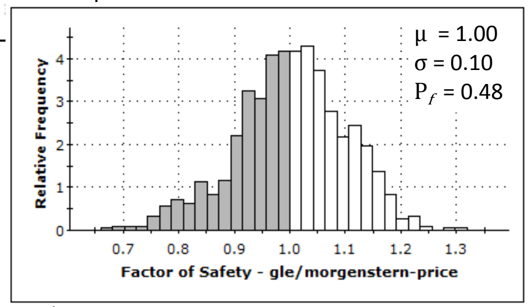
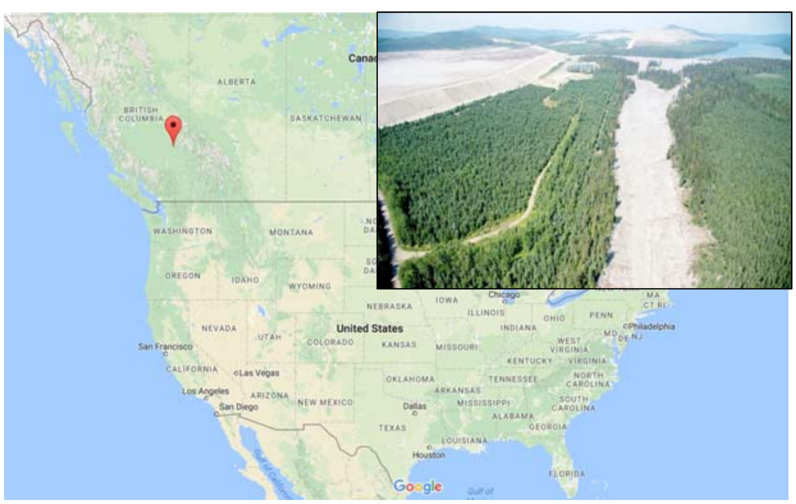
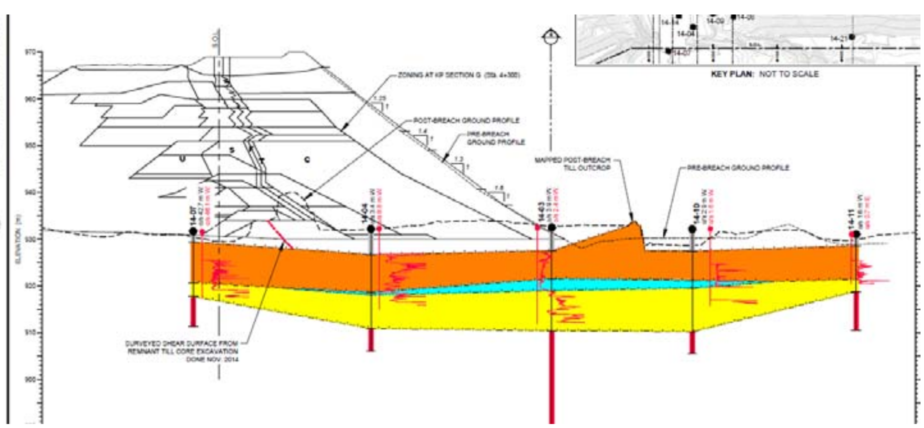


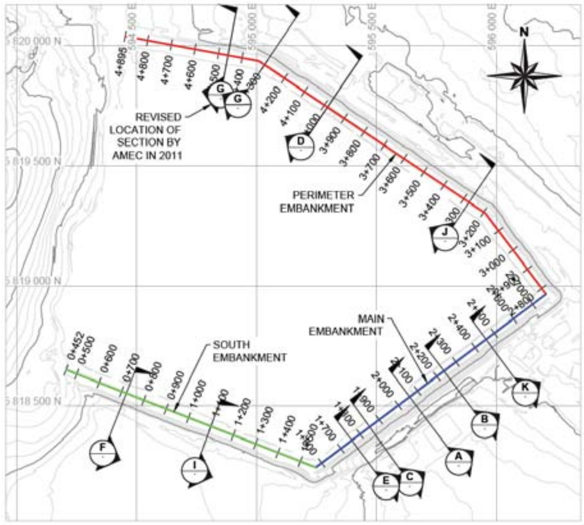
Case Study



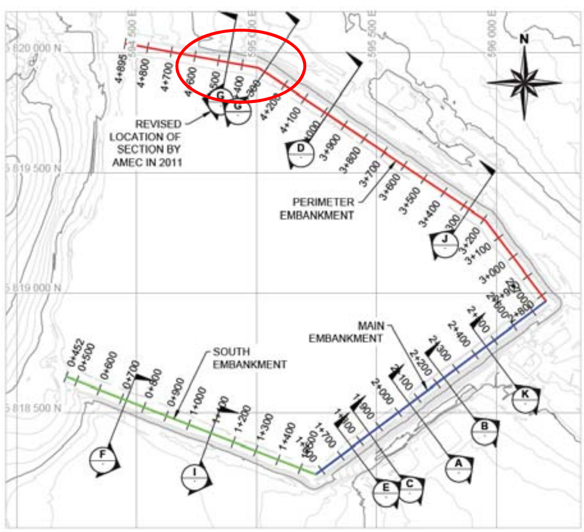
Methodology



Methodology



Methodology



Methodology

Analytical Model: Morgenstern-Price 2D Limit Equilibrium

Reliability Analysis Method: Monte Carlo Simulation

Defining the Failure: Factor of Safety <1

Defining Material Properties: Literature review (Phoon & Kulhawy 1999), tailings data from similar mines, calculated some based on lab test data.

Analysis Tool: Slide by Rocscience

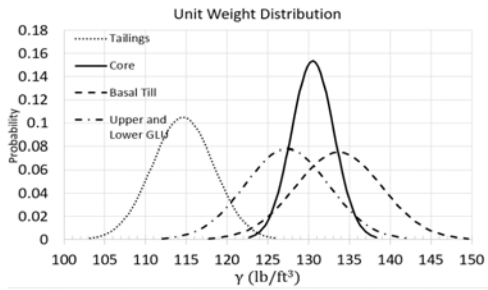
Methodology

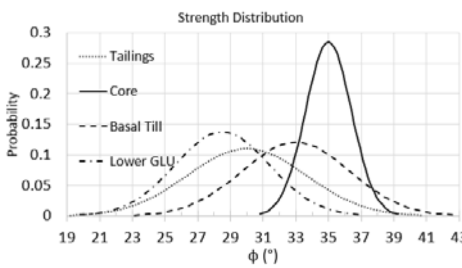
Defining Material Properties:

Material	Unit Weight			Strength				
	Mean (lb/ft³)	COV (%)	Standard Deviation	Strength Model	Strength	COV (%)	Standard Deviation	Cohesion (kPa)
Tailings	115	5.0%	5.7	Mohr-Coulomb	30°	12%	3.6°	0
Core	131	3.0%	3.9	Mohr-Coulomb	35°	4%	1.4°	0
Rockfill	140	-	-	Shear/Normal F.	Leps Function	-	-	-
Upper GLU	127	4.0%	5.1	Stress Ratio	0.24	15%	0.04	0
Lower GLU	127	4.0%	5.1	Mohr-Coulomb	28.5°	9%	2.6°	0
Basal Till	134	4.0%	5.3	Mohr-Coulomb	33°	10%	3.3°	0

Methodology

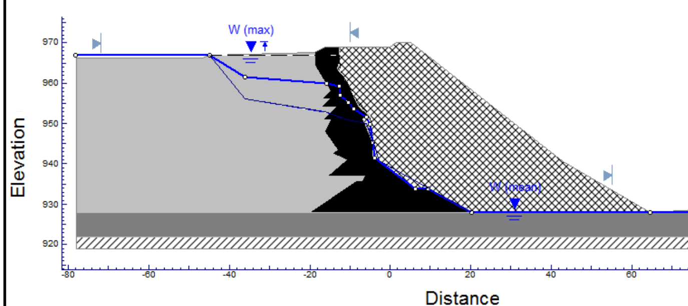
Defining Material Properties:





Methodology

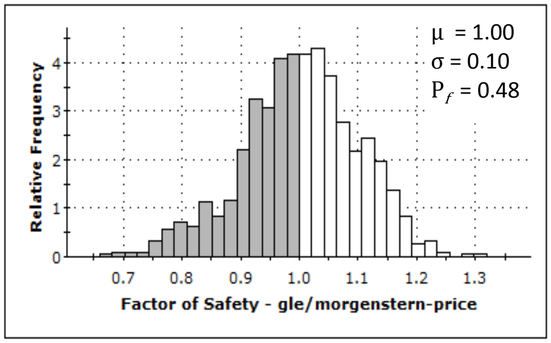
Model Calibration:



Material Name	Color	Water Surface
Core		Water Surface
Rock		None
Tailings		Water Surface
Upper Till		Water Surface
Upper Glaciolacustrine		Water Surface

Methodology

Model Calibration:



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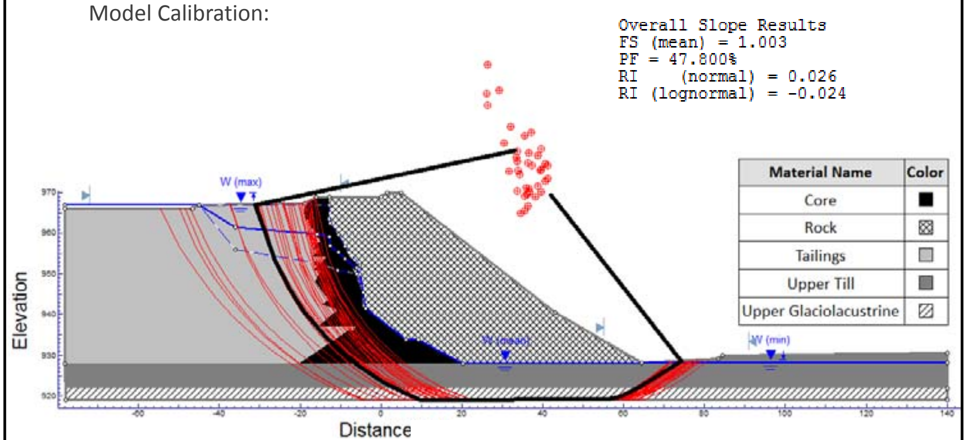
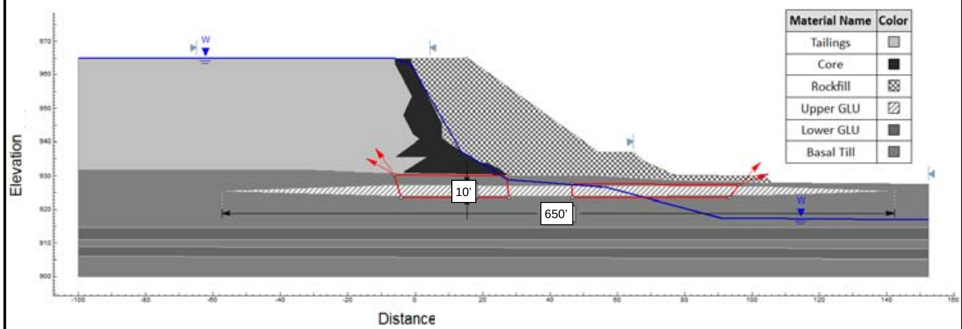


Methodology

Defining Geological Model:



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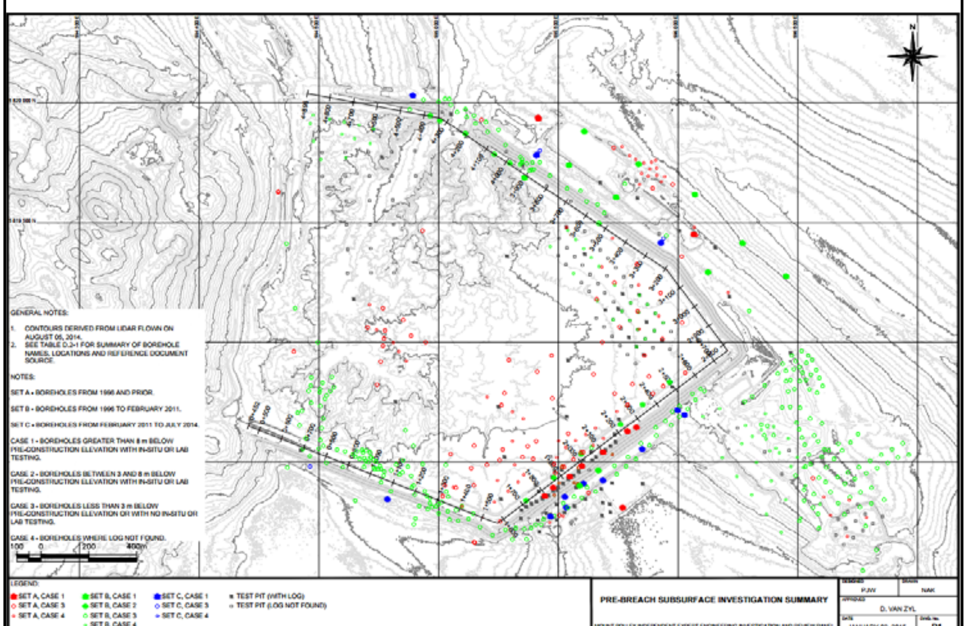

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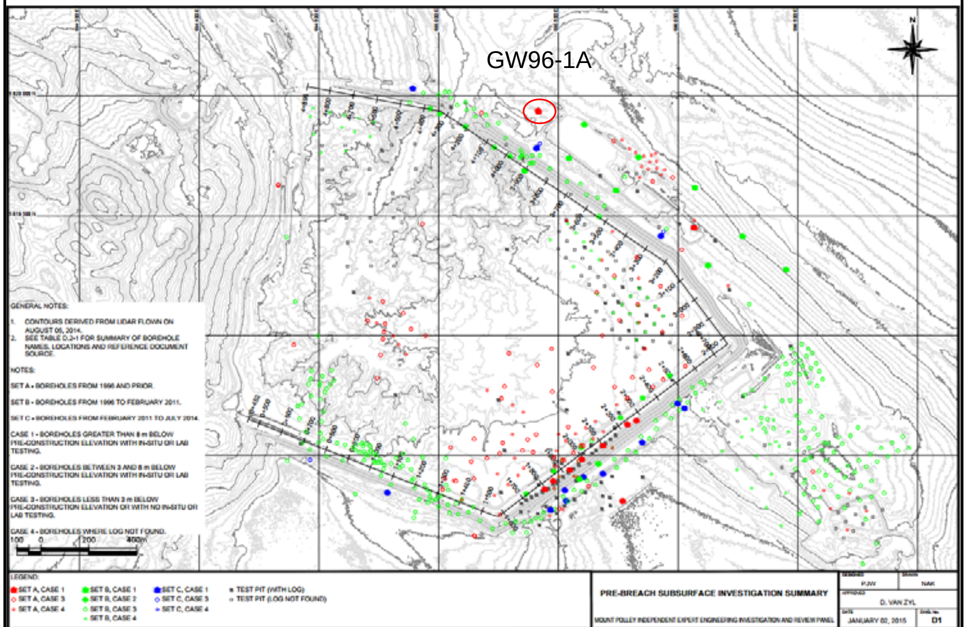
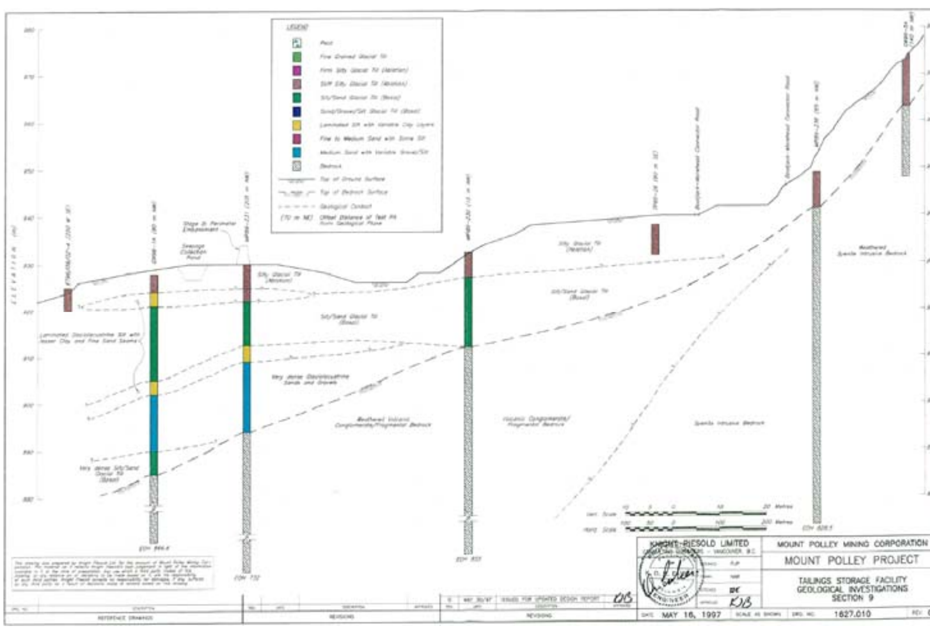
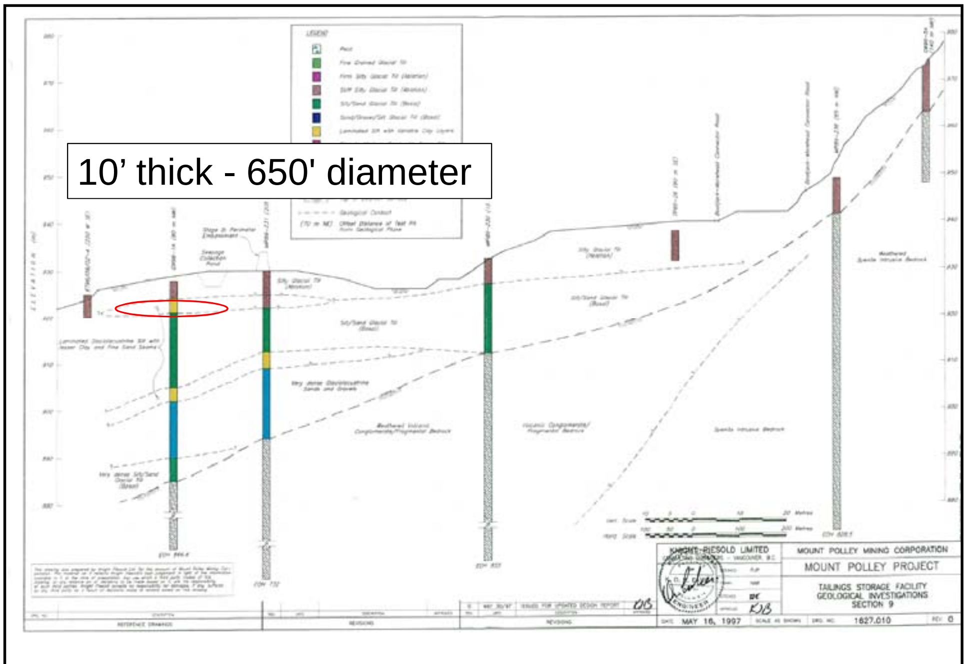
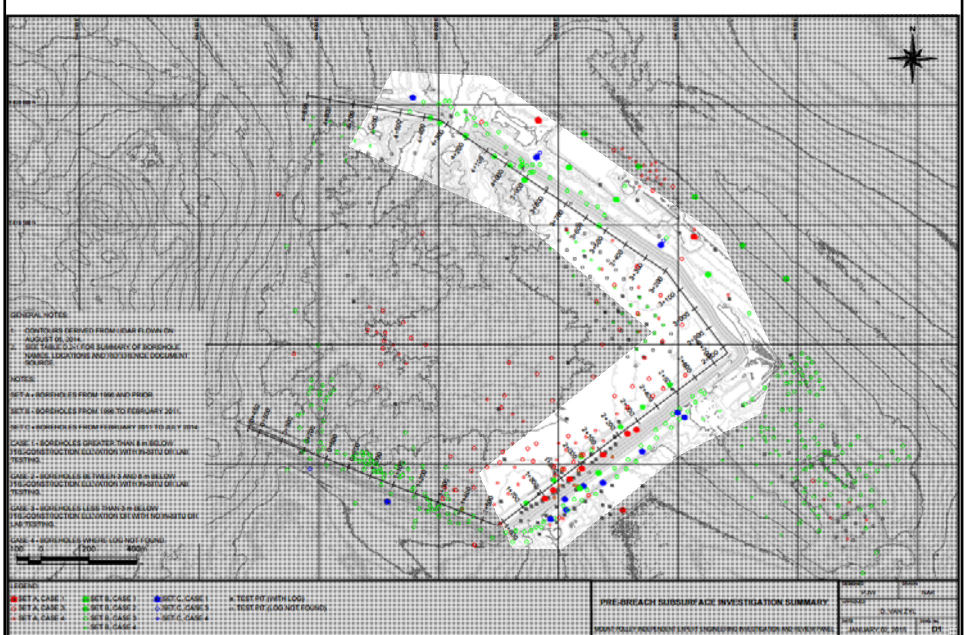

GW96-1A
GENERAL NOTES:
1. CONTOURS DERIVED FROM LIDAR FLOWN ON AUGUST 05, 2014.
2. SEE TABLE D.3-1 FOR SUMMARY OF BOREHOLE NAMES, LOCATIONS AND REFERENCE DOCUMENT SOURCE.
NOTES:
SET A - BOREHOLES FROM 1996 AND PRIOR.
SET B - BOREHOLES FROM 1996 TO FEBRUARY 2011.
SET C - BOREHOLES FROM FEBRUARY 2011 TO JULY 2014.
CASE 1 - BOREHOLES GREATER THAN 8 m BELOW PRE-CONSTRUCTION ELEVATION WITH IN-SITU OR LAB TESTING.
CASE 2 - BOREHOLES BETWEEN 3 AND 8 m BELOW PRE-CONSTRUCTION ELEVATION WITH IN-SITU OR LAB TESTING.
CASE 3 - BOREHOLES LESS THAN 3 m BELOW PRE-CONSTRUCTION ELEVATION OR WITH NO IN-SITU OR LAB TESTING.
CASE 4 - BOREHOLES WHERE LOG NOT FOUND.
100 0 200 400m
LEGEND:
SET A, CASE 1
SET A, CASE 3
SET A, CASE 4
SET B, CASE 1
SET B, CASE 2
SET B, CASE 3
SET B, CASE 4
SET C, CASE 1
SET C, CASE 3
SET C, CASE 4
TEST PIT (WITH LOG)
TEST PIT (LOG NOT FOUND)
PRE-BREACH SUBSURFACE INVESTIGATION SUMMARY
MOUNT POLLEY INDEPENDENT EXPERT ENGINEERING INVESTIGATION AND REVIEW PANEL
D. VAN ZYL
JANUARY 02, 2015
D1


KNIGHT PIESOLD LIMITED
MOUNT POLLEY MINING CORPORATION
MOUNT POLLEY PROJECT
TAILINGS STORAGE FACILITY
GEOLOGICAL INVESTIGATIONS
SECTION 9
MAY 16, 1997
1627.010


10’ thick - 650' diameter
KNIGHT PIESOLD LIMITED
MOUNT POLLEY MINING CORPORATION
MOUNT POLLEY PROJECT
TAILINGS STORAGE FACILITY
GEOLOGICAL INVESTIGATIONS
SECTION 9
MAY 16, 1997
1627.010

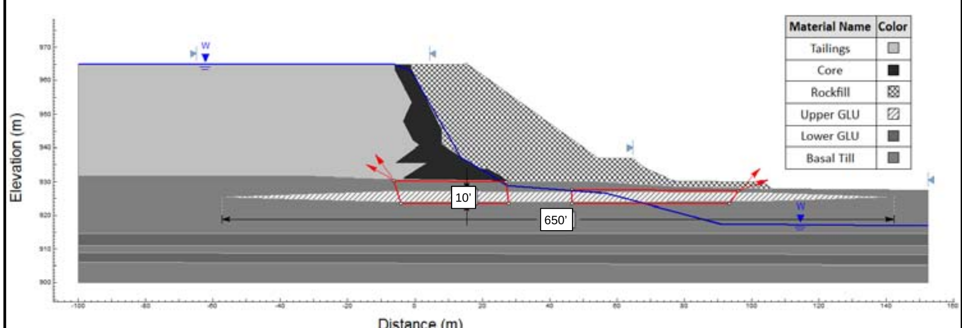

GENERAL NOTES:
NOTES:
LEGEND:
PRE-BREACH SUBSURFACE INVESTIGATION SUMMARY
D. VAN ZYL
D1

Methodology

Case	Description	Likelihood (%)
1	No upper GLU	90.3%
2	GLU at 3’-10’ depth	0.5%
3	GLU at 10’-20’ depth	2.3%
4	GLU at 20’-30’ depth	2.3%
5	GLU at 30’-40’ depth	2.3%
6	GLU at 40’-50’ depth	2.3%

Methodology

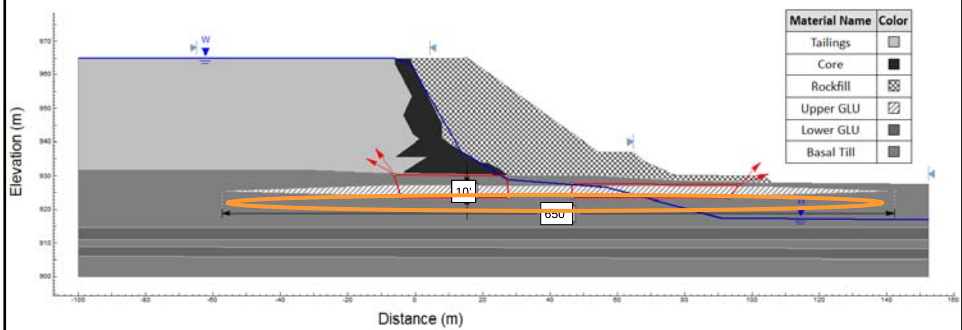
Defining Geological Model:



10’ – 20’

Methodology

Defining Geological Model:



20' – 30'

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Methodology

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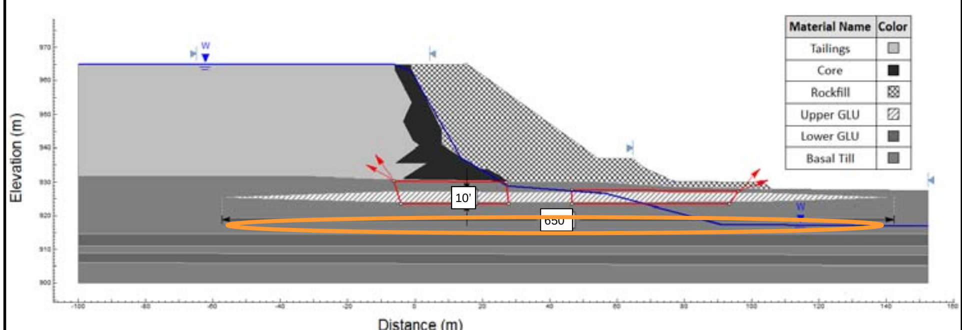

30' – 40'

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Results

Case	Description	Likelihood (p_X)	P_f (x_i)
1	No upper GLU	90.3%	0.00
2	GLU at 3'-10'	*0.5%*	*0.90*
3	GLU at 10'-20'	2.3%	0.84
4	GLU at 20'-30'	2.3%	0.70
5	GLU at 30'-40'	2.3%	0.58
6	GLU at 40'-50'	2.3%	0.25
Weighted probability of slope stability failure			**5.90%**

Conclusion

- Risk = Probability x Consequence
- Discount cash flow valuations when valuing projects for business cases
- Justifying site investigation costs – "You pay for a site investigation program whether you have one or not." So how many boreholes do we need?

Questions?

Results

Case	Description	Trials	Minutes	Deterministic FS	Factor of Safety Mean (μ)	Std. Dev. (σ)	Min	Max	Distribution	Reliability β	P_f
Calibration Model	Panel Back-analysis	850	4	1.01	1.00	0.10	0.66	1.30	Normal	0.026	0.48
1	No upper GLU	700	3	1.77	1.74	0.15	1.27	2.02	Beta	5.054	2.16E-07
2	GLU at 3'-10'	700	10	0.89	0.88	0.11	0.53	1.20	Beta	-1.060	0.85
3	GLU at 10'-20'	700	10	0.91	0.90	0.10	0.56	1.22	Normal	-1.004	0.84
4	GLU at 20'-30'	700	10	0.95	0.94	0.10	0.58	1.24	Normal	-0.543	0.70
5	GLU at 30'-40'	700	10	0.98	0.98	0.11	0.67	1.30	Normal	-0.197	0.58
6	GLU at 40'-50'	700	10	1.09	1.08	0.11	0.70	1.45	Normal	0.673	0.25