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The AANDC Cover Systems in Cold Regions Guidance Document –

Rationale for Advocating use of an FMEA for Design and Presentation of the Document's FMEA Case Studies

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Presentation Summary (Part 1)

- **Overview / Highlights of the Guidance Document**

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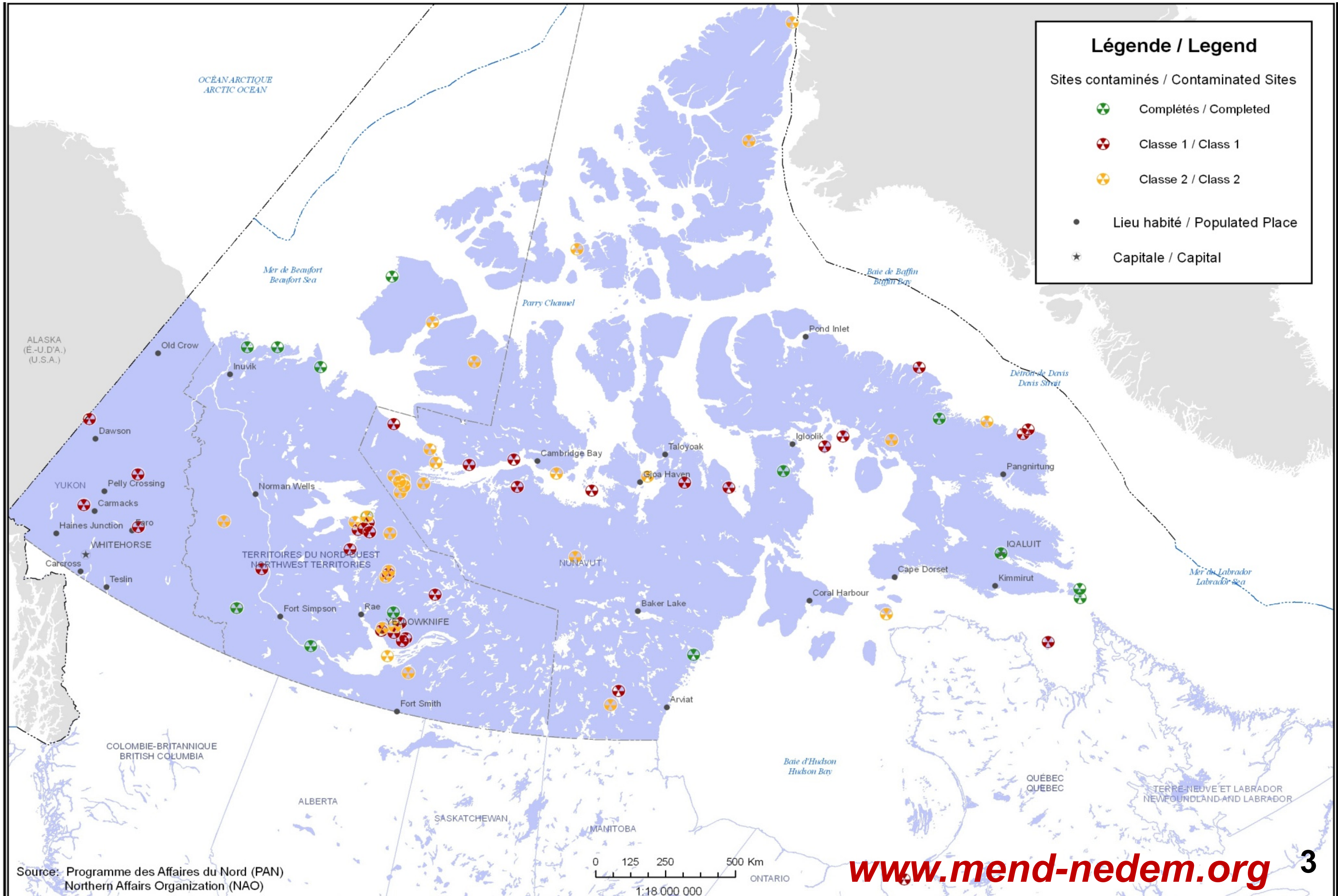
- **Overview of the FMEA Process**
- **Description of Two Case Studies Outlined in the Guidance Document**
- **Presentation of Failure Modes**
- **Group Exercise—Failure Mode Ranking and Discussion of Mitigation Measures**

Background



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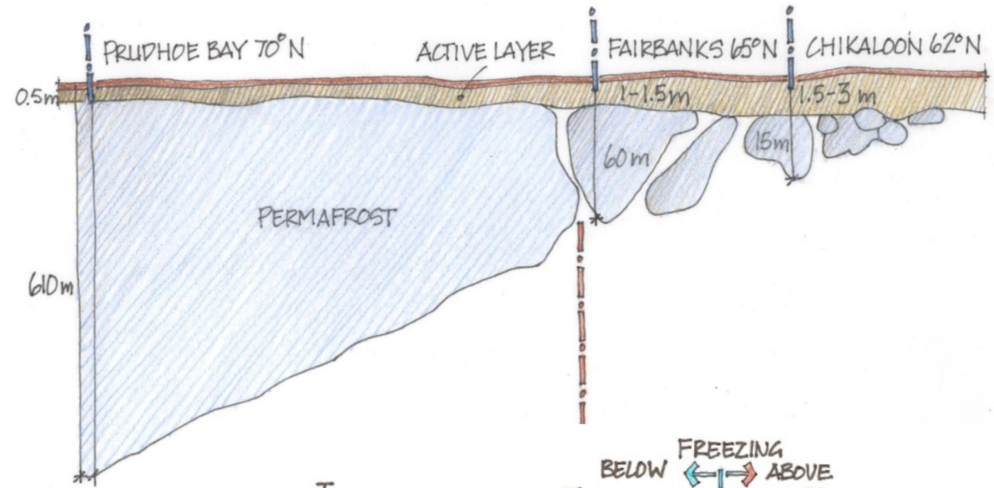
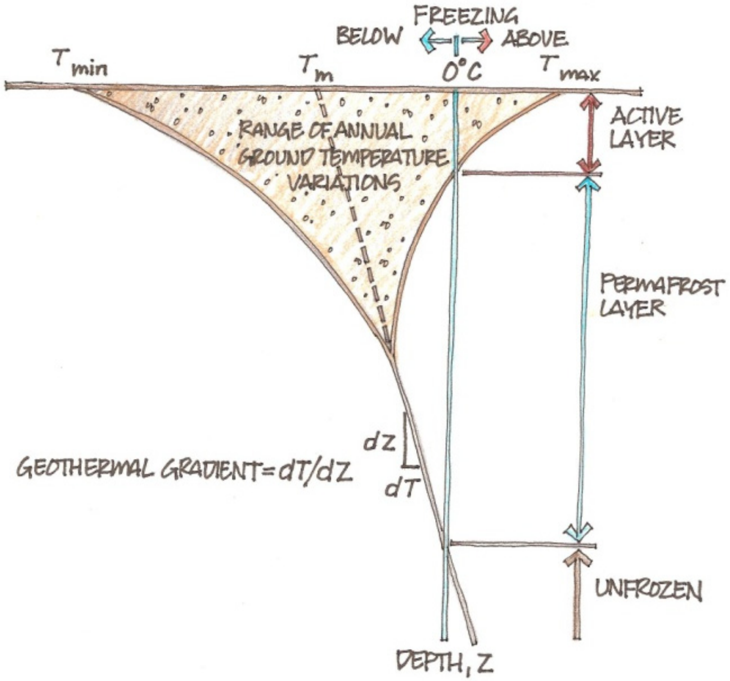
Background

- ***Previous MEND Reports***
  - ***MEND 1.61.1. 1997***
    - ***Roles of Ice, in the Water Cover Option, and Permafrost in Controlling Acid Generation f… Sulphide Tailings***
  - ***MEND 2.21.4. 2004***
    - ***Design, Construction and Performance Monitoring of Cover Systems for Waste Roc… and Tailings***
  - ***MEND 1.61.6. 2006***
    - ***Update on Cold Temperature Effects on Geochemical Weathering***
  - ***MEND 2.21.5. 2007***
    - ***Macro-Scale Cover Design and Performance Monitoring Reference Manual***
  - ***MEND 1.61.5a. 2009***
    - ***Mine Waste Covers in Cold Regions***
  - ***MEND 1.61.5b. 2010***
    - ***Cold Regions Cover Research – Phase 2***





Andersland and Ladanyi (2004)

Technical Advisory Group (TAG)

- ***Dr. Lee Barbour***, **University of Saskatchewan;**
- ***Mr. John Brodie***, **Brodie Consulting Ltd.;**
- ***Dr. Sean Carey***, **McMaster University;**
- ***Dr. Gord McKenna***, **BGC Engineering Inc.;**
- ***Mr. Mike Nahir***, **AANDC-CSP;**
- ***Mr. Mike O'Kane***, **O'Kane Consultants Inc.;**
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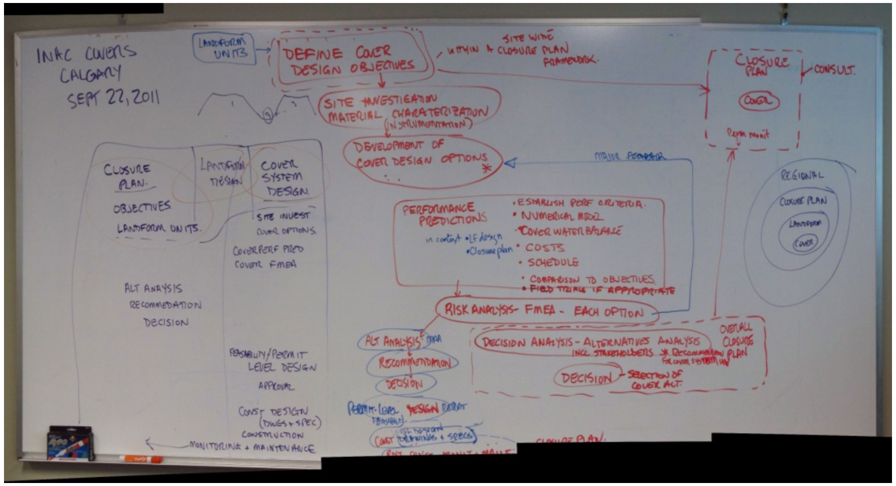
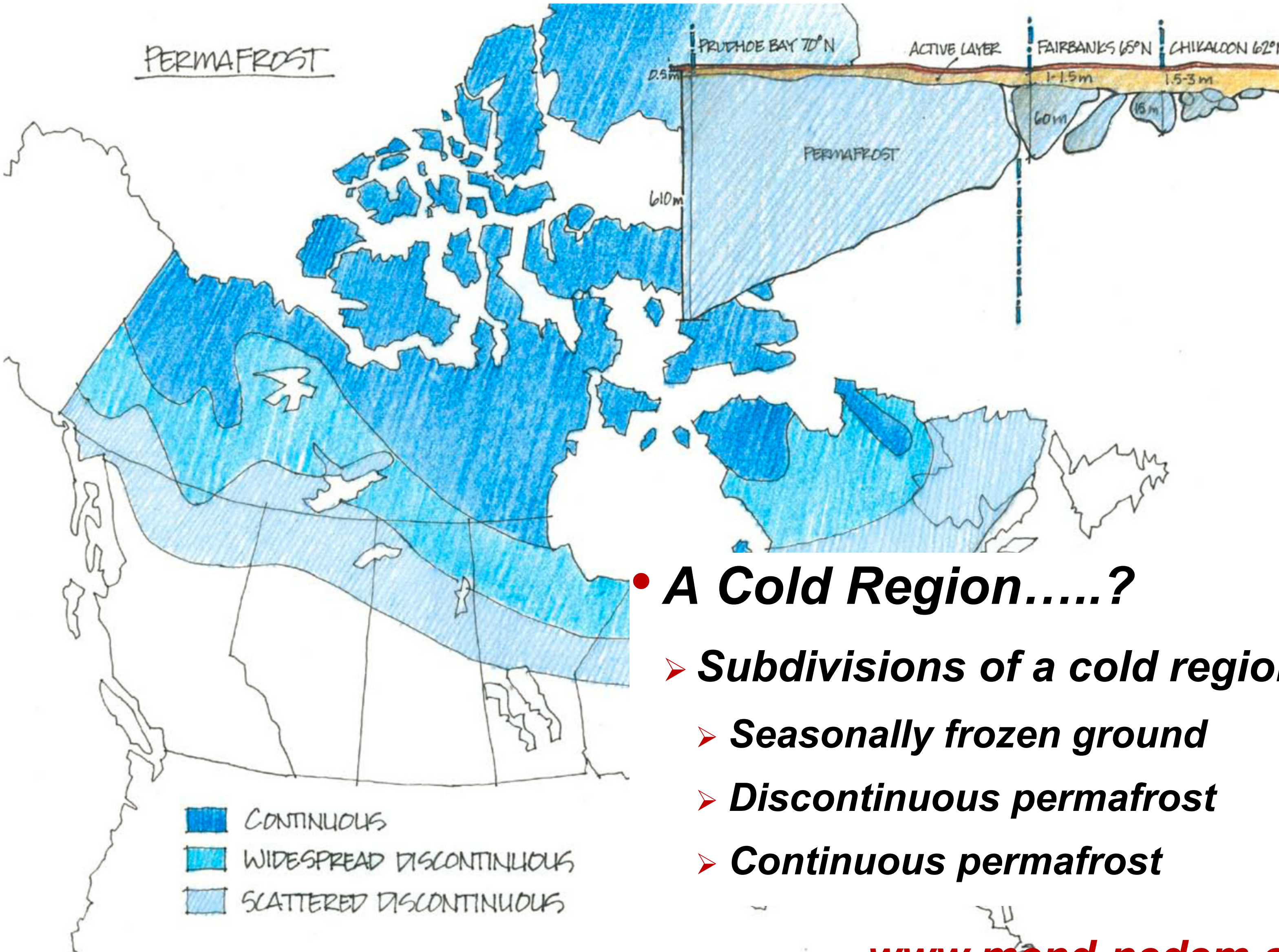
- ***Dr. David Sego***, **University of Alberta; and**
- ***Mr. Justin Straker***, **Integral Ecology Group.**



Technical Guidance Document

- **Chapter One**: Introduction
  - General Purpose of Cover Systems
- **Chapter Two**: Geographic Extent and Key Attributes of Cold Regions
  - Key Failure Mechanisms for Cover Systems in Cold Regions
- **Chapter Three**: Cover System Design Philosophy for Cold Regions
  - Utilizing Attributes of the Canadian North
  - Assessment Period and Design Life
- **Chapter Four:** Basic Theory and Fundamental Concepts
- **Chapter Five**: Cover System Design Alternatives for Cold Regions
  - Description of Cover System Design Alternatives
- **Chapter Six**: Cover System Design Methodology for Cold Regions
  - Highlights on the Recommended Approach
  - Five Critical Factors Affecting Cover Performance in Cold Regions
- **Chapter Seven**: Application of the FMEA Process

Background



- ***A Cold Region…..?***
  - ***Subdivisions of a cold region***
    - ***Seasonally frozen ground***
    - ***Discontinuous permafrost***
    - ***Continuous permafrost***

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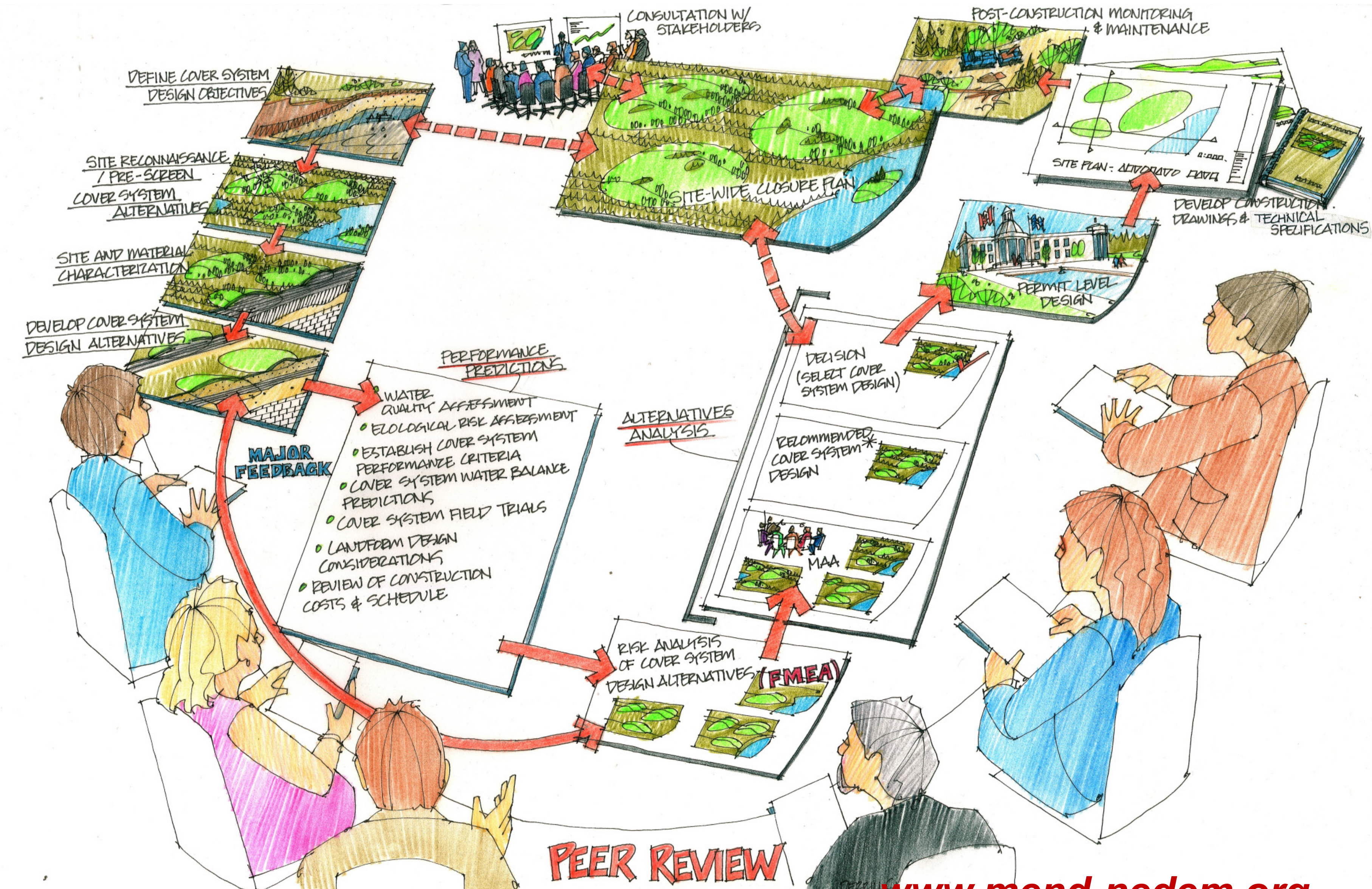
Design Methodology for Cold Regions



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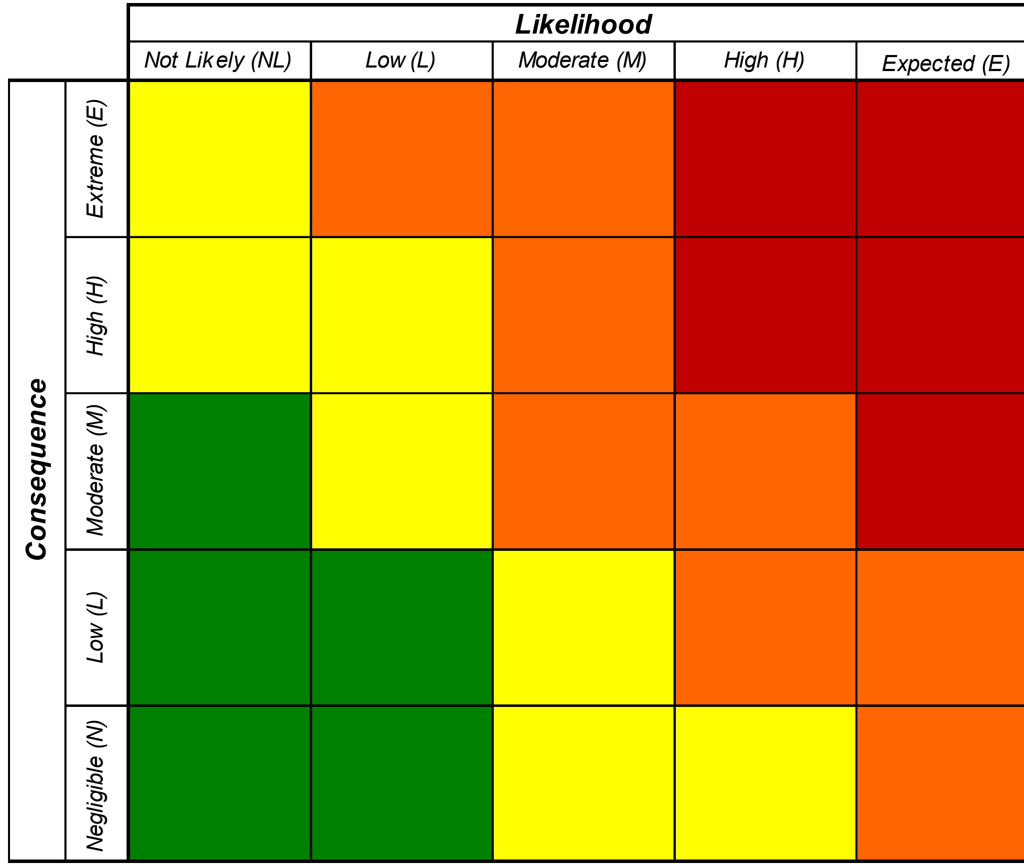
FMEA for Cold Regions

- ***Failure Modes and Effects Analysis***
  - **Objective of an FMEA is to *identify* and *quantify* risks in order to either avoid or mitigate them.**
  - **Combines the likelihood of failure with the consequences of a failure to express the outcome as a risk.**

Risk Matrix



Risk Level	Guidelines for Risk Matrix
Extreme	Eliminate, avoid, implement specific action plans / procedures to manage and monitor
High	Proactively manage
Medium	Actively manage
Low	Monitor and manage as apprpriate

FMEA for Cold Regions

- **FMEA (Robertson and Shaw, 2003) :**
  - **“a top down/ expert system approach to risk identification and quantification, and mitigation measure identification and prioritization”**
- **FMEA value and effectiveness depends on having participation of “experts” with the appropriate knowledge and experience.**
- **“Experts” are those who understand the geotechnique, hydrology, environmental impacts, and regulatory requirements as well as the past history of the mine's design, construction, operation and performance.**

FMEA for Cold Regions

- FMEA allows for a risk analysis *early* in the design process.
- FMEA is site-specific: incorporates local climate, available materials, and unique stakeholder needs.
- Cover designs with high potential failure rates can be omitted from consideration (e.g. long-term maintenance).
- Final risk rankings are comparable, defensible, and lead to constructive discussion of mitigation methods.

FMEA for Cold Regions

- *Failure Modes*
  - Naturally initiated (e.g. an 'act of God' such as an earthquake)
  - Initiated by the failure of one of the engineered subsystems (e.g. instability of a dam)
  - Result from operational failure
  - A large number of potential failure modes could be included, but it is necessary to confine evaluations to those that represent a significant risk
  - Failure modes can also be combinations of events (e.g. a small trigger event sets off a chain of events)

FMEA for Cold Regions

- ***What Does Failure Mean?***
  - **TAG developed the following for the Canadian North (net percolation of cover systems as % of MAP):**
    - **Very low: <5%**
    - **Low: 5-10%**
    - **Moderate: 10-15%**
    - **High: 15-40%**

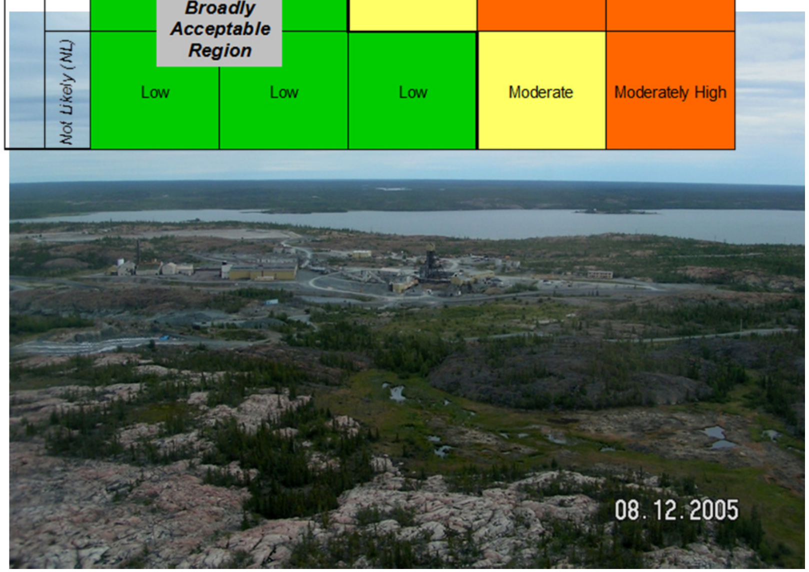
Application of FMEA Process

Likelihood		Consequence Severity				
		Low (L)	Minor (Mi)	Moderate (Mo)	Major (M)	Critical (C)
	Expected (E)	Moderate	Moderately High	High	Critical	Critical
	High (H)	Moderate	Moderate	Moderately High	High	Critical
	Moderate (M)	Low	Moderate	Moderately High	High	High
	Low (L)	Low	Low	Moderate	Moderately High	Moderately High
	Not Likely (NL)	Low	Low	Low	Moderate	Moderately High

Intolerable Region

ALARP Region

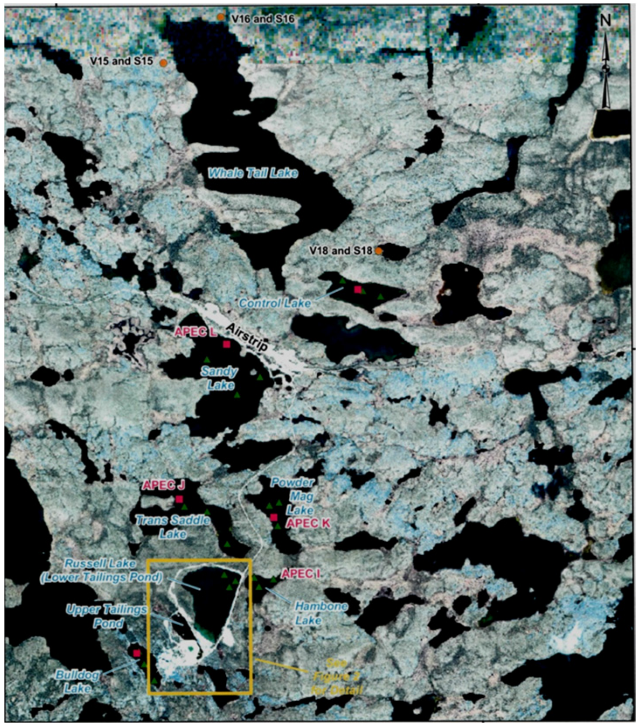
Broadly Acceptable Region



- **Case Study #1**
  - **Sporadic discontinuous permafrost (seasonal)**
  - **Highly reactive (acidic) waste rock**
- **Case Study #3**
  - **Edge of continuous permafrost**
  - **Potentially acid forming tailings with arsenic release**

Example: Case Study #3

- Tailings and WR in surface impoundments in continuous permafrost
- WR is potentially acid generating.
- Both WR and tailings have high concentrations of arsenic.
- Continuous permafrost: active layer depth varies between 1.5 m and 3.8 m



- 250 mm annual precipitation (40% as snow).
- Open water period is approximately 100 days.
- Potential evaporation 225–350 mm/yr.

Example: Case Study #3

- Tailings surface runoff is directed through a discharge channel to one of many nearby lakes.
- Elevated levels of arsenic and slightly acidic pH are present in groundwater below and downgradient of tailings impoundment.

- Potential cover materials include a sand and gravel esker material.
- Bedrock outcrops are common with a discontinuous veneer of till.
- Available quantities of materials are a limiting factor.

Example: Case Study #3

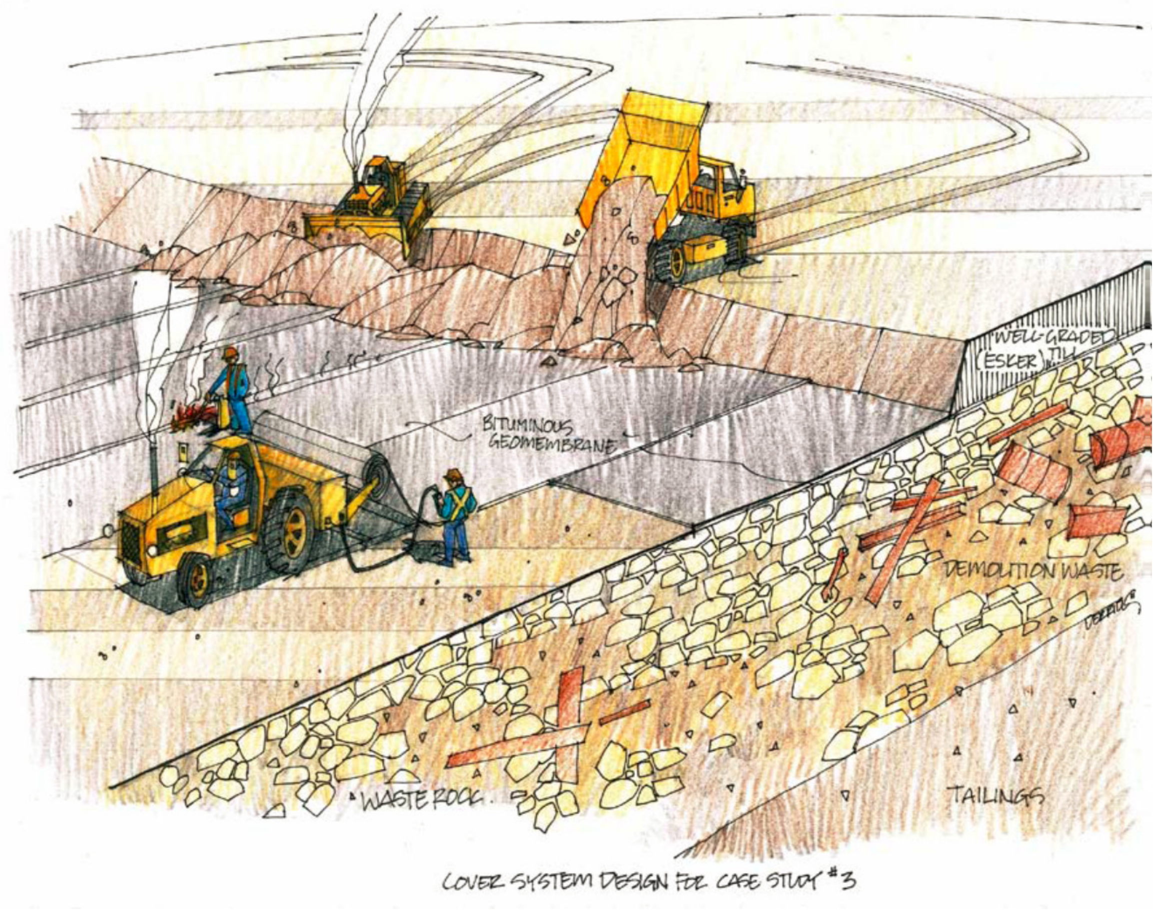
Cover system performance criteria:

- Very low net percolation (<5% of precipitation)
- Dust control
- Vegetation establishment
- Isolation of contaminants

Example: Case Study #3

Cover system design:

- Relocate WR to tailings pond to minimize surface area to be covered.
- BGM overlain by 75 cm of well-graded, sandy gravelly esker material.



Example: Case Study #1

- Abandoned zinc and lead mine.
- 32 Mt of sulphidic WRDs with both north- and south-facing slopes.
- WRDs composed of free draining coarse rock (potential for convective gas transport).
- Surrounding landforms include morainal till veneers and till blankets along with galciofluvial and glaciolacustrine deposits.

- Climate is semi-arid with 300 mm annual precipitation (1/3 as snow).
- AET ranges from 75 mm/yr (north facing) to 200 mm/yr.

Example: Case Study #1

- **Infiltration through WRD results in groundwater and surface water contamination.**
- **Cover material suitable for low permeability layer is available as is a granular cover material.**
- **Till material becomes dense and hard-packed leading to erosion and vegetation challenges**
- **Coarse rock fill and organic soils are not readily available.**

Example: Case Study #1

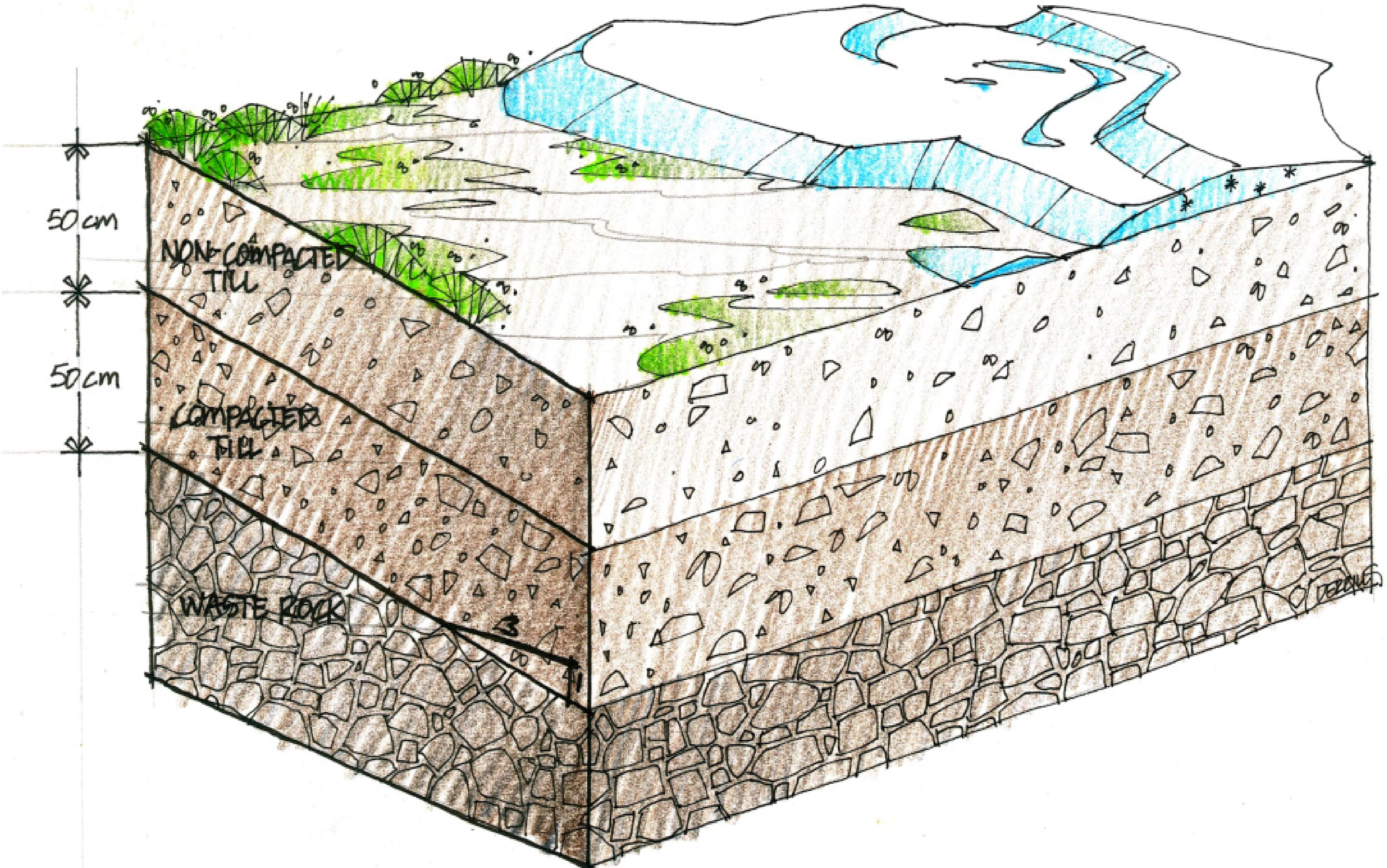
Cover system performance criteria:

- Low net percolation (5-10% of precipitation)
- Dust control
- Erosion control
- Geotechnical stability
- Vegetation establishment
- Control / reduce convective gas transport

Example: Case Study #1

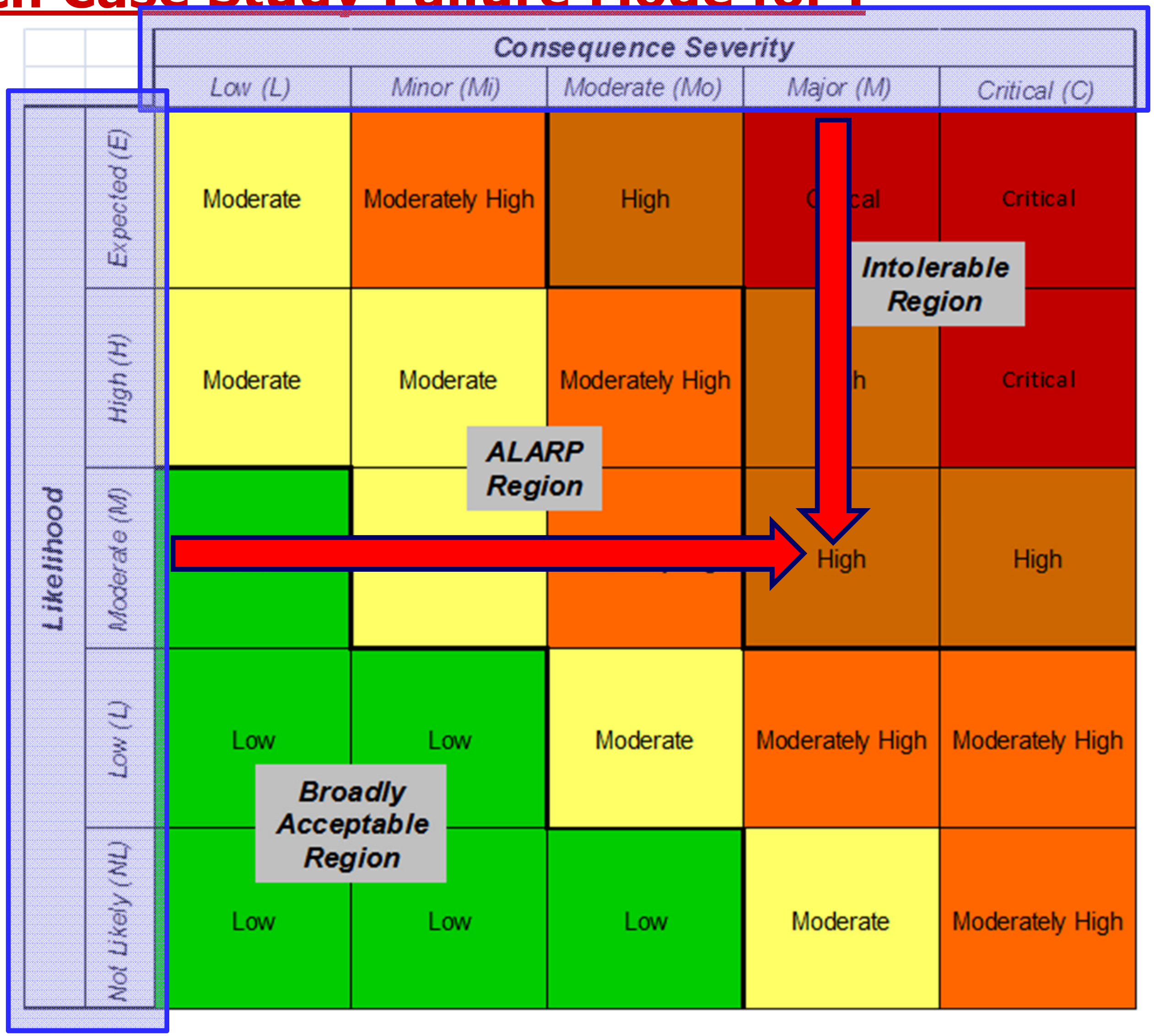
Cover system design:

- 0.5 m compacted till placed on WR surface
- 0.5 m non-compacted till



FMEA: Group Exercise

Rank Each Case Study Failure Mode for :



FMEA: Group Exercise

Case Study 1:

1. Erosion of spillway-ponding and bypass
2. Freeze/thaw wet/dry degrading cover performance
3. Vegetation effects on cover performance
4. Cracking at top of dump leading to venting of lethal gas
5. Egress of lethal gas

FMEA: Group Exercise

Wireless: SFUNET

Open browser and enter:

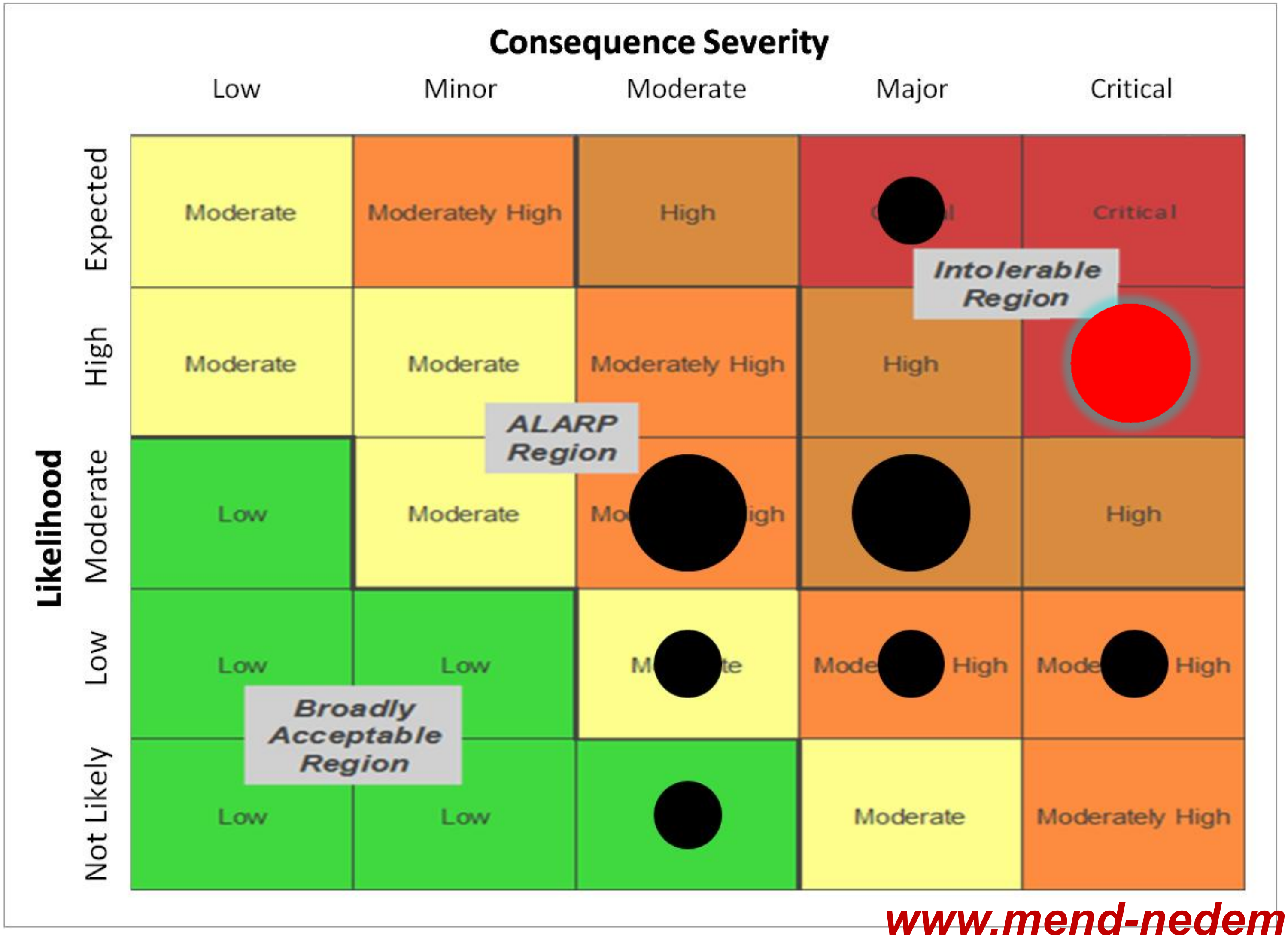
ID: lw926

Password: u8PU#66@

https://www.surveymonkey.com/s/8QFT39Q

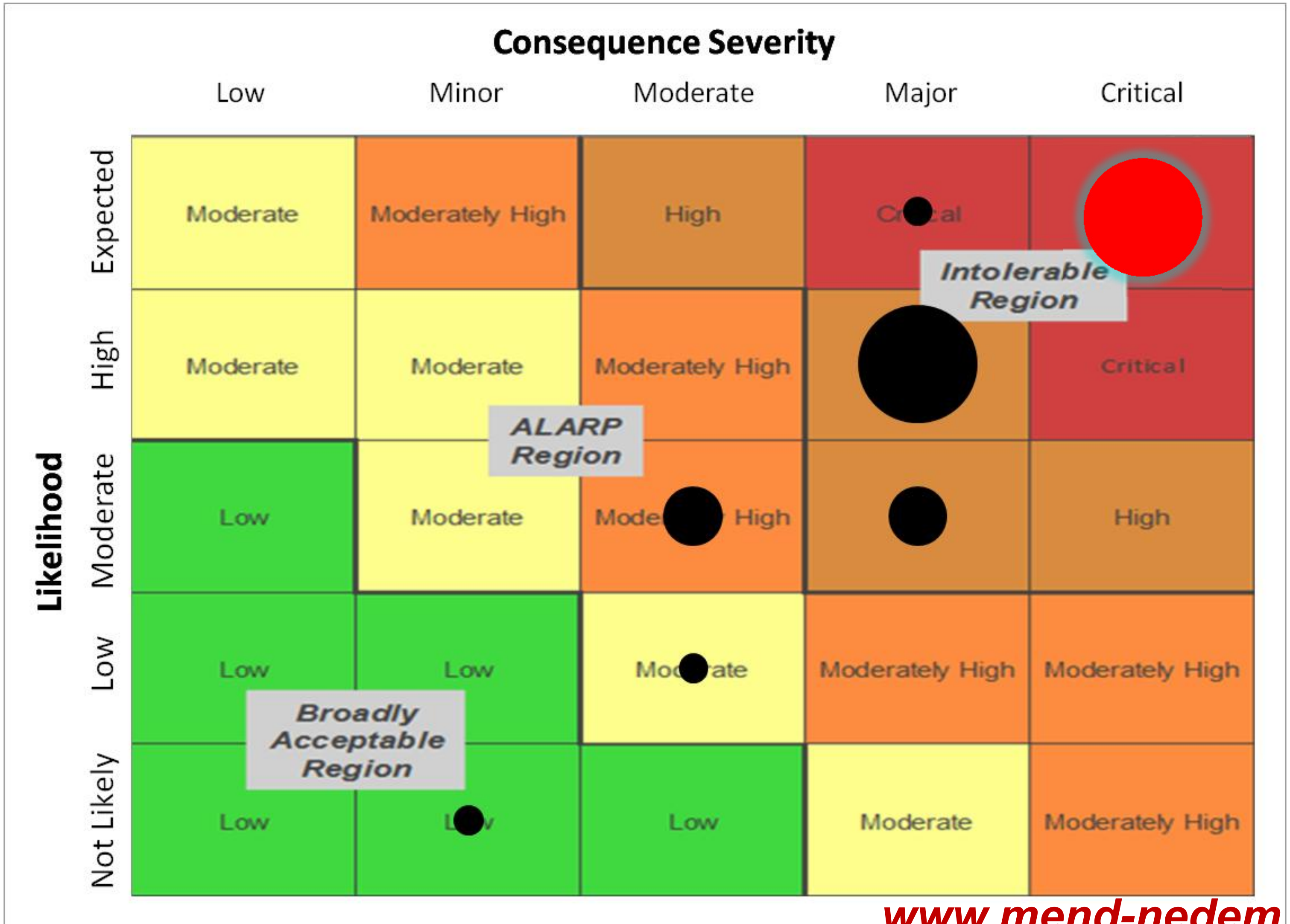
Group Exercise: Case Study #1

1. Erosion to the extent that spillway performance is degraded and ponding and bypass occurs :



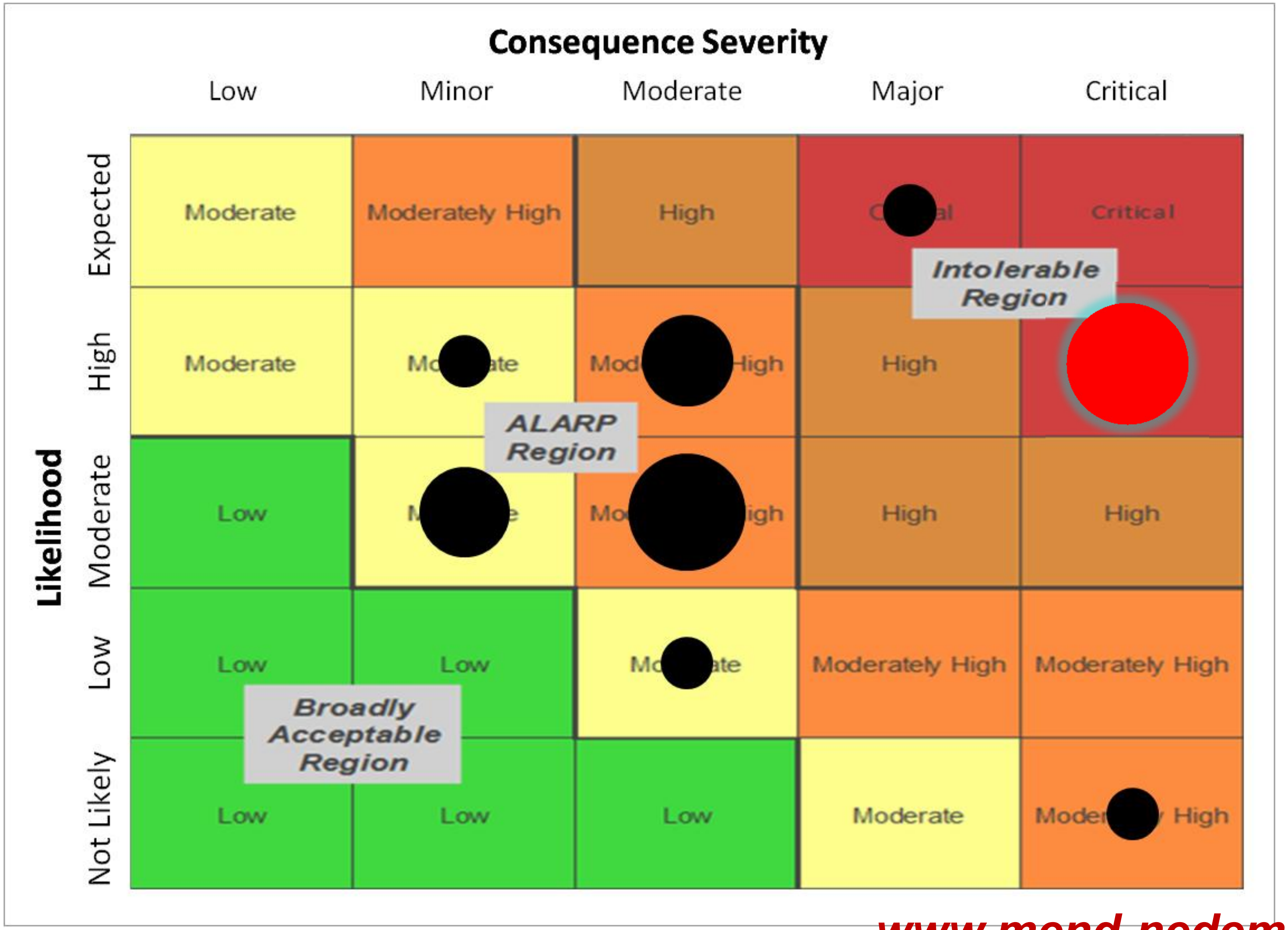
Group Exercise: Case Study #1

2. Freeze/thaw cycles, wet/dry settlement, and development of hummocks leading to cracking of the cover:



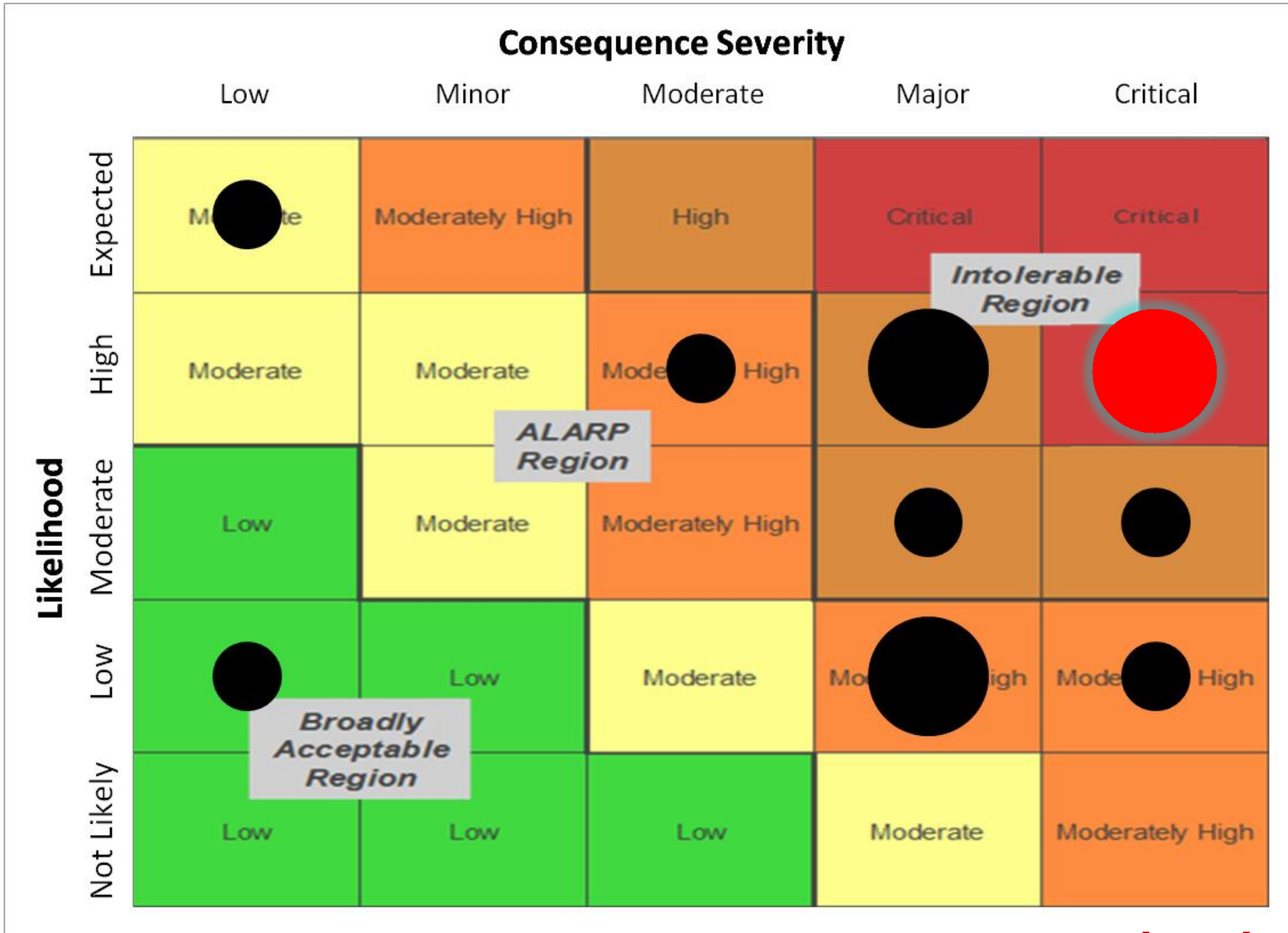
Group Exercise: Case Study #1

3. Vegetation effects on cover performance due to root penetration, blow down, etc.:



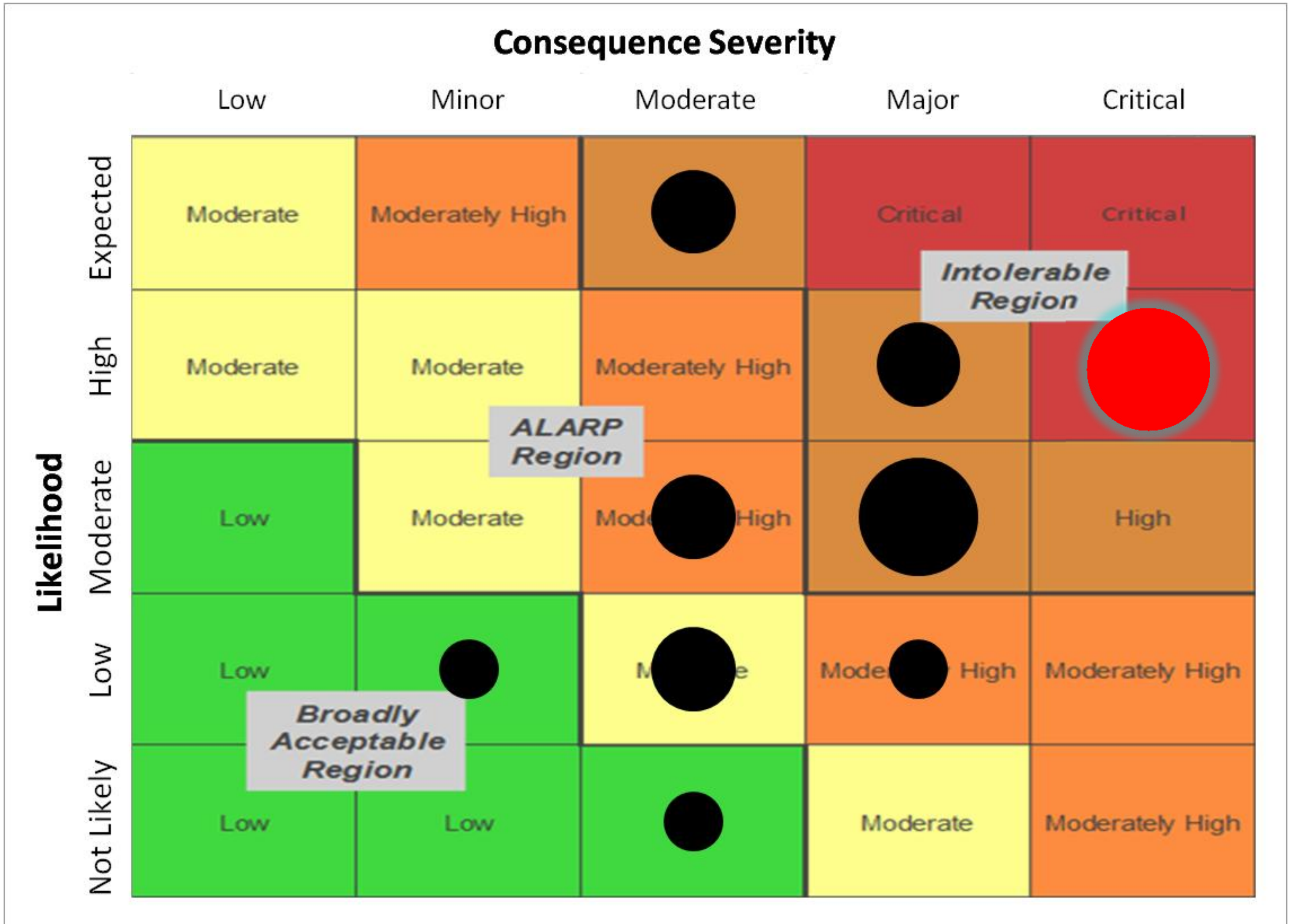
Group Exercise: Case Study #1

4. Cracking of top of dump cover leading to venting of lethal gas and accumulation in enclosures on top of dump.:



Group Exercise: Case Study #1

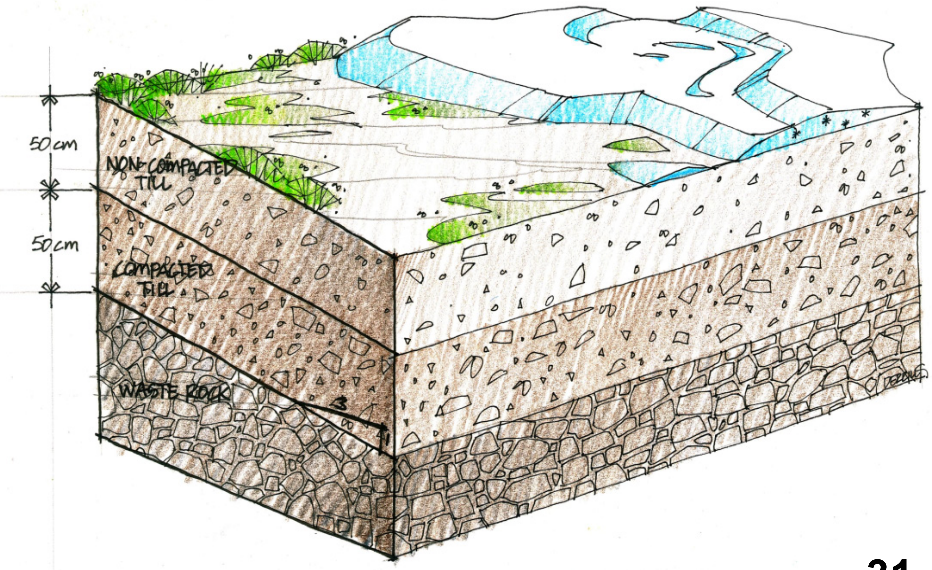
5. Egress of lethal gas from waste storage facility:



Mitigation Methods: Case Study #1

1. Erosion to the extent that spillway performance is degraded and ponding and bypass occurs :

- Design erosion resistant channels leading into the spillway.
- Observe/measure cover performance under site climatic conditions.
- Inspection of cover following a storm event.
- Maintenance of rills/gullies.

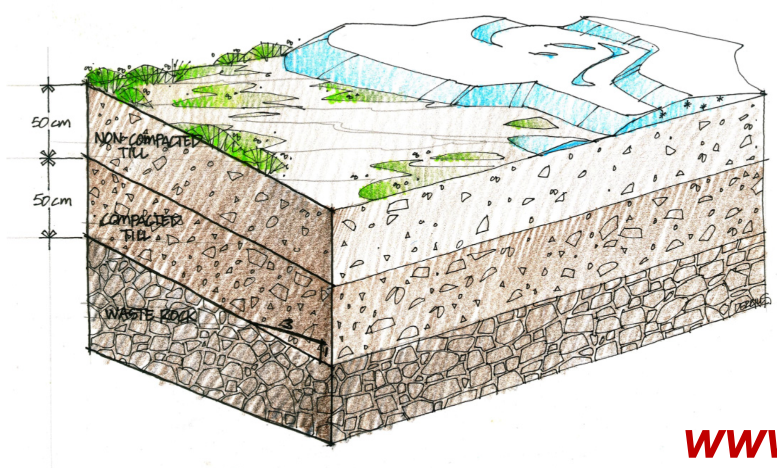


Mitigation Methods: Case Study #1

1. Erosion to the extent that spillway performance is degraded and ponding and bypass occurs :

From a design perspective:

- increase the thickness of cover (growth medium)
- increase design storm event criteria
- vegetation capable of controlling erosion in the long-term?
- surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is established
- re-designing the landform and/or surface water management system



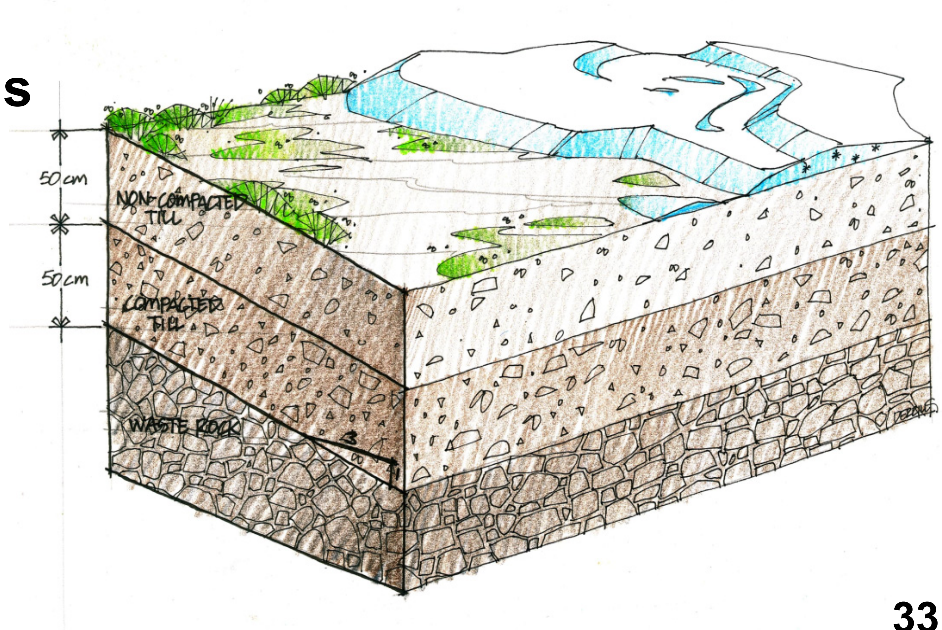
Mitigation Methods: Case Study #1

2. Freeze/thaw cycles, wet/dry settlement, and development of hummocks leading to cracking of the cover:

- Inspect landform at regular intervals; and
- Perform routine maintenance to repair cracks.

From design perspective:

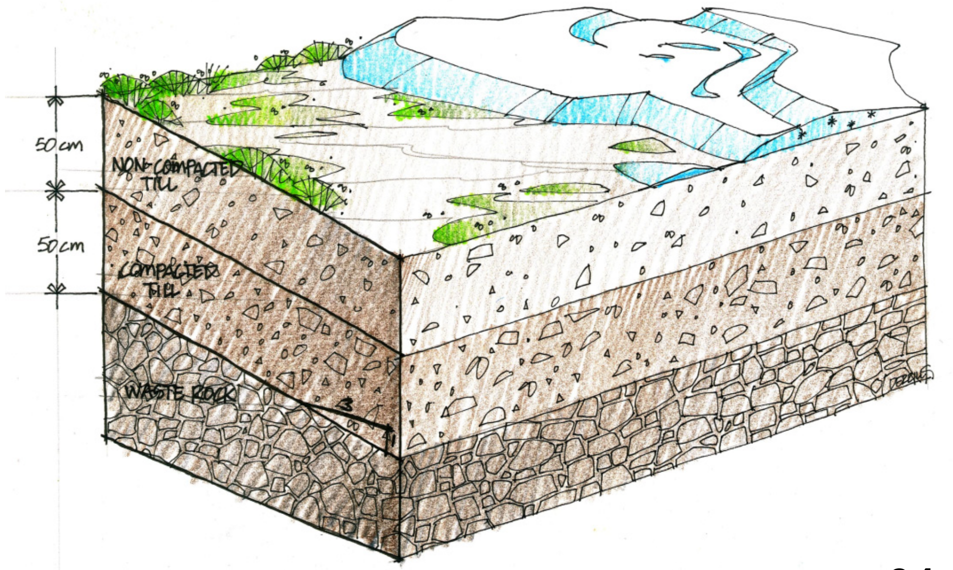
Incorporate change in hydraulic characteristics of cover materials due to frost action into the design.



Mitigation Methods: Case Study #1

3. Vegetation effects on cover performance due to root penetration, blow down, etc.:

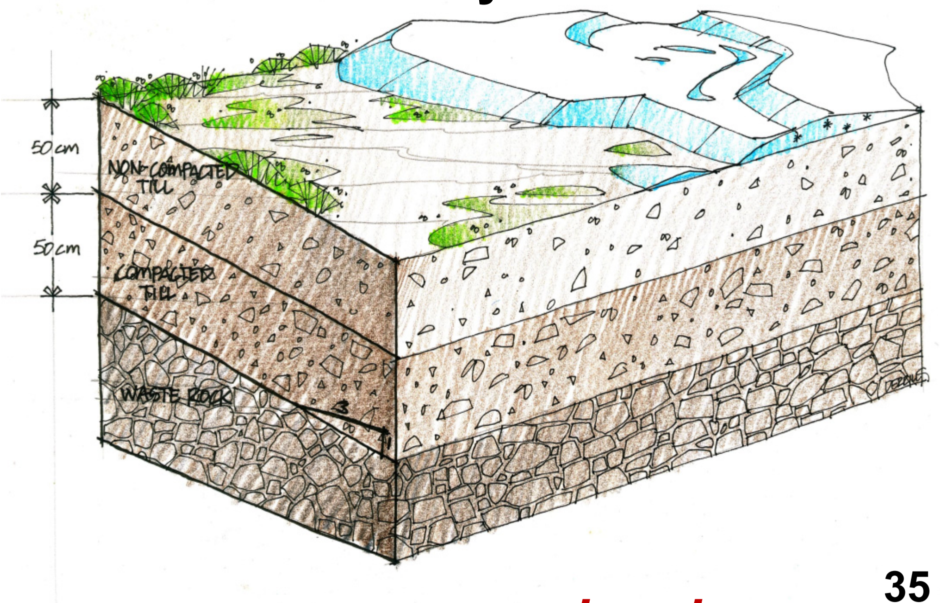
- Increase the thickness of the growth medium layer.



Mitigation Methods: Case Study #1

4. Cracking of top of dump cover leading to venting of lethal gas and accumulation in enclosures on top of dump.:

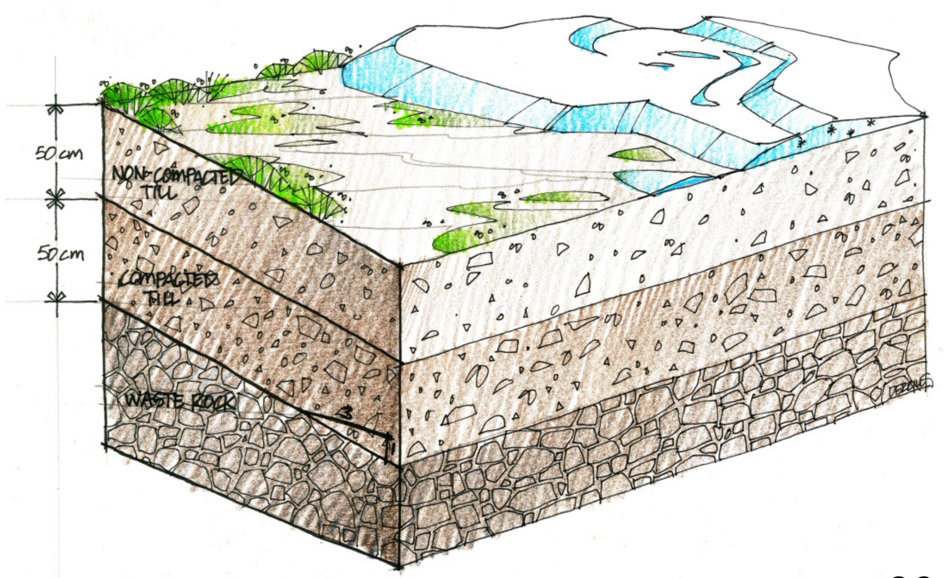
- Implement institutional controls (e.g. fencing);
- Prevent camping;
- Prevent placement of structures on WRDs; and
- Install warning signs that dangerous conditions may exist.



Mitigation Methods: Case Study #1

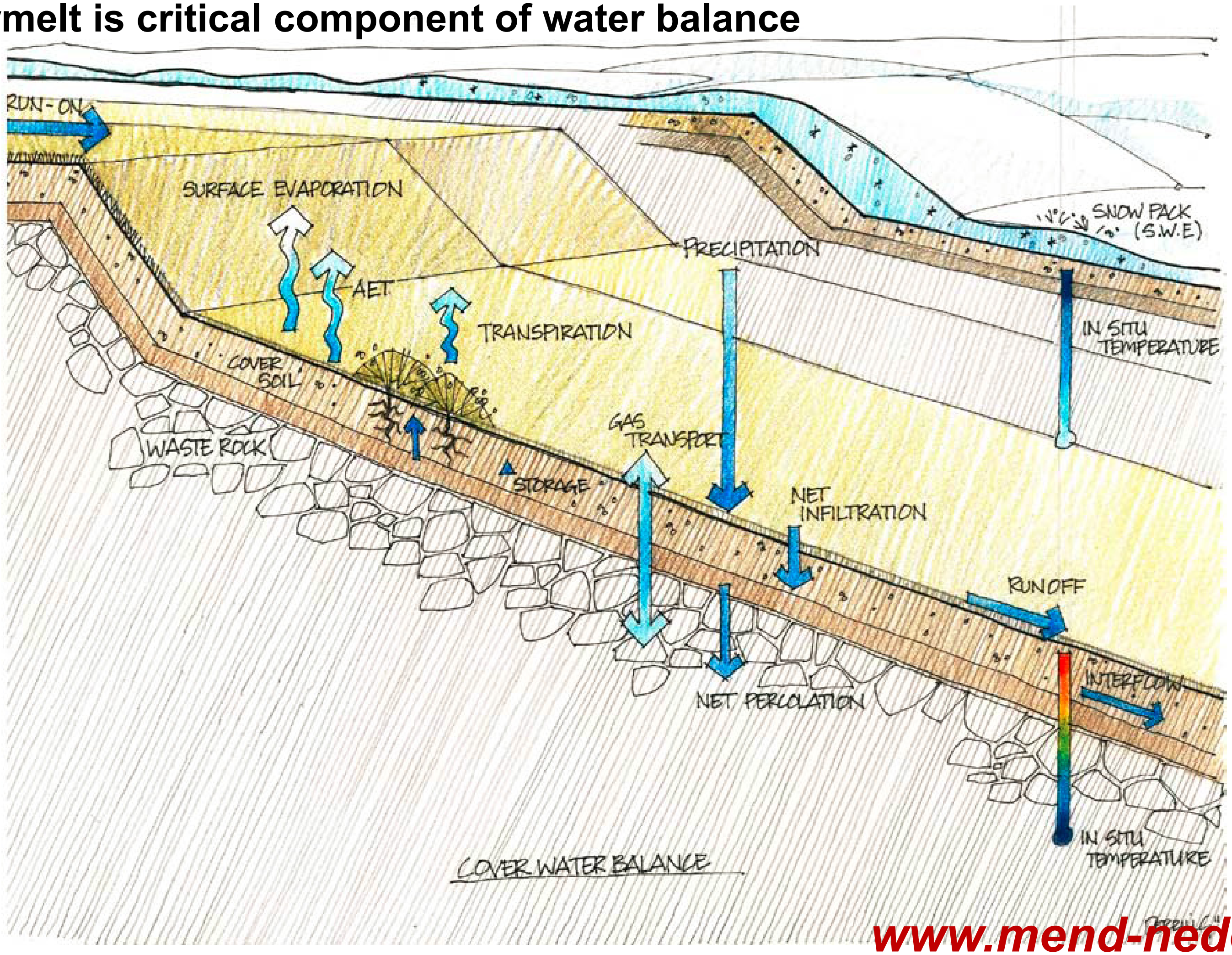
5. Egress of lethal gas from waste storage facility:

- Factors that may contribute to lethal gas accumulation, such as poor air circulation and mixing, need to be evaluated



Considerations

- ***Temperate Climate***
  - **Focus on water balance, but response to snowmelt is critical component of water balance**



Considerations

- ***Cold Region***
  - **Hydrology strongly controlled by the presence, distribution and timing of ground frost relative to snowmelt**
  - **Strongly influenced by slope and aspect (radiation), snowpack accumulation and melt, material type, and antecedent moisture conditions prior to freeze-up**
  - **Potential development of frost phenomena that might have a detrimental effect on cover performance?**
  - **Result of changes in energy balance (freeze or thaw) caused by disturbance of the thermal regime during cover placement or landform development and the resulting thermal disequilibrium**
  - **Reliance on seasonal or permanent development of ground frost to control water and/or gas movement.**

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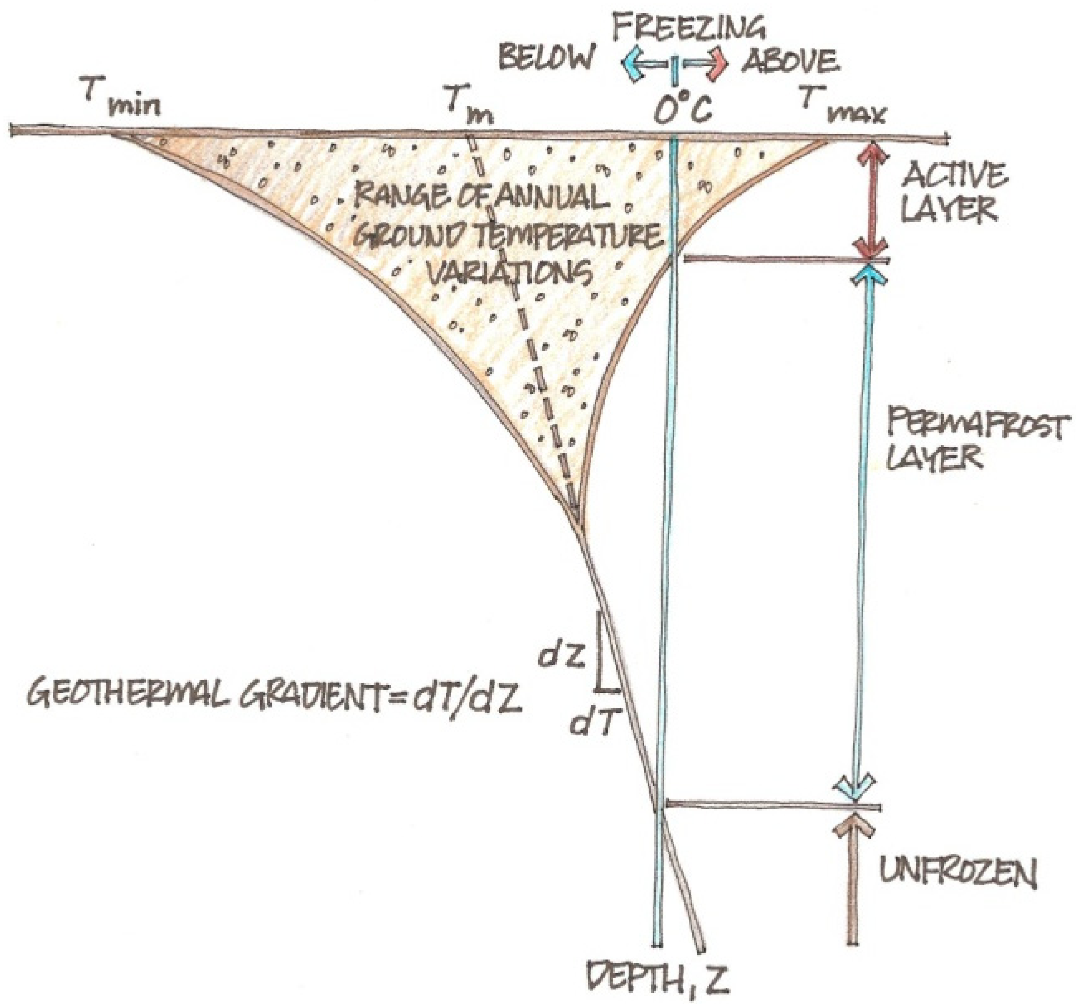
Design Methodology for Cold Regions

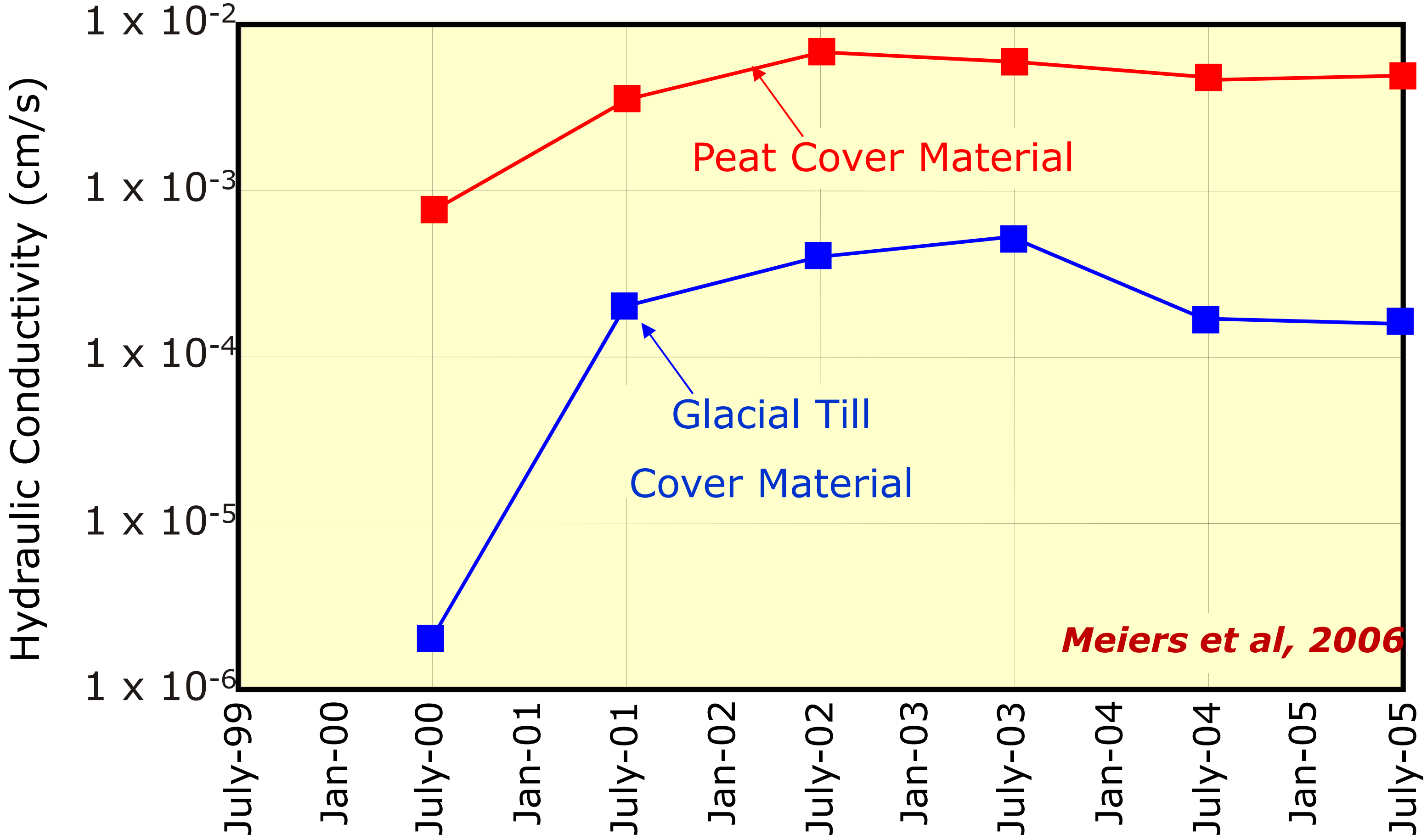
Not Just About….



Design Methodology for Cold Regions

Not Just About…

Increase in k_{fs} due to F/T Cycling



Design Methodology for Cold Regions

Thermal (energy) and Water Balance Evaluation a MUST to Properly Design a Cover System for a Cold Region

1) Frost,

Longer duration of the year and to a greater depth than in temperate regions where many covers systems are being evaluated

2) Slope / Aspect,

Magnified compared to warmer climates; sun angle is lower and seasonal variation in net radiation greater
Slope aspect affects snow accumulation, frost penetration, and results in delayed snowmelt.

3) Water Availability,

Precipitation vs. Potential Evaporation
Must consider PPT and PE on a seasonal or monthly basis rather than on an annual basis (PROBABILITY)

4) Vegetation, and

Aesthetics, Erosion, S&R Cover Performance, Water Availabilty
Native vs. Agronomic
Short frost-free period… short growing season
No vegetation….. Is that Realistic??

5) Cover Material.

Finer vs. Coarser, Availability,
Erosion, Establishment of Vegetation, LANDFORM DESIGN

All Factors are Interrelated

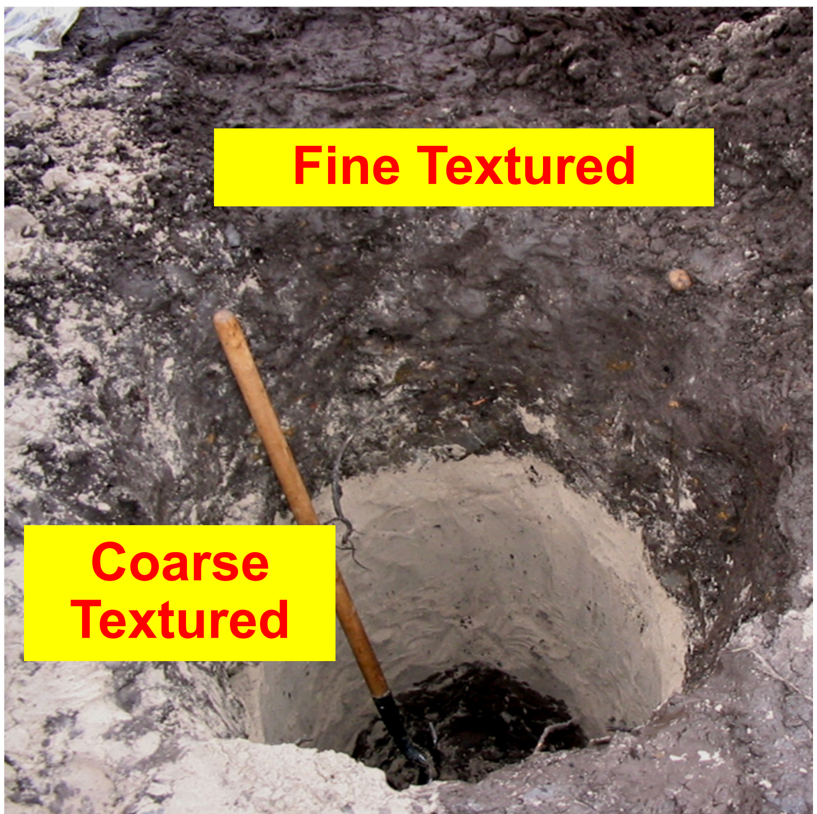
Cover System Design Alternatives

Capillary Break (form of enhanced S&R)

**Growth Medium
(finer textured)**

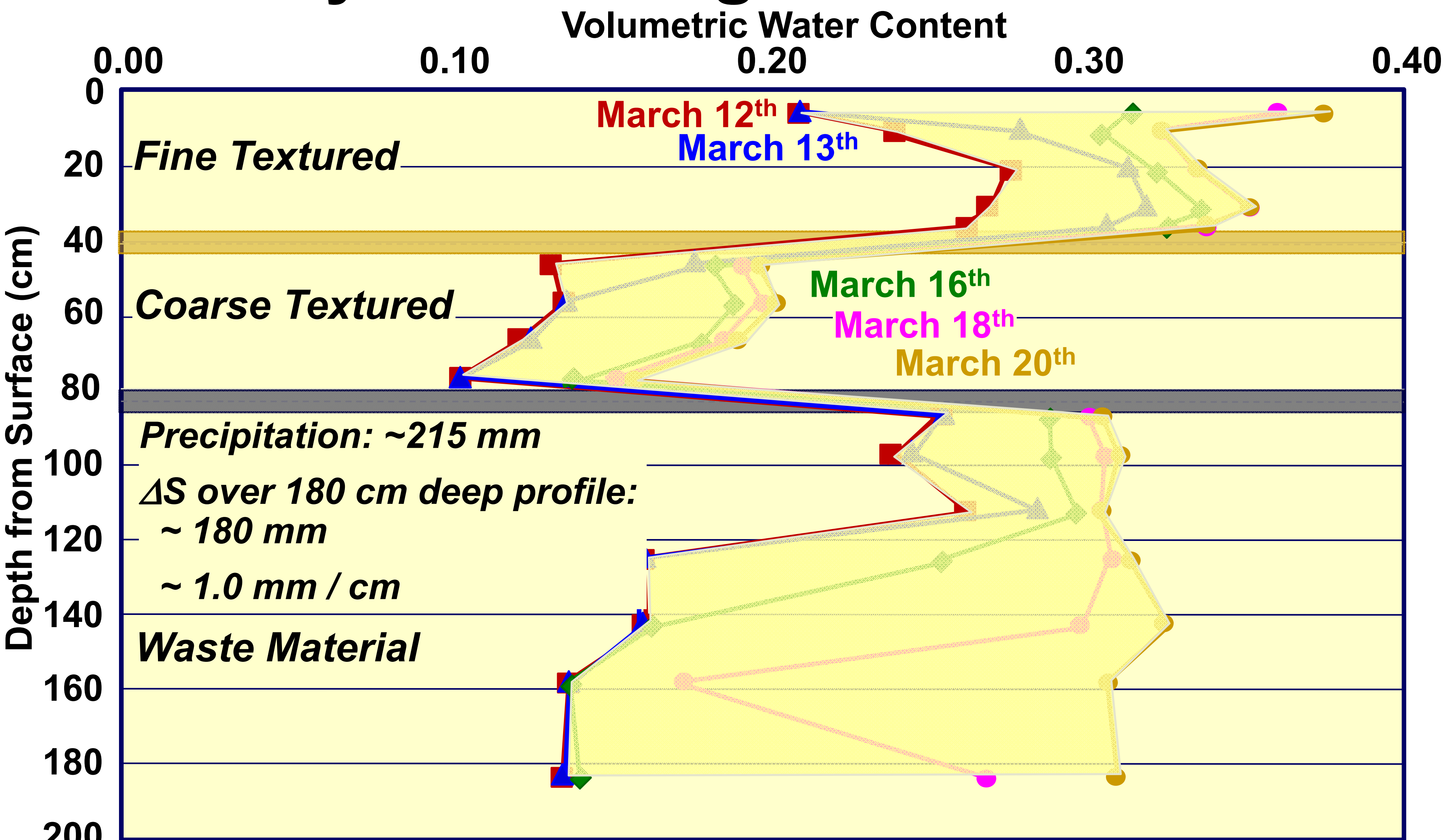
overlying

Coarse Textured Material



- ***Enhance moisture retention***
- ***Reduce net percolation***
- ***Mitigate against upward movement of salts etc.***

Cover System Design Alternatives



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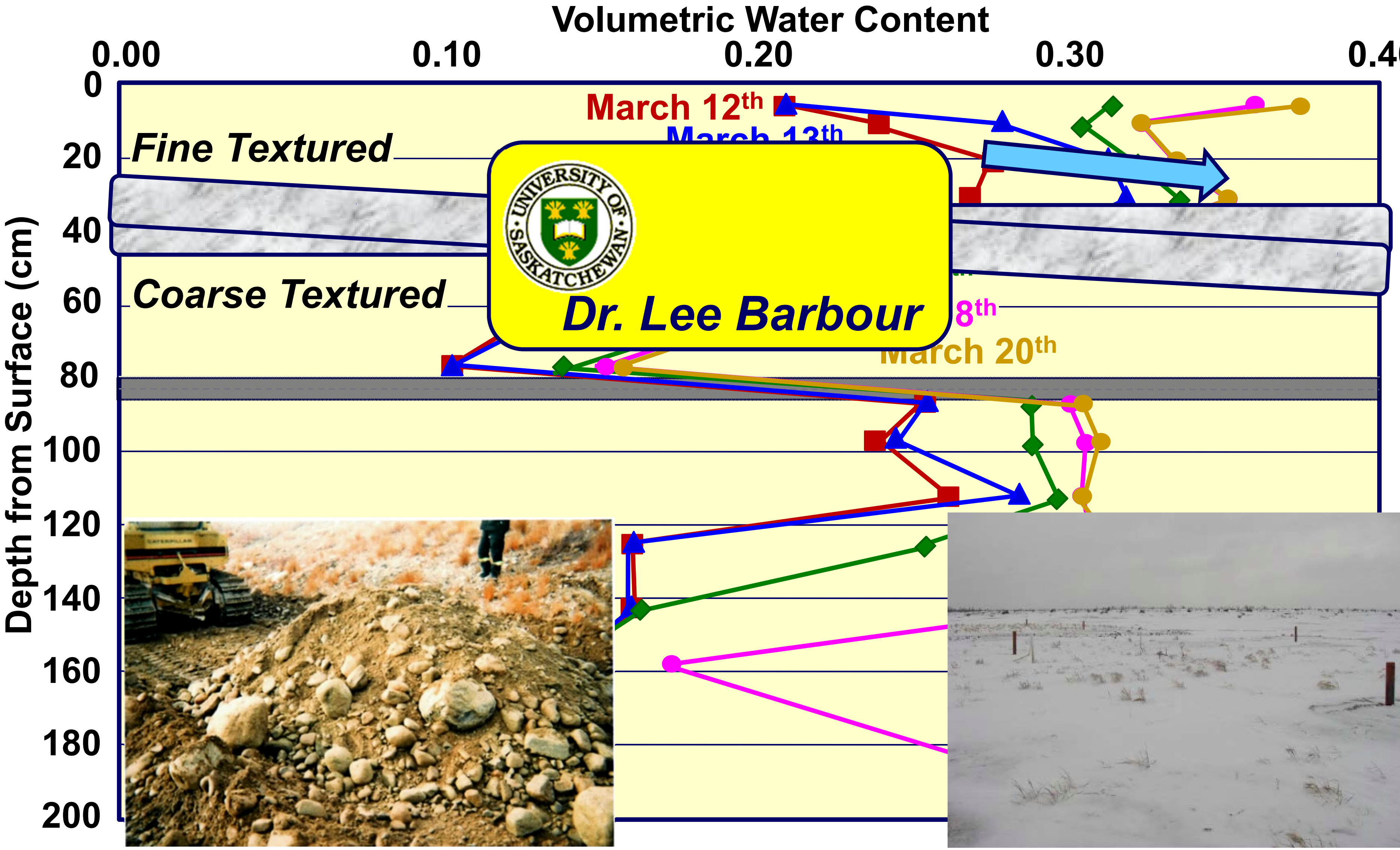
Taking Advantage……



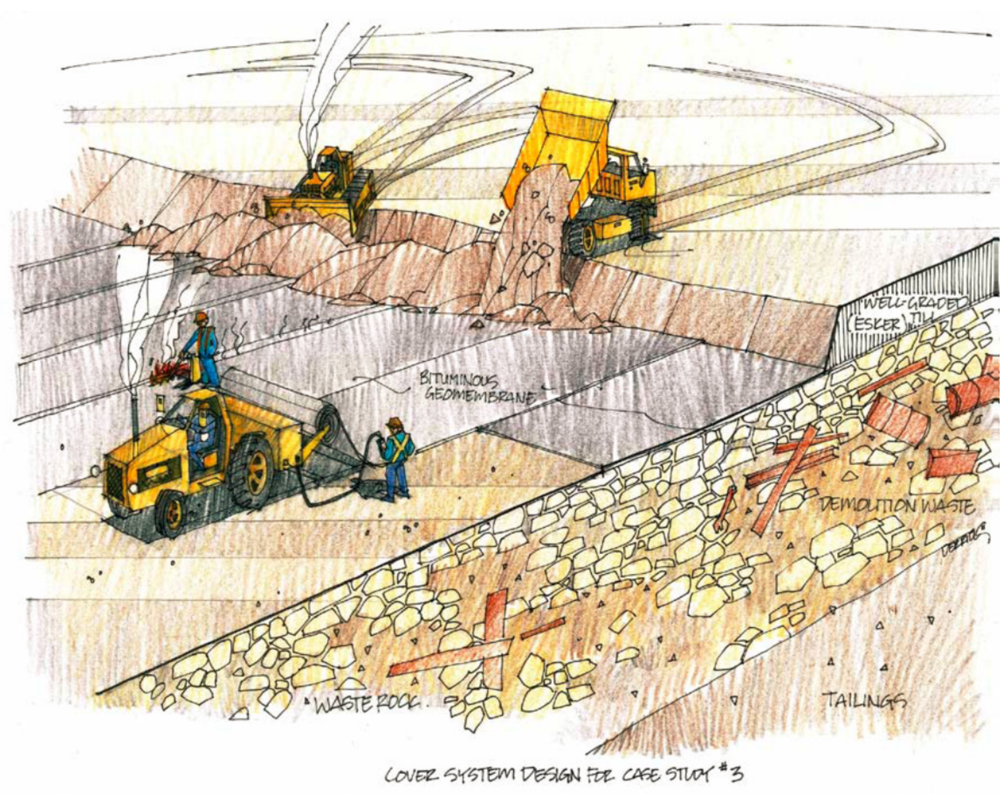
Seasonally Frozen Capillary Break Diversion (SFCBD)

Summary Discussion

- ***Document available at:***
  - ***www.mend-nedem.org***
  - ***MEND 1.61.5c***
- ***Taking Advantage….***
- ***Thermal (Energy) and Water Balance***
- ***FMEA Process***
- ***Design Life and Assessment Period***
  - ***Minimum of 100 year performance***
  - ***Risk-based approach: 1 in 1000***

Claypool (2009)

Example: Case Study #3



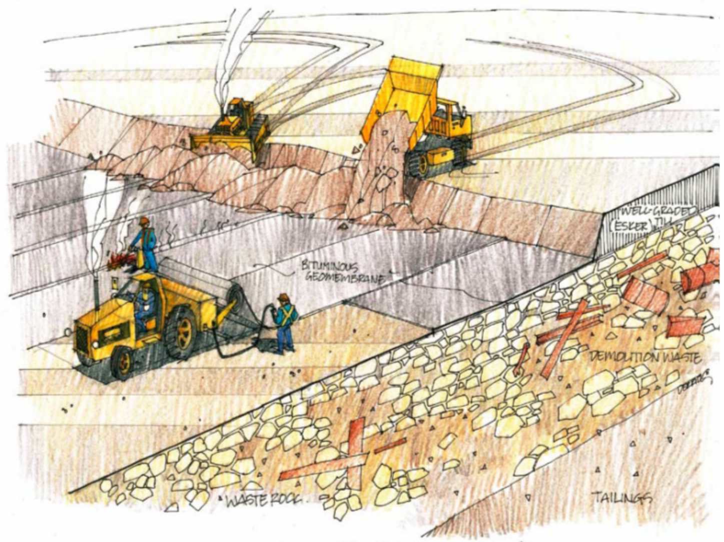
Failure Mode ID	Failure Mode Description	Effects and Pathways	High Concern Issue
1	Erosion due to rainfall and snowmelt to the extent that cover profile is breached	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	low
2	Erosion due to rainfall and snowmelt to the extent that cover performance does not meet design criteria	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	moderate
3	Erosion due to an extreme event to the extent that the cover profile is breached	Storm event causes erosion of cover and exposure of waste material. Loss of isolation and material (BUT THIS SHOULD not necessarily be CONSIDERED TO BE AN INSTANEOUS EVENT (first extreme event may cause the weakness and then a subsequent event results in the actual failure). Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	moderate
4	Erosion to the extent that spillway performance is degraded such that ponding and bypass occurs (spillway may be other than the dam spillway; it is simply a location where water is focused on the cover system to transport water off the cover surface)	Results in erosion extending back up into / onto the cover system and breach of the cover system, loss of isolation of tailings and transport of tailings into environment.	moderately high
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking	Expect deterioration leading to one-order magnitude higher NP than expected from intact (uncracked) BGM liner.	moderately high
6	Blockage of surface water drainage swales and/or channels due to sedimentation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
7	Blockage of surface water drainage swales and/or channels due to vegetation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
8	Blockage of surface water drainage swales and/or channels due to snow / ice	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	high
8a	Blockage of surface water drainage swales and/or channels due to animals (beavers)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	low
9	Alteration of surface water drainage swales and/or channels due to disruption (frost heave, settlement, including thermokarsts, etc.)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderately high
10	Cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support.	high
11	Inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increased seepage for the period of repair until repair occurs or could have chronic adverse impacts on performance latter being less likely.	moderately high
12	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover performance (net percolation), if vegetation is relied on to limit net percolation.	moderate
13	Cover detachment, slippage, sloughing and piping (assume underlying structure is stable)	Exposure of the waste material and/or degradation of cover system performance.	low
14	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover system performance. Potential for human harm.	low
15	Consolidation / settlement causing ponding	Potential for adverse effect on surface water management system(s) and ponding of water. Can enhance thaw consolidation. Challenges with cover material placement (soft tailings).	moderately high
16	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	low
17	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding / hummock formation	Solifluction may lead to the development of micro-topography, which would decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also affect runoff and infiltration rates and potentially vegetation growth.	moderate
18	Change in active layer depth due to climate change	Degradation of cover system performance.	moderate
19	Dispersion / erosion	Change in surface infiltration characteristics and enhanced erosion (lack of moisture for vegetation).	low
20	Burrowing animals	Focused infiltration and potential for increases in net percolation rates.	low
21	Vegetation effects (root penetration, blow down, etc.)	Focused infiltration and potential for increases in net percolation rates.	low
22	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher erosion rates, leading to breach of cover profile.	low
23	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher net percolation rates such that cover performance does not meet design criteria.	moderately high
24	Anthropogenic activity which leads to aids the formation of any of the above failure modes	Results in higher net percolation rates such that cover performance does not meet design criteria.	moderately high
25	Inappropriate inclusion of demolition waste in tailings impoundment	Results in damage to the BGM such as tearing, puncturing, etc.	

1. **Exposure of tailings**
2. **Surface water management and erosion**
3. **Glaciation**
4. **Frost Jacking**
5. **Constructibility**

Mitigation Methods: Case Study #3

1. Erosion to the extent that spillway performance is degraded and ponding and bypass occurs :

- Design erosion resistant channels leading into the spillway.
- Observe/measure cover performance under site climatic conditions.
- Inspection of cover following a storm event.
- Maintenance of rills/gullies.



COVER SYSTEM DESIGN FOR CASE STUDY #3

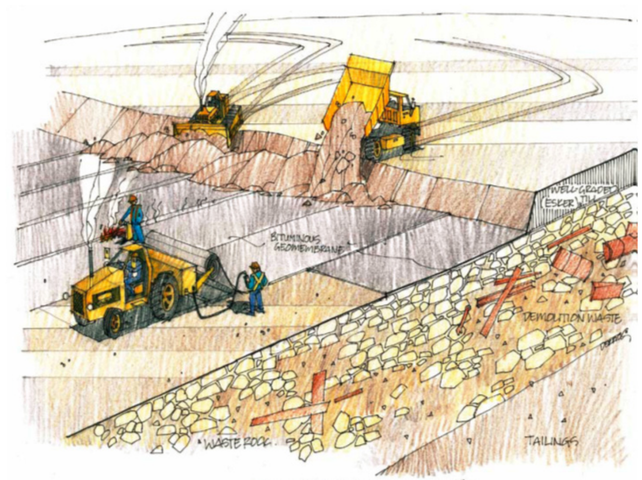
Mitigation Methods: Case Study #3

2. Surface water management:

- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.

From design perspective:

Increase design storm event criteria and re-design the landform and/or surface water management system.

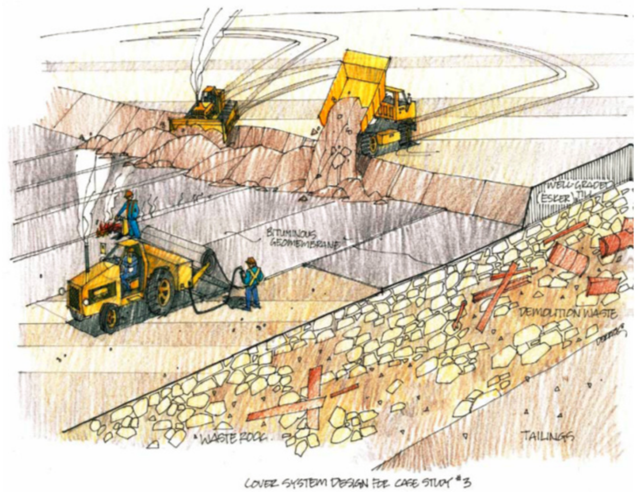


COVER SYSTEM DESIGN FOR CASE STUDY #3

Mitigation Methods: Case Study #3

3. Glaciation:

- Design wider channels and include erosion protection in swales;
- Construct erosion resistant channels leading into the spillway;
- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.



COVER SYSTEM DESIGN FOR CASE STUDY #3

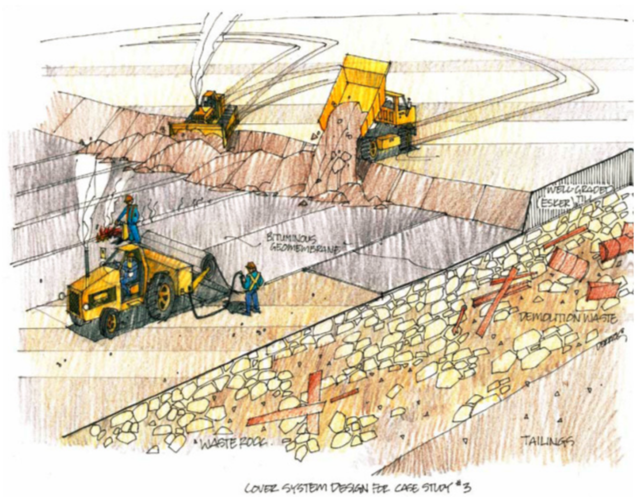
Mitigation Methods: Case Study #3

4. Freeze/thaw cycles, wet/dry settlement, and development of hummocks leading to cracking of the cover:

- **Inspect landform at regular intervals; and**
- **Perform routine maintenance to repair cracks.**

From design perspective:

Incorporate change in hydraulic characteristics of cover materials due to frost action into the design.



COVER SYSTEM DESIGN FOR CASE STUDY #3

Mitigation Methods: Case Study #3

5. Cover system constructability:

- No way to reduce these expected costs.
- TAG's recommendation for mitigation is limited to a change in cover design to avoid these constructability issues.