Mine Tailings Fundamentals: Current Technology and Practice for Mine Tailings Facilities Operations and Closure Part 1 – Mine Tailings Facility Design and Operations

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Course Outline

What are Mine Tailings?

- Types of Mine Tailings,
- Characteristics of Mine Tailings

How are Mine Tailings Stored?

- Past, Present and Future Practice

What are the critical features to consider in locating and designing mine tailings facilities?

- Hydrology
- Hydrogeology
- Geotechnical
- Construction Quality Control
- Designing for Closure
- Tailings Facility Hazard Rankings
- Other

How are tailings facilities constructed and operated?

- Construction Approaches
    - Centerline
    - Upstream
    - Downstream
    - Paste Tailings
    - Dry Stack Tailings
    - Lined or Unlined?
    - Which one is the right one???

Course Outline

What are the primary issues with operating tailings facilities?

- Seepage
- Dust
- Long-Term Liability
- Catastrophic Failures

What can be done to prevent future events like Mount Polley in British Columbia?

- The Mount Polley tailings breach – what took place
- Independent Expert Panel Findings
  - Site Characterization
  - Adherence to FOS
  - Minimization of Operating Pond Levels
- Independent Expert Panel Recommendations

Where should I go if I want to know more about tailings facility design and operations?

What are Mine Tailings?

Tailings are the waste materials left over after separating the valuable metals or minerals from an ore.

Types of Mine Tailings

- Gravity Process Tailings
- Flotation Process Tailings
- Leach Process Tailings
- Includes but not limited to tailings from copper, gold, iron, lead, rare earth, phosphate, platinum group, silver, uranium and zinc processing
- Waste rock and overburden are not Tailings

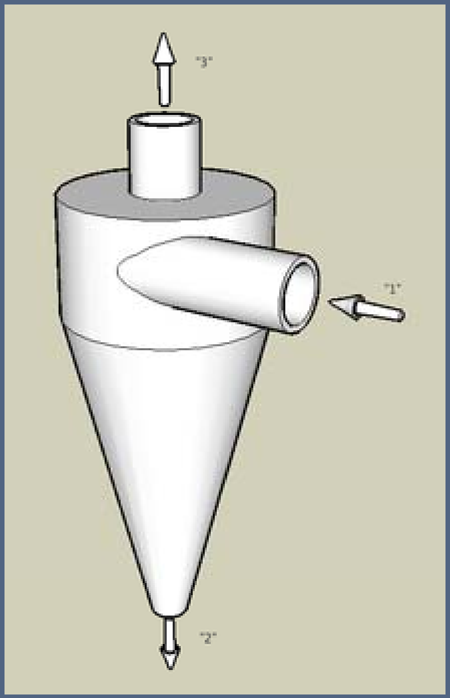
Mine Tailings – Subaerial Deposition

Photo Courtesy of Jack Caldwell

Mine Tailings – Subaqueous Deposition

Mine Tailings – Cycloning

Photo Courtesy of Jack Caldwell



Wikipedia

Mine Tailings – Thickened/Paste

Frank Palkovits Photo

Comparison of Tailings Features			
Type	**% Solids**	**Strength**	**Power Consumption**
Conventional	40-60%	Low	Low
High Density	55-70%	Moderate	Low
Paste	75-85%	High	Moderate
Filtered	>90%	Very High	Very High

Mine Tailings – Dry Stack (Filter Pressed)

Photo Courtesy of Jack Caldwell – Greens Creek Mine, AK

Mine Tailings – Co-Disposal with Waste Rock

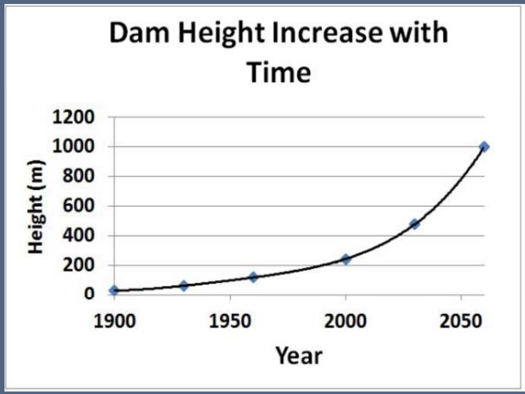
Table 6-2: Benefits and Considerations of Co-Disposal

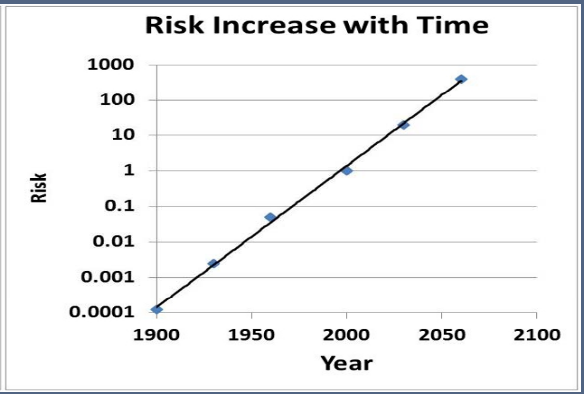
Additional Benefits	Considerations
•Minimization of footprint or volume required for disposal •Physical stability •Possible use as cover material •Possible elimination of the tailings dam •Creation of an elevated water table within deposits	•Waste production schedule and sequencing •Proportions of waste rock to tailings, or strip ratio •PAG/NAG ratio •Erodibility of gap graded mixtures •Methods for mixing and placement with respect to maximum particle size •Limitations on future remining of tailings

From GARD Guide

How are Mine Tailings Stored?

Mine Tailings Deposition - Past, Present and Future Practice		
Past Practice	**Present Practice**	**Future Practice**
Incidental in nature due to site-specific objectives and requirements	Results from engineering and regulatory objectives and requirements based on local practice	Results from use of Best Professional Technology and Best Professional Practice augmented by regulatory objectives and requirements
Primarily subaerial with various levels of engineered containment	Utilizes a wide variety of deposition methods	Utilizes primarily methods which eliminate storage of water in TSFs such as paste and dry stack tailings
Highly susceptible to seepage and catastrophic events	Less susceptible but significant potential for catastrophic events and seepage depending on method	Zero tolerance for catastrophic events although they will still be possible and improved methods of controlling seepage
Difficult to reclaim and close	Typically reclamation and closure is considered as part of project design and is reasonably achievable	Reclamation and closure will always be integrated into project planning and will be incoporated simultaneously with processing



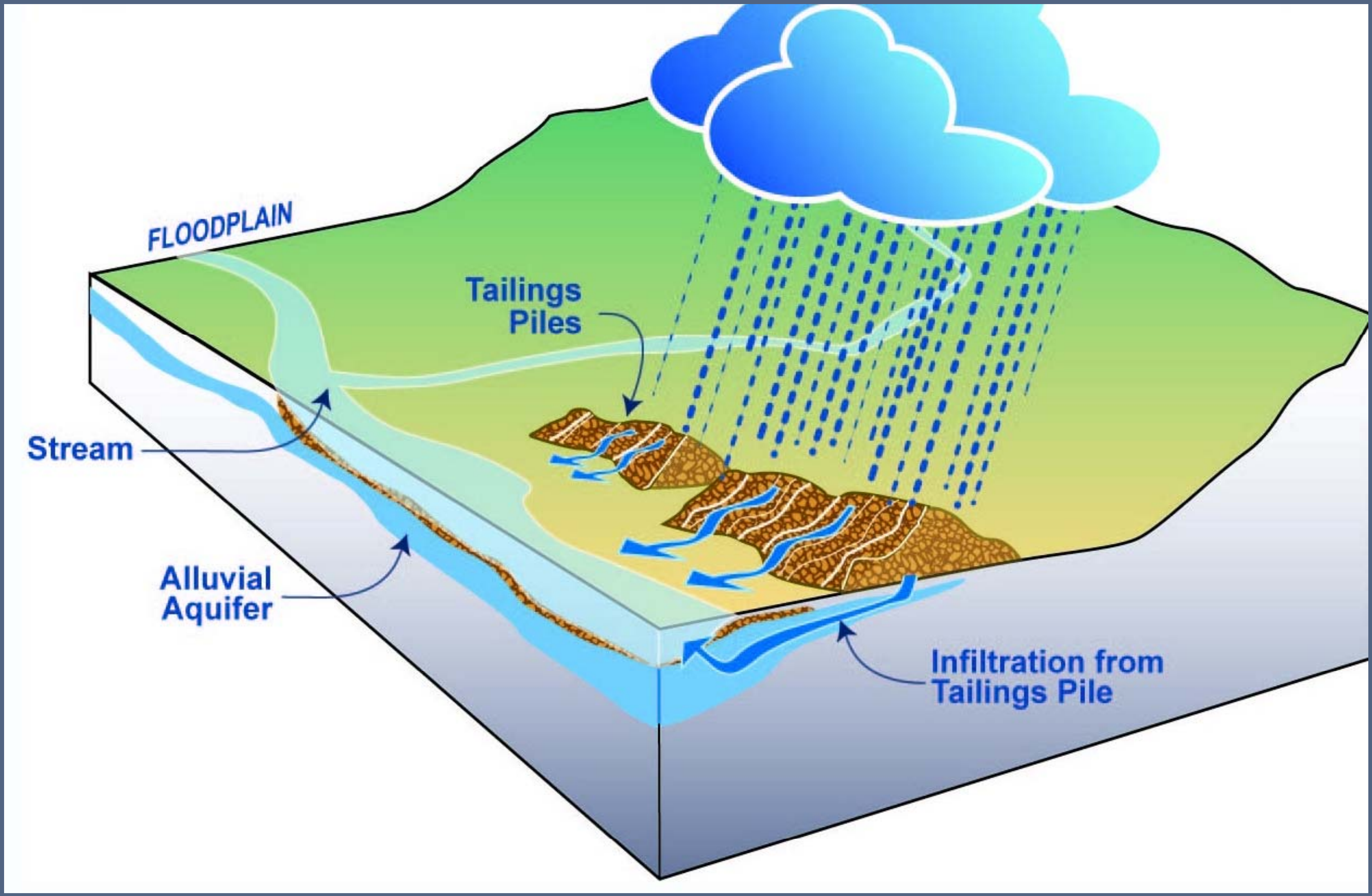


From A. Robertson

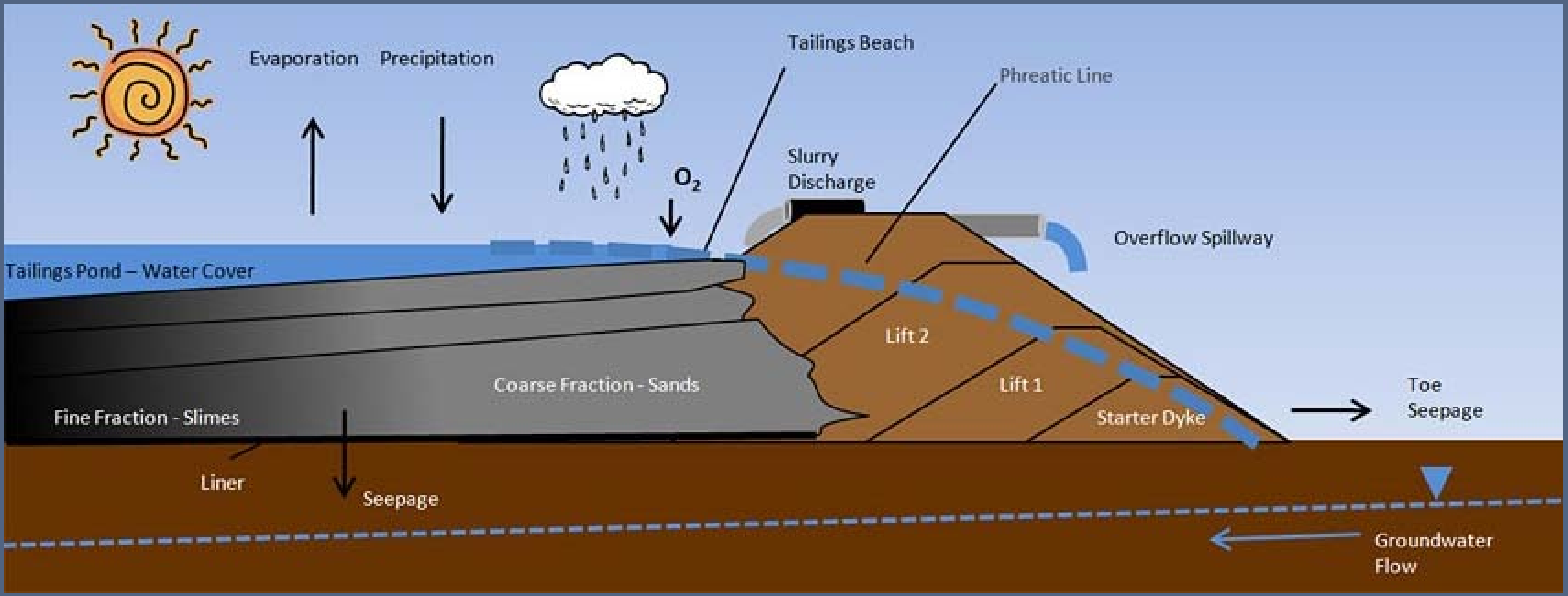
What are the critical features to consider in locating and designing mine tailings facilities?

- Hydrology
- Hydrogeology
- Geotechnical
- Geochemical
- Construction and Operation
- Designing for Closure
- Tailings Facility Hazard Rankings
- Other Considerations

Mine Tailings - Hydrology



Mine Tailings - Hydrogeology



From GARD Guide

Mine Tailings - Geotechnical

Recommended References: Edumine *Geotechnical Engineering for Mine Geowaste Facilities* by J. Caldwell

Common Tests

- Atterberg Limits – Liquid, Plastic and Shrinkage Limits
- Particle Specific Gravity
- Gradation

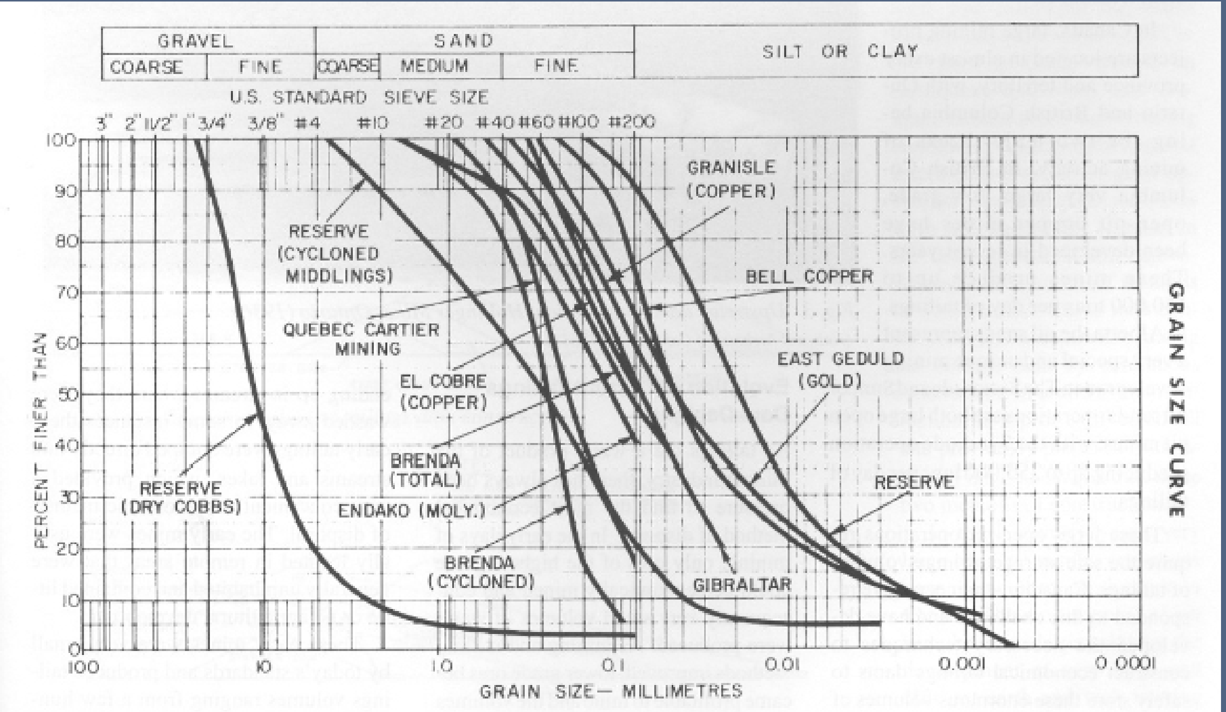


Fig. 1. Typical tailings grain size curves.

Mine Tailings - Geotechnical

<u>Common Tests</u>

- Permeability (Hydraulic Conductivity)
- Density
- Strength
- Compaction
- Consolidation
- Rheology

Major Stratigraphic Unit	Stratigraphic Sub-Unit	Consistency	Undrained Shear Strength from In Situ Vanes	CPT qt (Bars)	SPT N	LPT N	Color	Moisture Content	Plasitic Limit	Liquid Limit	Plasticity Index	Liquidity Index	Gradation	Classification
Upper Till		Firm to Hard	Inconclusive due to gravel	10 - 120	5 - 20	8 - 25	Grey-Brown to Grey	5 - 30	10 - 20	20 - 40	5 - 20	0 - 0.2	Gravel 5 - 30%, Sand 25 - 40%, Fines 35 - 65%	SC/GC to CL to GM
Upper Glaciolacustrine (Upper GLU)		Firm to Stiff	Peak 90 - 140 kPa Residual 40 to 65 kPa Remolded 20 - 35 kPa	10 - 35	-	5 - 9	Grey	15 - 40	10 - 25	20 - 70	10 - 50	0.4 - 0.7	Gravel 0 to 5%, Sand 0 - 20%, Fines 80 - 100%	CL to CH
Lower Tills	Lower Basal Till	Very Stiff to Hard / Very Dense	Inconclusive due to gravel	20 - 215	-	-	Grey	5 - 20	10 - 20	20 - 40	5 - 20	0 - 0.1	Gravel 10 - 40%, Sand 30 - 50%, Fines 30 - 60%	SC to GC
	Lower Glaciolacustrine (Lower GLU)	Very Stiff to Hard	-	35 - 200	-	40 - 60	Grey to Brown	10 - 30	15 - 25	30 - 50	10 - 30	0.1 - 0.4	Gravel 0 - 5%, Sand 0 - 15%, Fines 85 - 100%	CL to CL/ML
	Glaciofluvial	Compact to Very Dense	-	80 - 270	-	-	Grey to Brown	10 - 25	-	-	-	-	Gravel 0 - 60%, Sand 20 - 95%, Fines 5 - 80%	GP/SP to SM to ML
	Lower Basal Till	Very Stiff to Hard / Very Dense	-	100 - 300	-	-	Highly variable	5 - 30	-	-	-	-	Gravel 10 - 40%, Sand 30 - 50%, Fines 30 - 60%	SC to GC
Weak Bedrock		Hard Soil / Weak Rock	-	100 - 300	-	-	Highly variable	5 - 55	-	-	-	-	Gravel 0 - 90%, Sand 0 - 90%, Fines 10 - 100%	GM to ML to CH

Ranges given are general and may not be exclusive. Refer to laboratory results and test hole logs for complete information.
Consistency descriptions from CPT and Vane Shear test data, not from visual observations of disturbed core.
Text in red is estimated from field descriptions of sonic core without laboratory results.

<u>Geotechnical Properties Summary Table – Mt Polley TSF Foundation</u>

Mine Tailings - Geotechnical

Stability Analysis

- Static
  - Foundation
  - Tailings
  - Embankment materials
  - Seepage
- Seismic
  - Magnitude
  - Distance to fault
  - Soil conditions
  - Tailings
  - Disposal method

Mine Tailings – Geochemical

- Mining Influenced Water
  - Acid Drainage
    - Reduced pH
    - Elevated sulfates and metals
  - Neutral and Saline Drainage
    - Increased pH
    - Elevated TDS and metals (arsenic, selenium, other negative charged metals)
  - Chemical Influenced Drainage
    - Cyanide
    - Sulfuric Acid
    - Other
  - Long-term
    - Drainage
    - Degradation of physical properties

Mine Tailings – Construction and Operation

- Construction Oversight
- Construction QA/QC
- Operations
  - Mining Association of Canada (MAC) Guides.
    - A Guide to the Management of Tailings Facilities
    - Operation, Maintenance, and Surveillance Manual
    - A Guide to Audit and Assessment of Tailings Facility Management

Mine Tailings - Tailings Facility Hazard Rankings
US Dept of Homeland Security - FEMA

US FEMA - Federal Guidelines for Dam Safety Hazard Potential Classification System for Dams		
Hazard Potential Classification	**Loss of Human Life**	**Economic, Environmental, Lifeline Losses**
Low	None expected	Low and generally limited to owner
Significant	None expected	Yes
High	Probable. One or more expected	Yes (but not necessary for this classification)

Mine Tailings - Tailings Facility Hazard Rankings
Canadian Dam Association

Table 2-1: Dam Classification

Dam class	Population at risk [note 1]	Incremental losses		
		Loss of life [note 2]	Environmental and cultural values	Infrastructure and economics
Low	None	0	Minimal short-term loss No long-term loss	Low economic losses; area contains limited infrastructure or services
Significant	Temporary only	Unspecified	No significant loss or deterioration of fish or wildlife habitat Loss of marginal habitat only Restoration or compensation in kind highly possible	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes
High	Permanent	10 or fewer	Significant loss or deterioration of *important* fish or wildlife habitat Restoration or compensation in kind highly possible	High economic losses affecting infrastructure, public transportation, and commercial facilities
Very high	Permanent	100 or fewer	Significant loss or deterioration of *critical* fish or wildlife habitat Restoration or compensation in kind possible but impractical	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	Major loss of *critical* fish or wildlife habitat Restoration or compensation in kind impossible	Extreme losses affecting critical infrastructure or services (e.g., hospital, major industrial complex, major storage facilities for dangerous substances)

Note 1. Definitions for population at risk:

None—There is no identifiable population at risk, so there is no possibility of loss of life other than through unforeseeable misadventure.

Temporary—People are only temporarily in the dam-breach inundation zone (e.g., seasonal cottage use, passing through on transportation routes, participating in recreational activities).

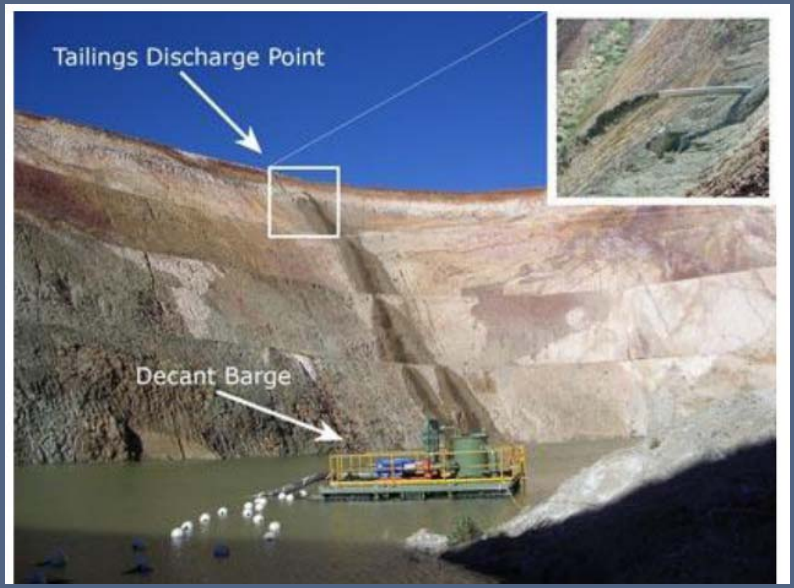
Permanent—The population at risk is ordinarily located in the dam-breach inundation zone (e.g., as permanent residents); three consequence classes (high, very high, extreme) are proposed to allow for more detailed estimates of potential loss of life (to assist in decision-making if the appropriate analysis is carried out).

Note 2. Implications for loss of life:

Unspecified—The appropriate level of safety required at a dam where people are temporarily at risk depends on the number of people, the exposure time, the nature of their activity, and other conditions. A higher class could be appropriate, depending on the requirements. However, the design flood requirement, for example, might not be higher if the temporary population is not likely to be present during the flood season.

Mine Tailings – Other Considerations

- Climate
- Terrain
- Use of Open Pits
- Return Water Facilities



How are tailings facilities constructed and operated?

Tailings Discharge Systems

Construction Approaches

- Upstream
- Centerline
- Downstream
- Paste Tailings
- Dry Stack Tailings
- Lined or Unlined?
- Which one is the right one???

Mine Tailings – Tailings Discharge Systems

Table 1: Tailings discharge systems

Means of Tailings Discharge	Advantages	Disadvantages
Single/point	ease of installation/operation	cone formation and non-uniform stacking near spigot; fluctuations in the slurry SG may cause beach erosion
Multiple	ease of installation/operation; improved cell coverage vs. single	unbalanced outflow from spigots due to pipe losses
Continuous/linear	lateral cell coverage; emulates sheet flow	pipeline blockages; lower flow rate per spigot may not provide adequate down-gradient coverage
Radial	cell coverage	slightly more complicated distribution line vs. single/multiple

Table Courtesy of Jack Caldwell

Mine Tailings – Upstream, Centerline and Downstream Construction

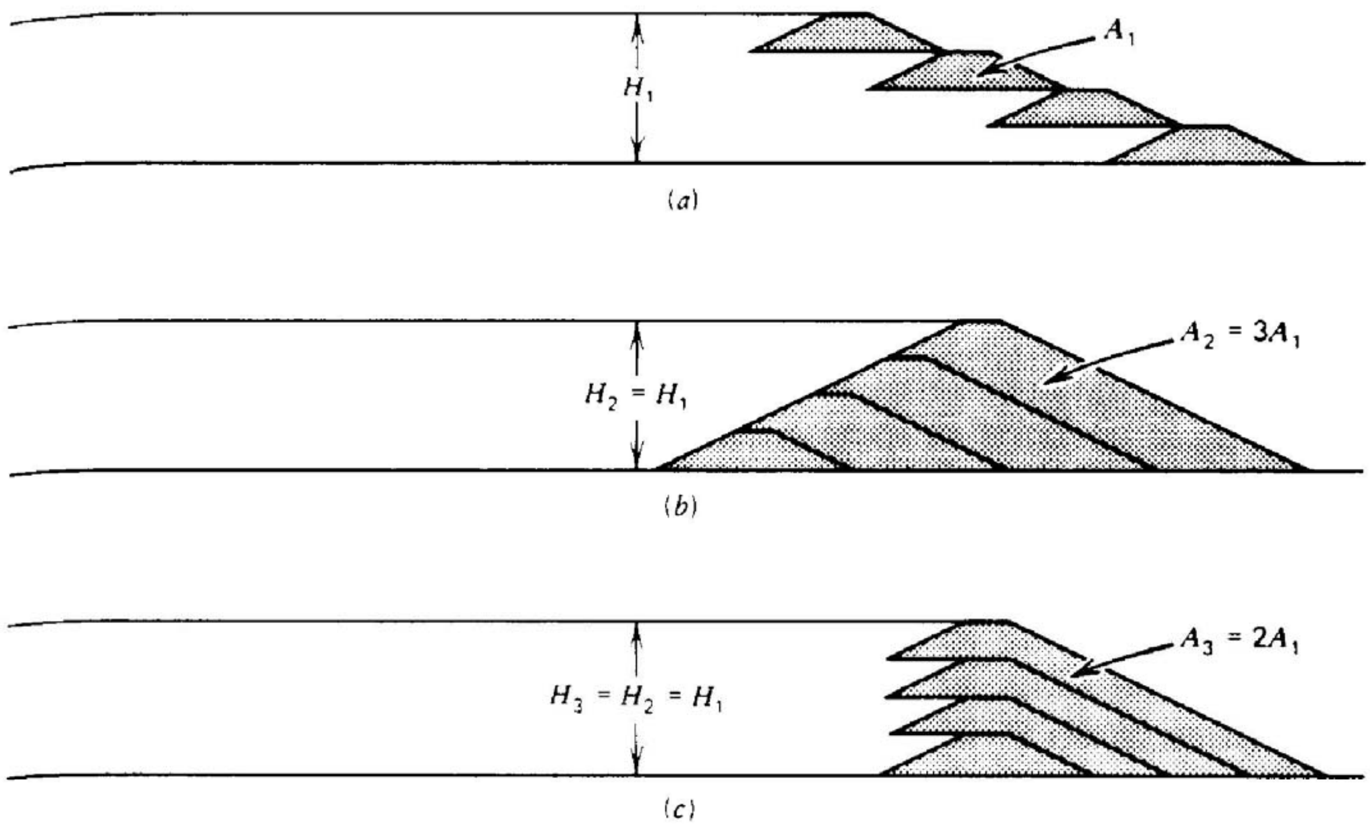


Figure 2. Embankment Types: (a) Upstream, (b) Centerline, (c) Downstream or Water Retention Type

(Source: Vick 1990)

Mine Tailings – Paste and Dry Stack Tailings Construction

Dave Chambers, CSP2 (2004) – Pogo Mine, AK Dry Stack Facility

Mine Tailings – Lined or Unlined

What are the primary issues with operating tailings facilities?

- Design
- Seepage
- Dust
- Long-Term Liability
- Catastrophic Failures

Mine Tailings - Design

- Basic Requirements
  - Obey the laws of physics
    - Aka gravity and stability
  - Stuff happens
    - Earthquakes and other catastrophic events
  - Time will take its toll
    - Erosion and other long-term impacts will take place
  - Water management!!!
  - Economic feasibility
    - Is the least cost option the least cost option?
- Laws and Regulations

Mine Tailings - Design

Dealing with Uncertainty and the Observational Method

Ralph B. Peck (1969), Advantages and limitations of the observational method in applied soil mechanics

- Sufficiently explore to establish at least the general nature, pattern, and properties of the deposits, but not necessarily in detail.
- Assess the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.
- Establish a design based on a working hypothesis of behaviour anticipated under the most favourable conditions.
- Select quantities to be observed as construction proceeds, and calculate their anticipated values on the basis of the working hypothesis.
- Calculate the value of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
- In advance, select a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
- Measure quantities to be observed, and evaluate actual conditions.
- Modify the design to suit actual conditions.

Mine Tailings - Seepage

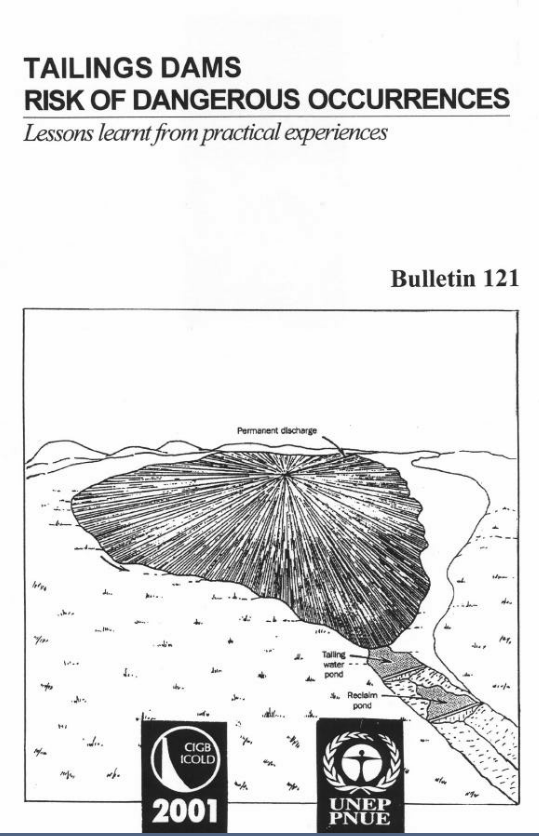
- Key terms
  - Infiltration – water that seeps into tailings
  - Through-flow – water that seeps through tailings
  - Exfiltration – water that seeps from tailings
- Types of Seepage
  - Beach infiltration
  - Pool infiltration
  - Exfiltration
- Groundwater Impacts
- Water Balance

Mine Tailings - Dust

Mine Tailings – Long-Term Liability

- Release of contaminants to groundwater
- Release of contaminants and tailings to surface water
- Dust prevention
- Institutional Controls
- Maintenance requirements
  - Cover/vegetation
  - Stormwater conveyances
  - Access

Mine Tailings – Catastrophic Failures



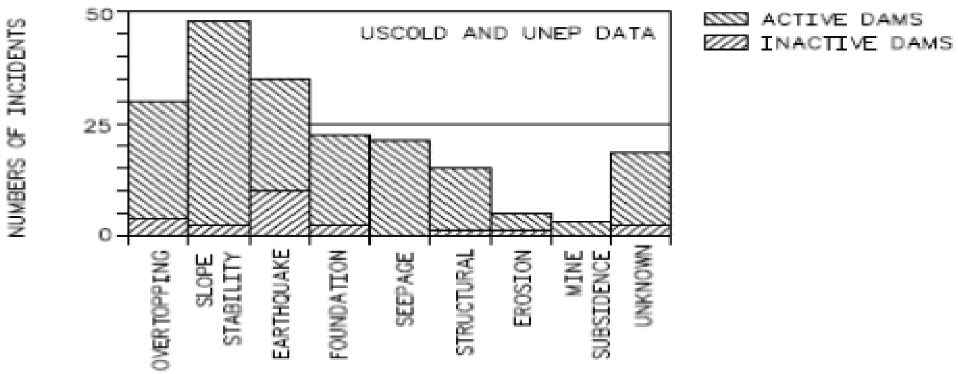


Figure 7. Tailings dam incident cause comparison with dam status.

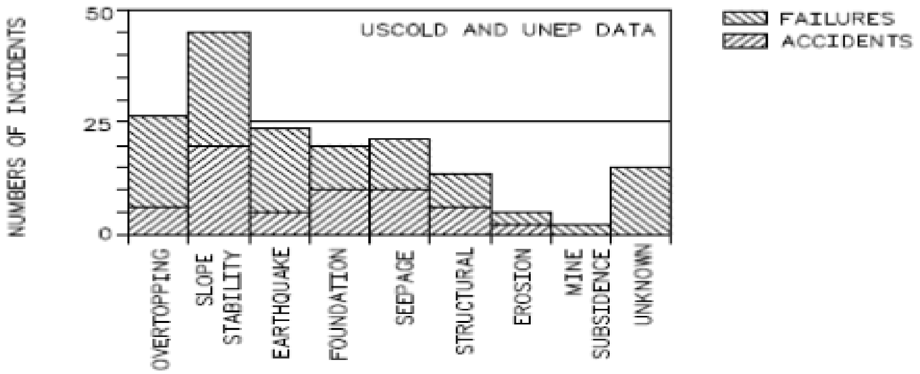


Figure 8. Tailings dam incident cause comparison with incident type for active dams.

Mount Polley Tailings Breach, British Columbia

The Mount Polley tailings breach – what took place

- Mount Polley tailings storage facility used to store copper-gold flotation tailings
- On August 4, 2014 the Mount Polley Mine tailings storage facility (TSF) breached releasing an estimated 15 million cubic meters of tailings and water.
- On August 18, 2014, an independent review panel of three geotechnical experts was established to investigate into and report on the breach of the TSF.
- On January 30, 2015, the panel delivered its final report and recommendations "Independent Expert Engineering Investigation and Review Mount Polley Tailings Storage Facility Breach" to the British Columbia Minister of Energy and Mines, the Williams Lake Indian Band and the Soda Creek Indian Band.
- The full report, appendices and background material are available at https://www.mountpolleyreviewpanel.ca/

Mount Polley Tailings Breach

Mount Polley Tailings Breach

Independent Expert Panel Findings

- The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the TSF foundation.
- Foundation investigations and associated site characterization failed to identify a continuous GLU layer in the vicinity of the breach and to recognize that it was susceptible to undrained failure when subject to the stresses associated with the embankment.
- The specifics of the failure were triggered by the construction of the downstream rockfill zone at a steep slope of 1.3 horizontal to 1.0 vertical.
- Had the downstream slope in recent years been flattened to 2.0 horizontal to 1.0 vertical, as proposed in the original design, failure would have been avoided. The slope was on the way to being flattened to meet its ultimate design criteria at the time of the incident.

What can be done to prevent future events like Mount Polley in British Columbia?

Independent Expert Panel Recommendations

1. PERFORMANCE OF B.C. TAILINGS DAMS

"...the Panel may make recommendations to government on actions that could be taken to ensure that a similar failure does not occur at other mine sites in B.C."

"…statistically there is approximately a 1-in-600 chance of a tailings dam failure in any given year, based on historical performance over the period of record. While these numbers may seem small, their implications are not."

The Panel firmly rejects any notion that business as usual can continue.

What can be done to prevent future events like Mount Polley in British Columbia?

Independent Expert Panel Recommendations

2. GETTING TO ZERO

"In risk-based dam safety practice for conventional water dams, some particular level of tolerable risk is often specified that, in turn, implies some tolerable failure rate. The Panel does not accept the concept of a tolerable failure rate for tailings dams. To do so, no matter how small, would institutionalize failure. First Nations will not accept this, the public will not permit it, government will not allow it, and the mining industry will not survive it."

"Clearly, improvements to current practice provide an essential starting point on the path to zero failures. But the Panel's evaluation of portfolio risk shows that incremental changes will not be sufficient to achieve this objective."

<u>The path to zero needs an added dimension, and that dimension is technology.</u>

What can be done to prevent future events like Mount Polley in British Columbia?

Independent Expert Panel Recommendations

3. BEST AVAILABLE TAILINGS TECHNOLOGY

9.3.1 BAT PRINCIPLES

"BAT has three components that derive from first principles of soil mechanics:

1. Eliminate surface water from the impoundment.
2. Promote unsaturated conditions in the tailings with drainage provisions.
3. Achieve dilatant conditions throughout the tailings deposit by compaction."

9.3.2 BAT METHODS

"The overarching goal of BAT is to reduce the number of tailings dams subject to failure. This can be achieved most directly by storing the majority of the tailings below ground—in mined-out pits for surface mining operations or as backfill for underground mines." "Apart from this, surface storage using filtered tailings technology is a prime candidate for BAT."

What can be done to prevent future events like Mount Polley in British Columbia?

Independent Expert Panel Recommendations

3. BEST AVAILABLE TAILINGS TECHNOLOGY

9.3.4 BAT RECOMMENDATIONS

For existing tailings impoundments. Constructing filtered tailings facilities on existing conventional impoundments poses several technical hurdles. Chief among them is undrained shear failure in the underlying saturated tailings, similar to what caused the Mount Polley incident. Attempting to retrofit existing conventional tailings impoundments is therefore not recommended, with reliance instead on best practices during their remaining active life.

For new tailings facilities. BAT should be actively encouraged for new tailings facilities at existing and proposed mines. Safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor.

What can be done to prevent future events like Mount Polley in British Columbia?

Independent Expert Panel Recommendations

4. BEST APPLICABLE PRACTICES (BAP)

9.4.1 CORPORATE GOVERNANCE

Towards Sustainable Mining (TSM) initiative launched by MAC in 2004.

"…these programs should not instill a sense of overconfidence and cannot themselves be seen as a substitute for more fundamental changes in technology."

9.4.2 CORPORATE TSF DESIGN RESPONSIBILITIES

"The Panel would require a bankable feasibility study and related permit application to have considered all technical, environmental, social and economic aspects of the project."

9.4.3 INDEPENDENT TAILINGS REVIEW BOARD (ITRB)

9.4.4 MINISTRY OF ENERGY AND MINES (MEM)

9.4.5 PROFESSIONAL PRACTICE

9.4.6 CANADIAN DAM ASSOCIATION (CDA) GUIDELINES

Where should I go if I want to know more about tailings facility design and operations?

- Infomine/Edumine
- Canadian Dam Association/Canadian Mining Association
- US ACOE and FEMA
- State Dam Safety Regulations
- Mt Polley Independent Review Panel Site


QUESTIONS? COMMENTS?