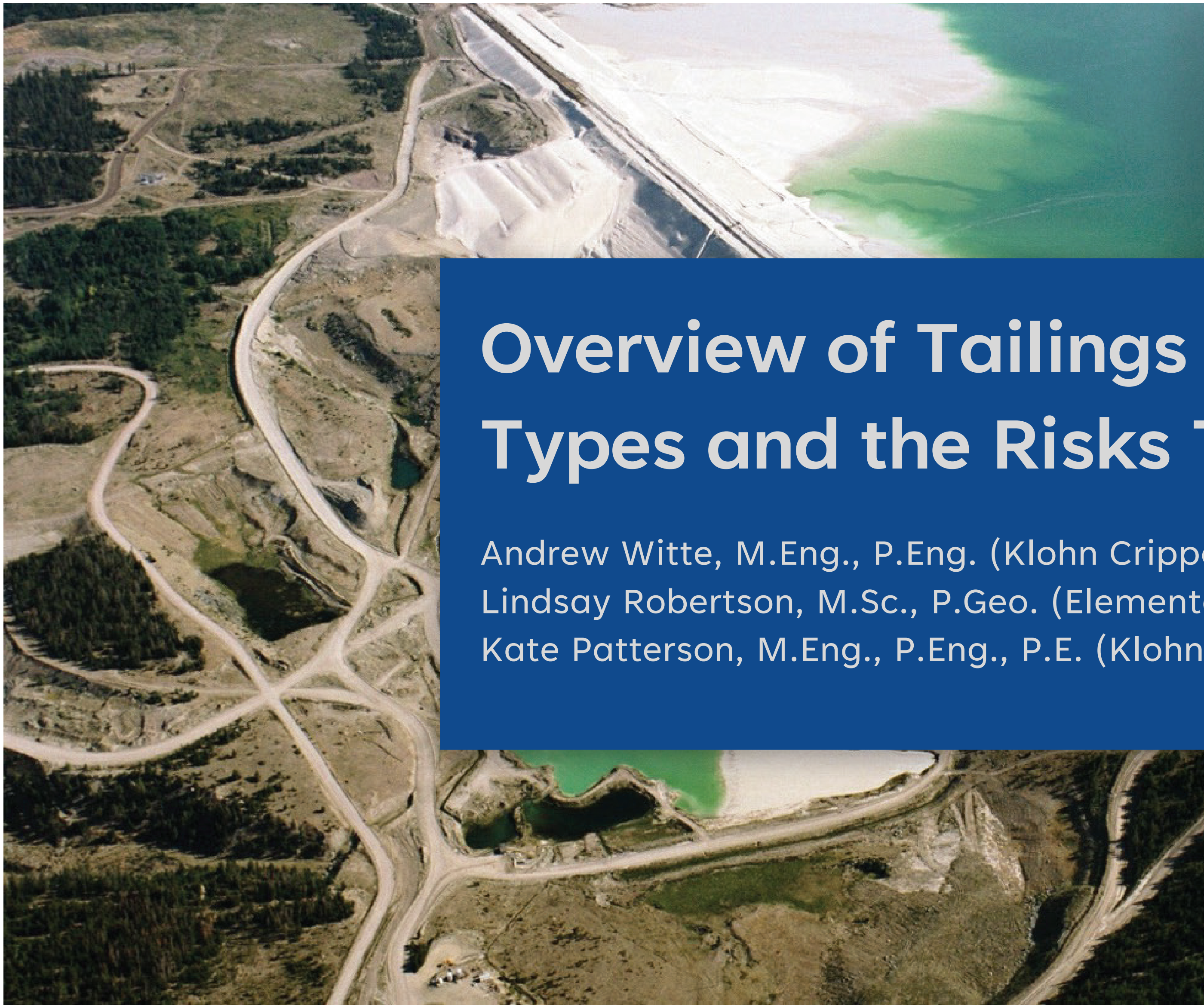


Overview of Tailings Facility Types and the Risks They Pose

Andrew Witte, M.Eng., P.Eng. (Klohn Crippen Berger)
Lindsay Robertson, M.Sc., P.Geo. (Elemental Geoscience)
Kate Patterson, M.Eng., P.Eng., P.E. (Klohn Crippen Berger)

Klohn Crippen Berger

Elemental Geoscience

Key Take Aways

There is no "one size fits all" solution to tailings management

Tailings management has risks, no matter what we do

There are good, established processes out there for assessing risks

There are good, established processes out there for effective decision making for tailings management

A good process for risk assessment and decision making is multi-disciplinary

Outline

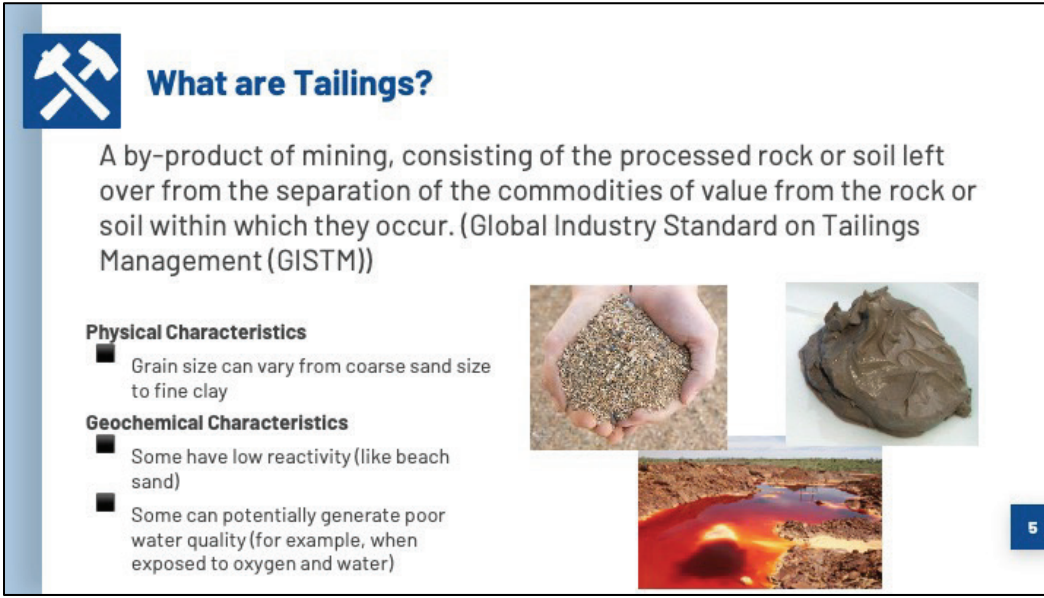
Part I – Introduction to Tailings and Risks

1. Types and Characteristics of Tailings
2. Types of Tailings Facilities and Risks

Part II – Risk Assessment and Decision Making

1. Risk Assessments for TSFs
2. Risk-Informed Decision Making

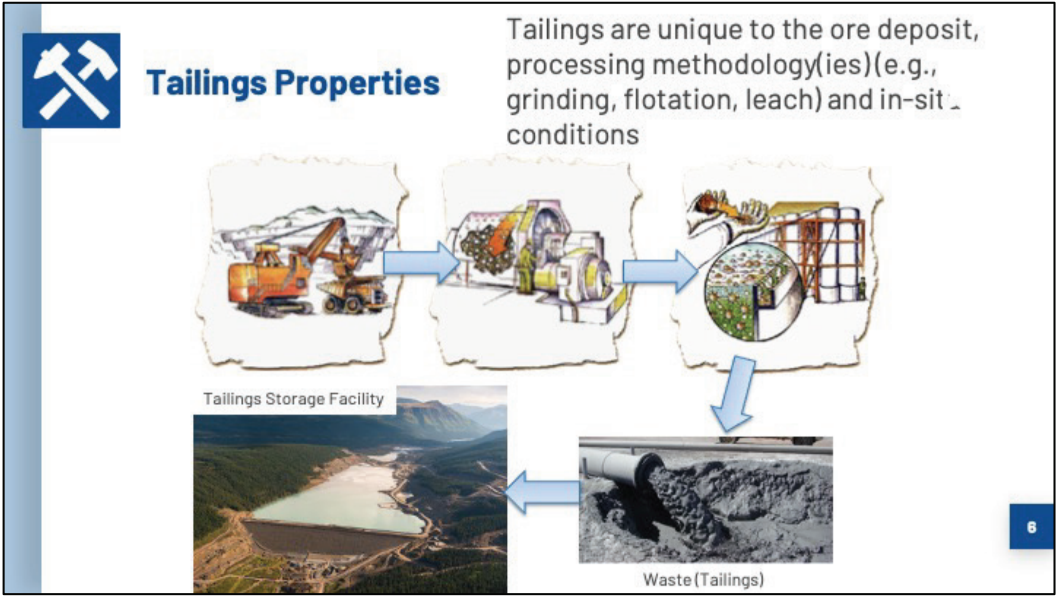
1. Types and Characteristics of Tailings



Large challenge. Engineering/science required to not become an environmental/public safety problem.

Processing is important because...

Grind size, ore body, clay content, production – tailings properties (how it can be used, e.g., Cycloning or how it behaves in the TSF)



https://www.mining-technology.com/news/trigon-produces-copper-kombat-mine/

Tailings Geochemical Properties

Parameter	Why do we care?
Minerology	Tailings mineralogy identifies components of minerals that contribute to acidity and neutralization and also provide an indication of the potential reactivity and elements that may be released.
Acid Base Accounting	The speciation of sulfur, carbon, and determination of neutralization potential and paste pH support the evaluation of either net neutral or acidic drainage over the life of the facility.
Elemental Analyses	Identifies the total elemental reservoir of a material and supports the identification of potential constituents of interest.
Leachate Testing	Static and kinetic testing to understand the leachable elements under different test conditions (i.e. SFE, NAG Leach, Kinetic Testing, etc.)

Big picture – geochemical properties of the tailings will influence the understanding of how constituents are released and support the development of mitigation options. These are also used to understand resulting water quality in the TSF and seepage.

- Note in general that metallurgical tailings and process tailings can be different and tailings can vary based on differences in the ore-body.

Tailings Facility Geochemical Properties

Parameter	Why do we care?
Minerology	The mineralogy of the dam fills and foundation materials can interact with the seepage resulting in non-ideal long-term conditions.
Acid Base Accounting	The potential environmental effects of dam fills needs to be well understood. Detailed properties of mine rock and pit walls need to be characterized as well for alternative tailings management strategies.
Elemental Analyses	
Leachate Testing	

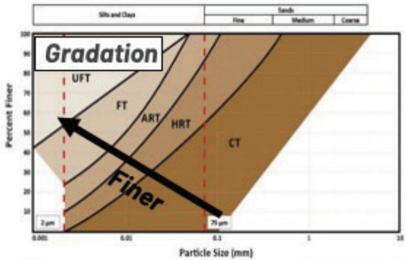
Big picture – TSF are large systems that are interacting with both geologic materials and the environment. The behaviour of one material independently (i.e. tailings) may not reflect the behaviour of co-stored materials (i.e. tailings and mine rock).

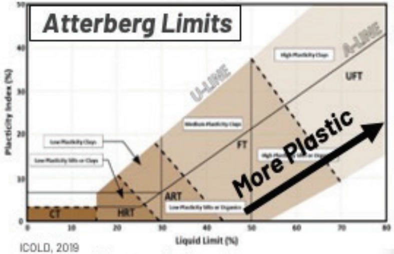
- Note in general that metallurgical tailings and process tailings can be different and tailings can vary based on differences in the ore-body.

Types of Tailings

Tailings Type	Examples
Coarse tailings	Salt, mineral sands, coarse coal rejects, iron ore sands,
Hard rock tailings	Copper, massive sulphide, nickel, gold,
Altered rock tailings	Porphyry copper with hydrothermal alteration, oxidized rock
Fine tailings	Fine coal rejects, bauxite residue (red mud)
Ultra fine tailings	Oil sand (mature fine tailings - MFT), phosphate fines, some kimberlite and coal fines

ICOLD, 2019





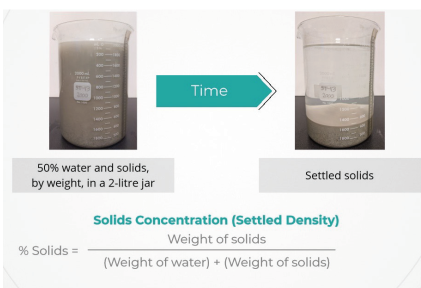
ICOLD, 2019

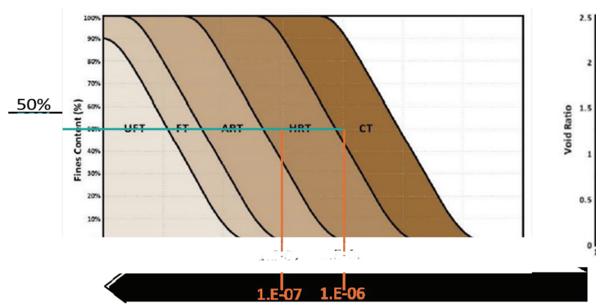
Big picture – different tailings will behave differently, important to understand for design of the TSF and selection of management strategy.

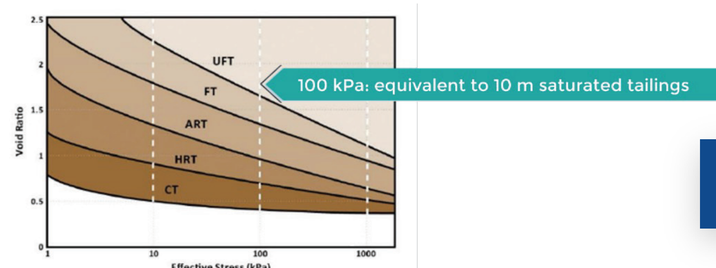
- Coarse tailings and fine tailings, fine tailings have clay – clay is tough to manage and harder to filter.
- Not all tailings can be filtered

Tailings Geotechnical Properties

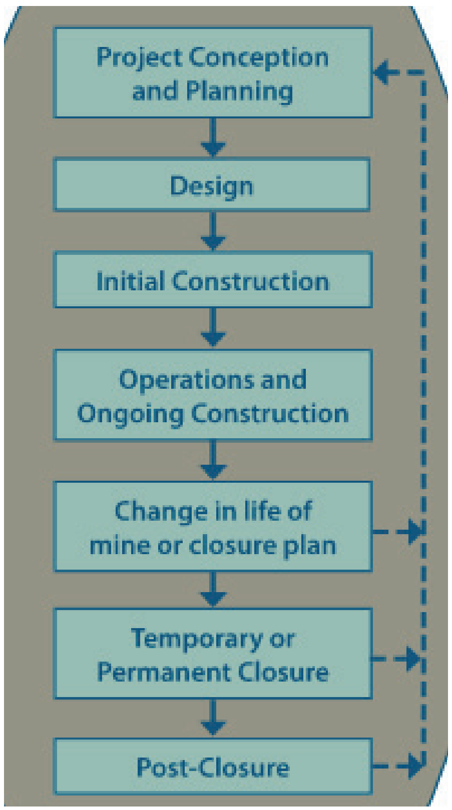
Parameter	Why do we care?
Specific Gravity	density of the tailings particles relative to water, it affects the correlations of other properties and settling behaviour
Void Ratio	void space within the tailings mass that can be occupied by water or air; relates density, strength, compressibility, and permeability
Strength	Peak and residual, impacts geotechnical design
Compressibility	Impacts storage estimates, water released from in-situ tailings, and density/strength for geotechnical design
Permeability	Impacts phreatic surface, seepage rates, and water holding capacity





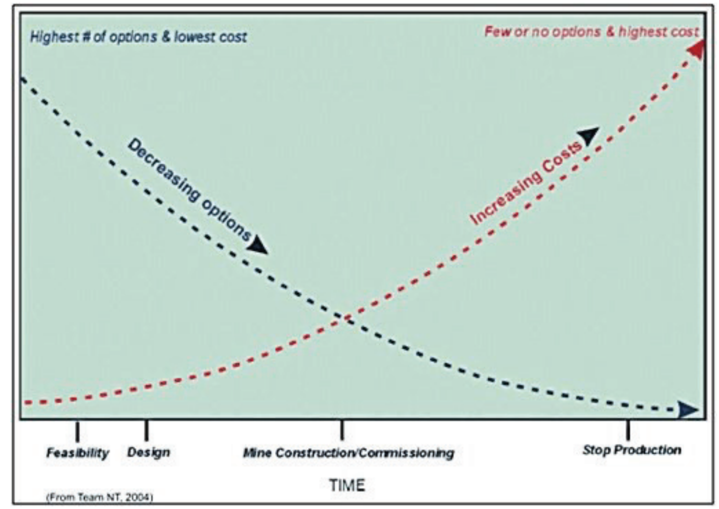


Tailings Facility Life Cycle



MAC Tailings Guide (2021)

Tailings facilities are forever!



from M. Fawcett. TEAM NT: Technologies for Environmental Advancement of Mining in the Northern Territory: Toolkit. Northern Territory Minerals Council (Inc.) and the Mines and Petroleum Management Division of the Northern Territory Government (TEAM NT), 2004.

What is Risk?

Risk = Likelihood x Consequence

- Likelihood can be assessed quantitatively (1:10,000 years) or qualitatively (descriptive)
- “tailings are forever”, long time-frames need to be considered
- Consequences can be broken out into different categories (environmental, economic, health and safety, etc.)
- Companies often have specific risk assessment criteria for determining the severity of a consequence

2. Types of Tailings Facilities and Risks

What is a Tailings Facility?

Thickened Tailings Facility

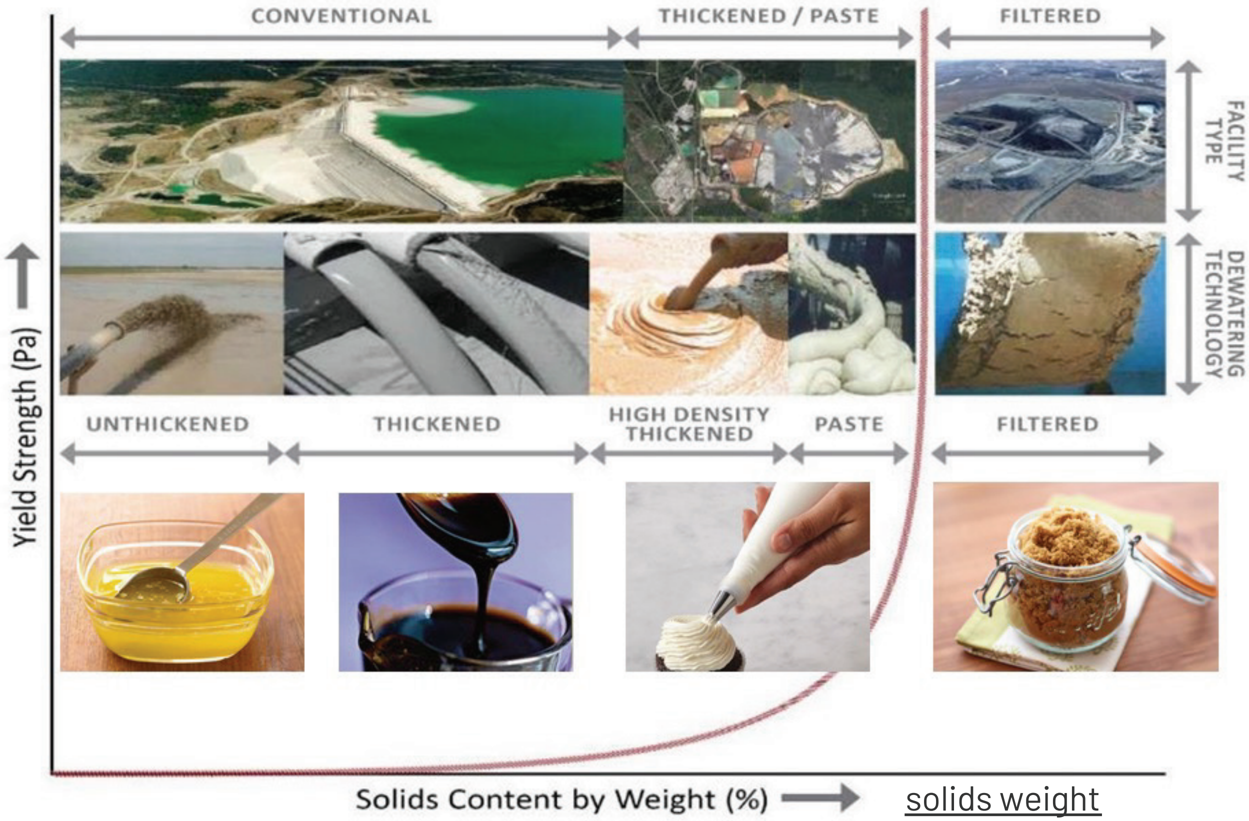
Centinela (Atacama Desert, Chile)

Tailings management is a challenge. Engineering/science solutions required to not become an environmental/ public safety problem.

Conventional Facility

Filtered Tailings Facility

Tailings Facility Types and Dewatering Technologies



Facility Type

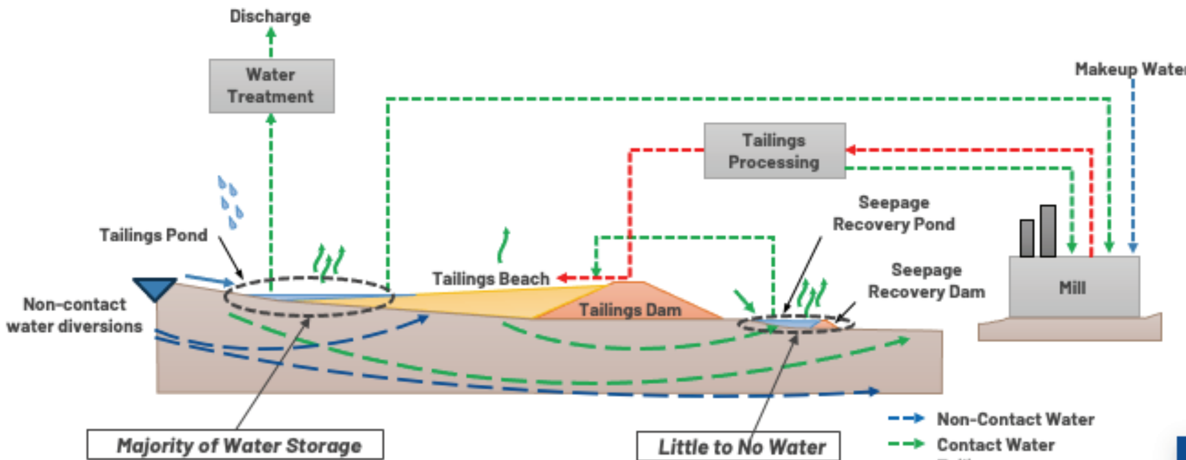
Dewatering Technology

$\frac{\text{solids weight}}{\text{solids + water weight}}$

Facility type images (left to right): KCB 2017a, Google 2016 & © Digital Globe 2016, Levac 2016
Dewatering technologies images: Fourie 2015 and Jewell and Fourie 2015

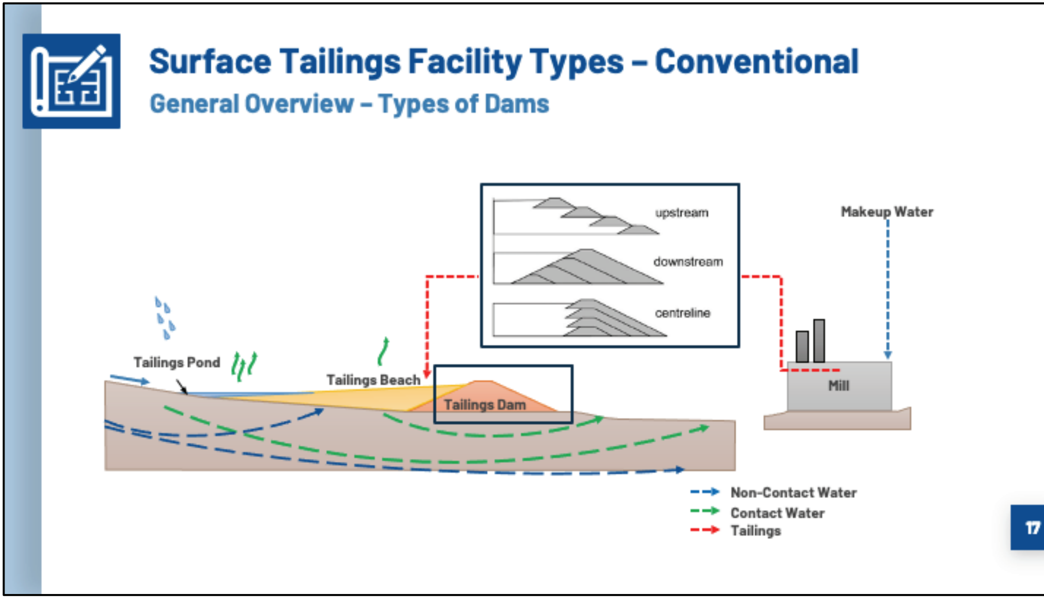
Surface Tailings Facility Types – Conventional

General Overview – Water Management



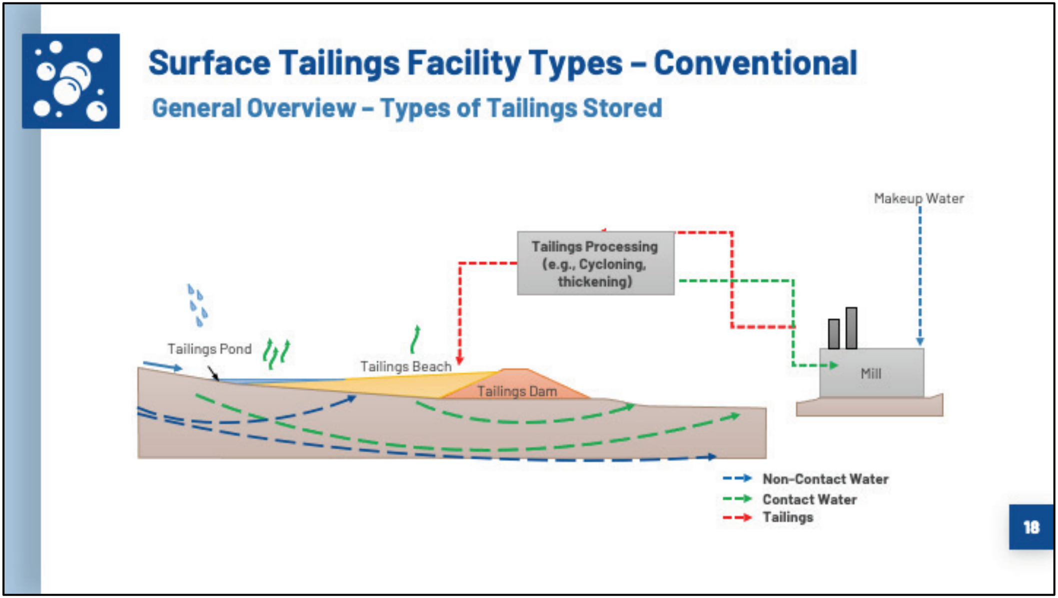
**Valley fill deposition layout illustrated

Overview of where water is stored



Slurry Tailings:

- Most common method
- Pumped at 30% to 50% solids content
- Large footprint
- Large pond
- Above and below ground
- Most economical *(changing)*



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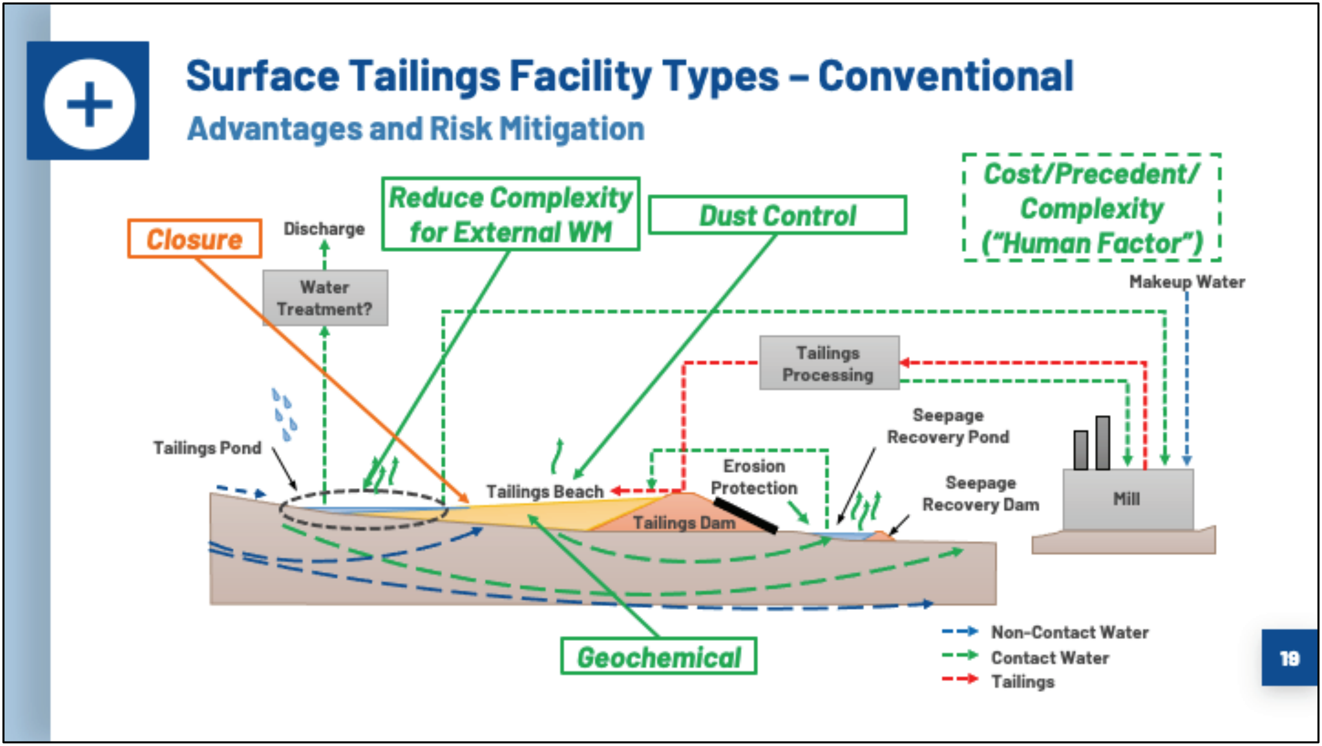
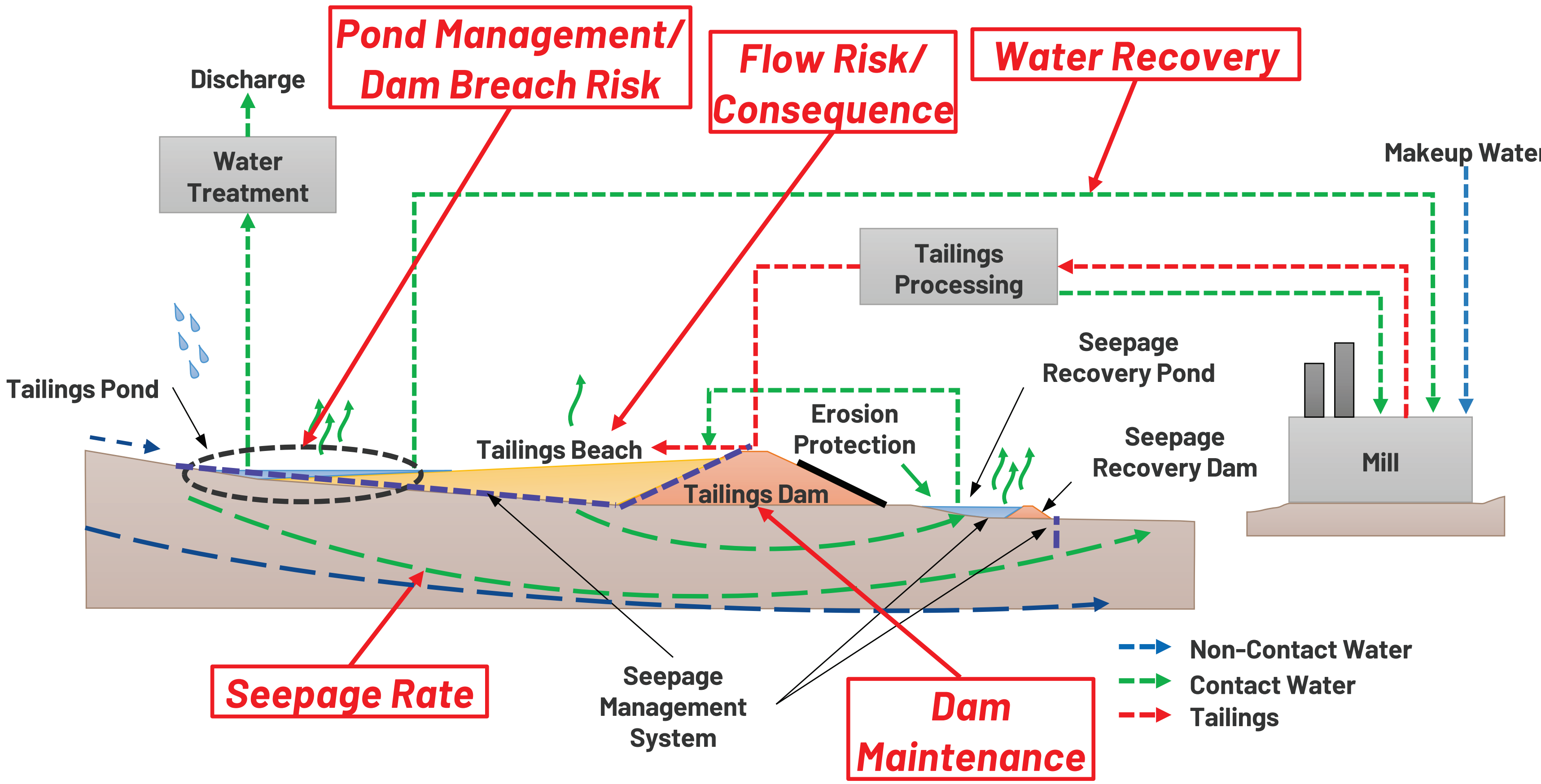


- "Human Factor" – the opportunity for human error to impact the system
  - As we narrow the band of our design target, we reduce the resiliency of the system and add complexity; more opportunities for miscommunication; KISS principle
  - Requires greater operator skill to meet the design targets <u>consistently</u>. Availability of skilled labor force capable of meeting the requirements could be a limiting factor

- A tailings pond can have benefits for reducing oxidation of sulfides and supporting the mitigation of MLARD, but water cover management in perpetuity can also be challenging as our understanding of climate change evolves (do we have enough water to cover the TSFS?)
- The beach depositional approach can also leave fine gained tailings in more concentrated areas away from the dam - these can be difficult to work on at closure.

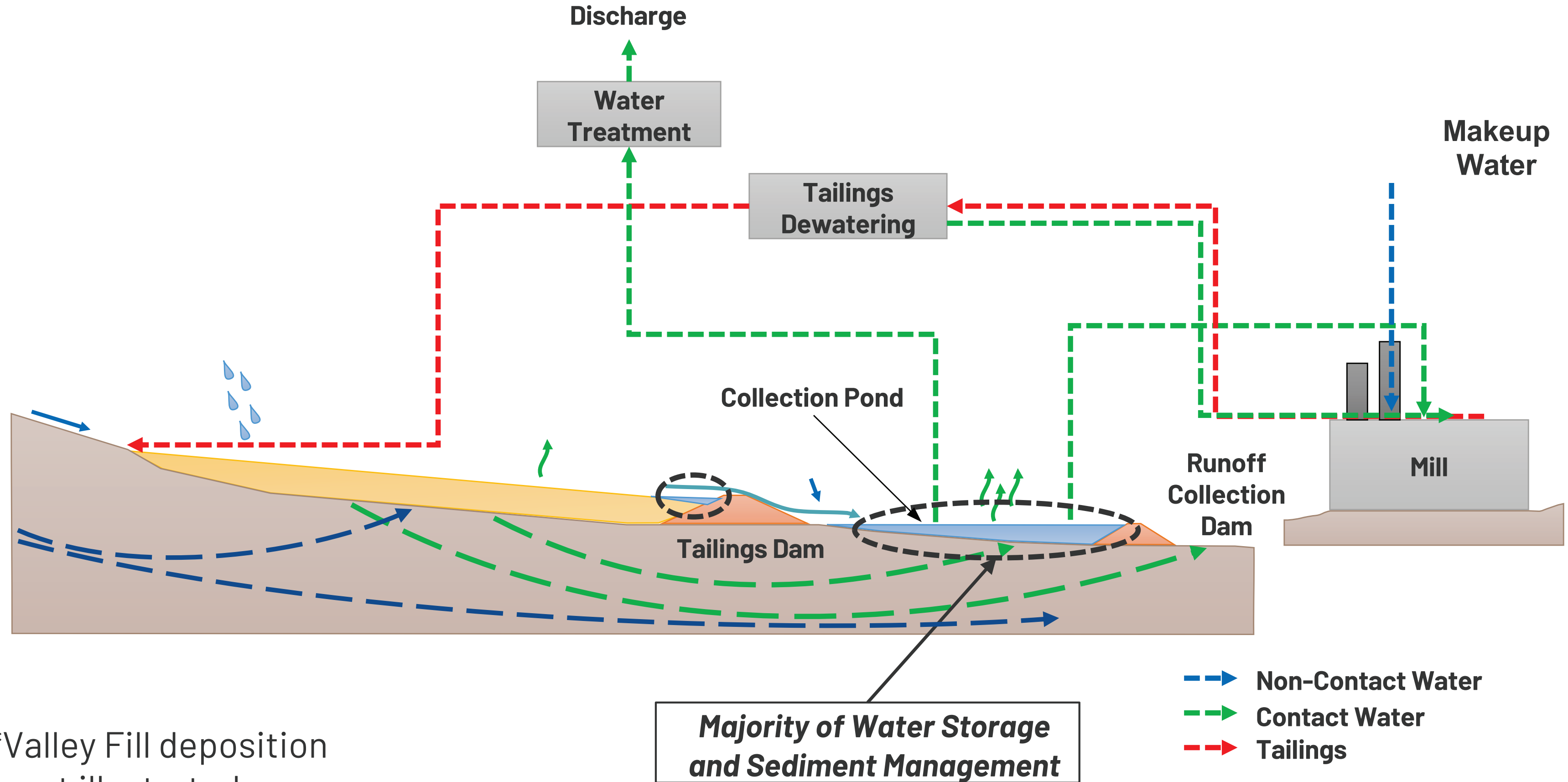
Surface Tailings Facility Types – Conventional

Disadvantages and Risks



Surf. Tailings Facility Types – Paste/HD Thickened

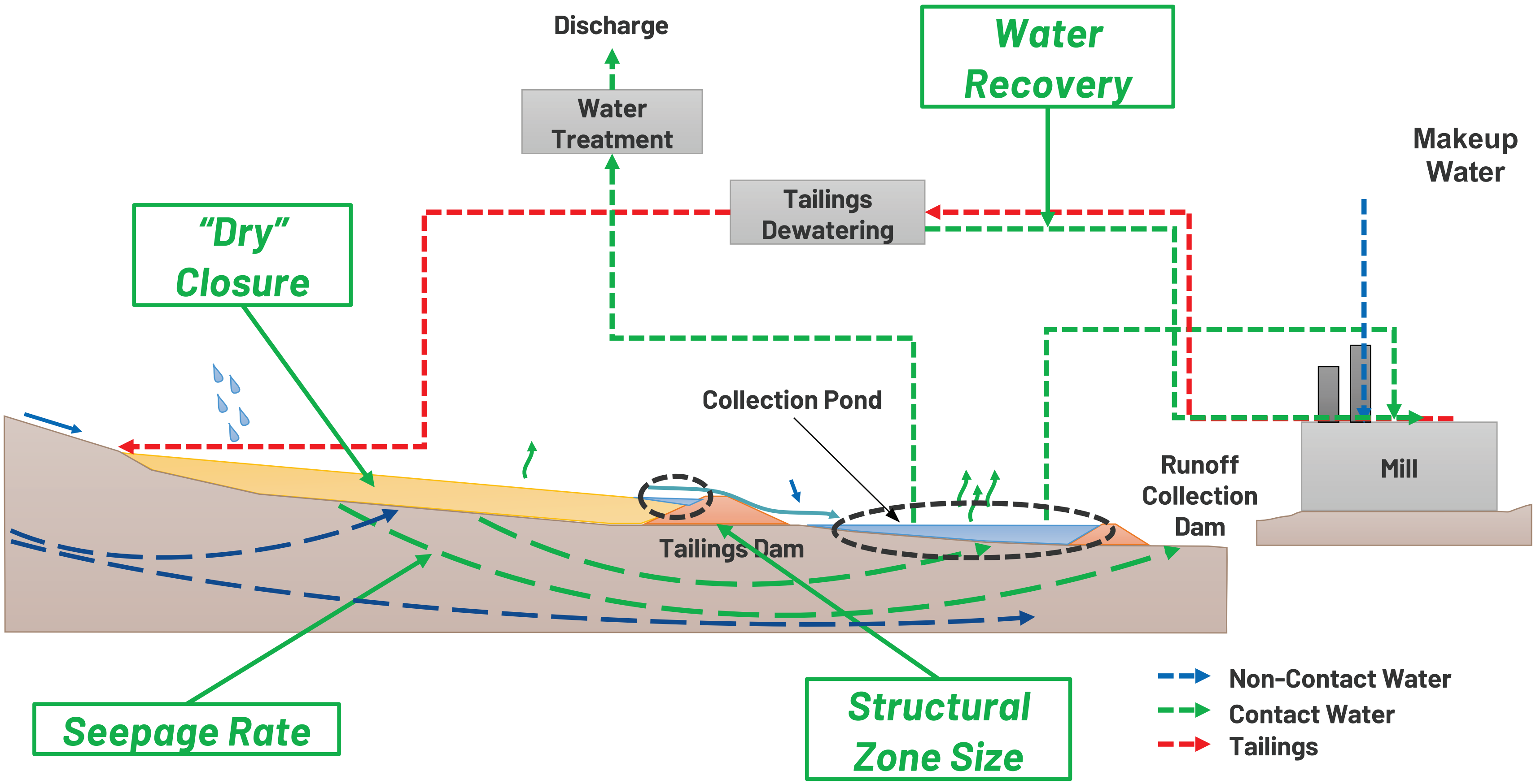
General Overview – Water Management



**Valley Fill deposition layout illustrated

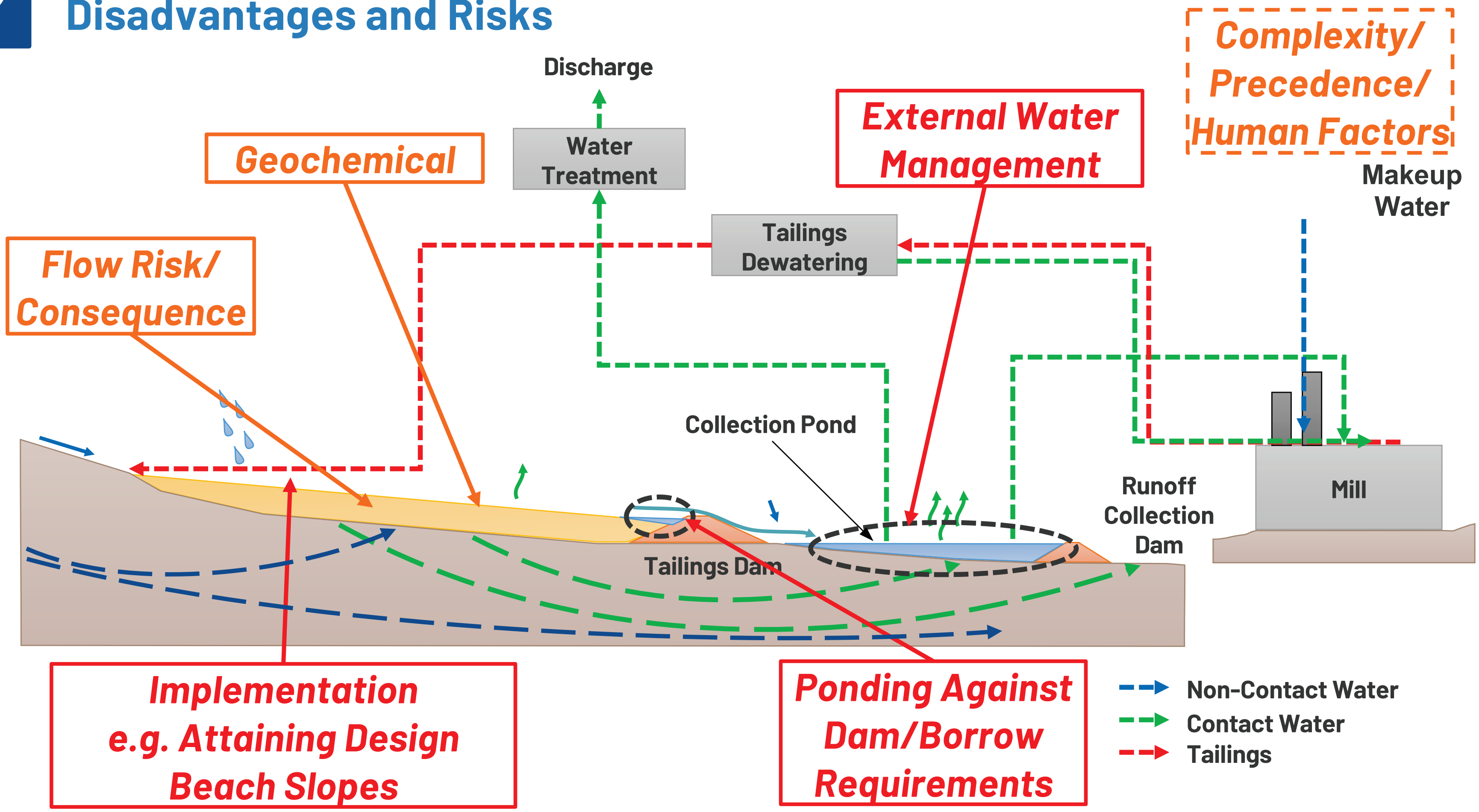
Surf. Tailings Facility Types – Paste/HD Thickened

Advantages and Risk Mitigation



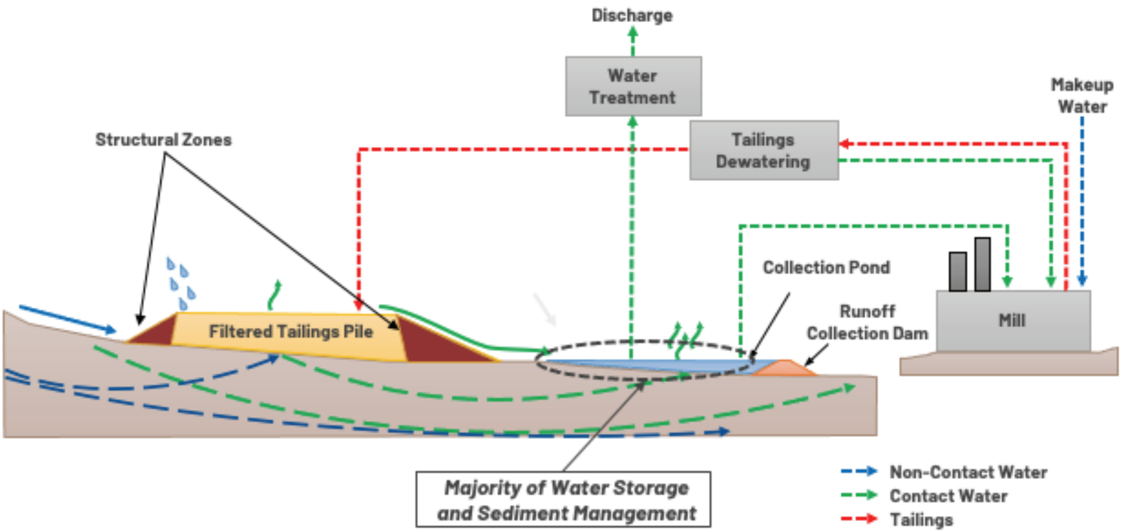
Surf. Tailings Facility Types – Paste/HD Thickened

Disadvantages and Risks



Surface Tailings Facility Types – Filtered

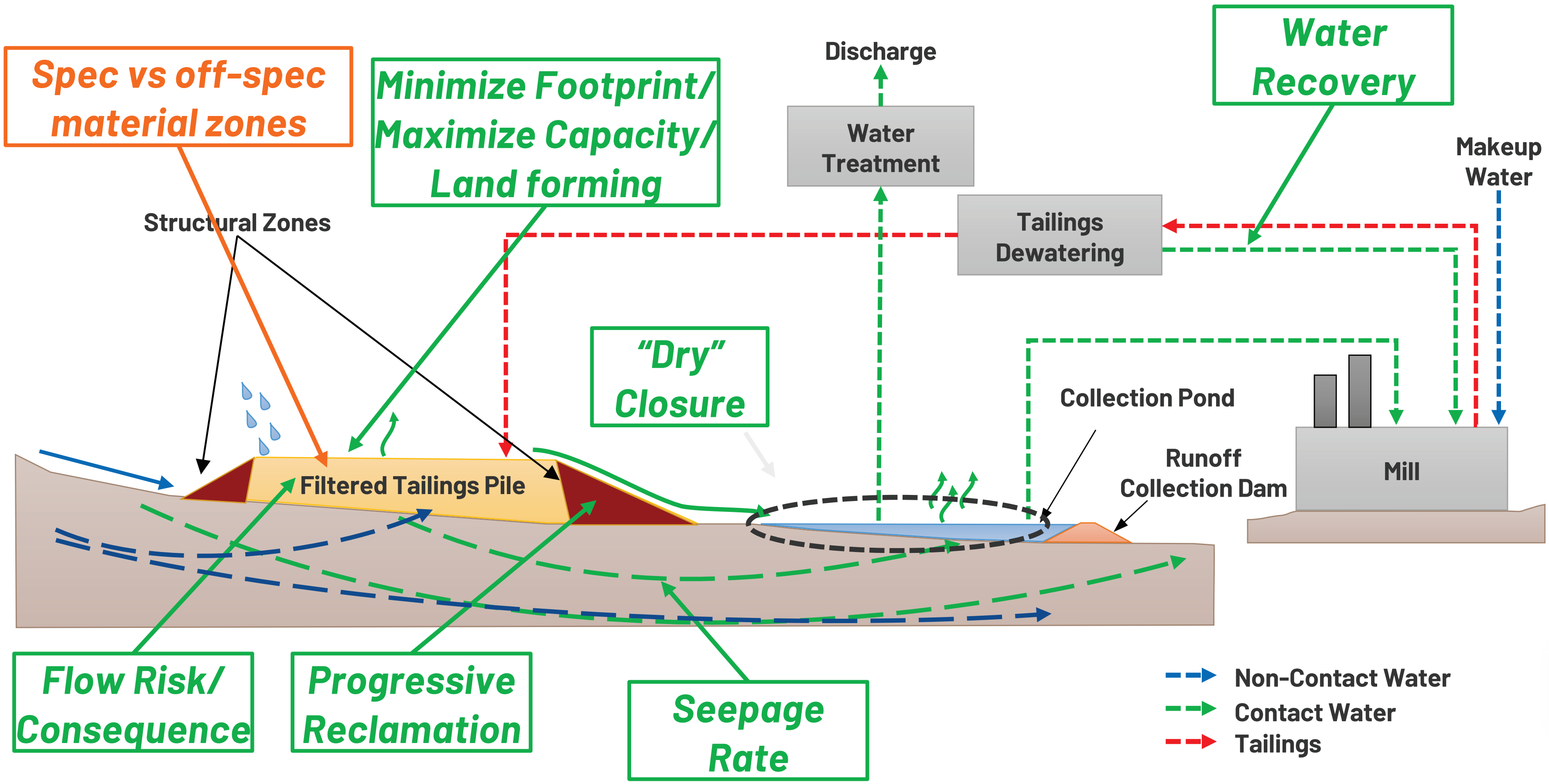
General Overview – Water Management



Tailings start out well dewatered but get wetter after placement depending on climate/site conditions…

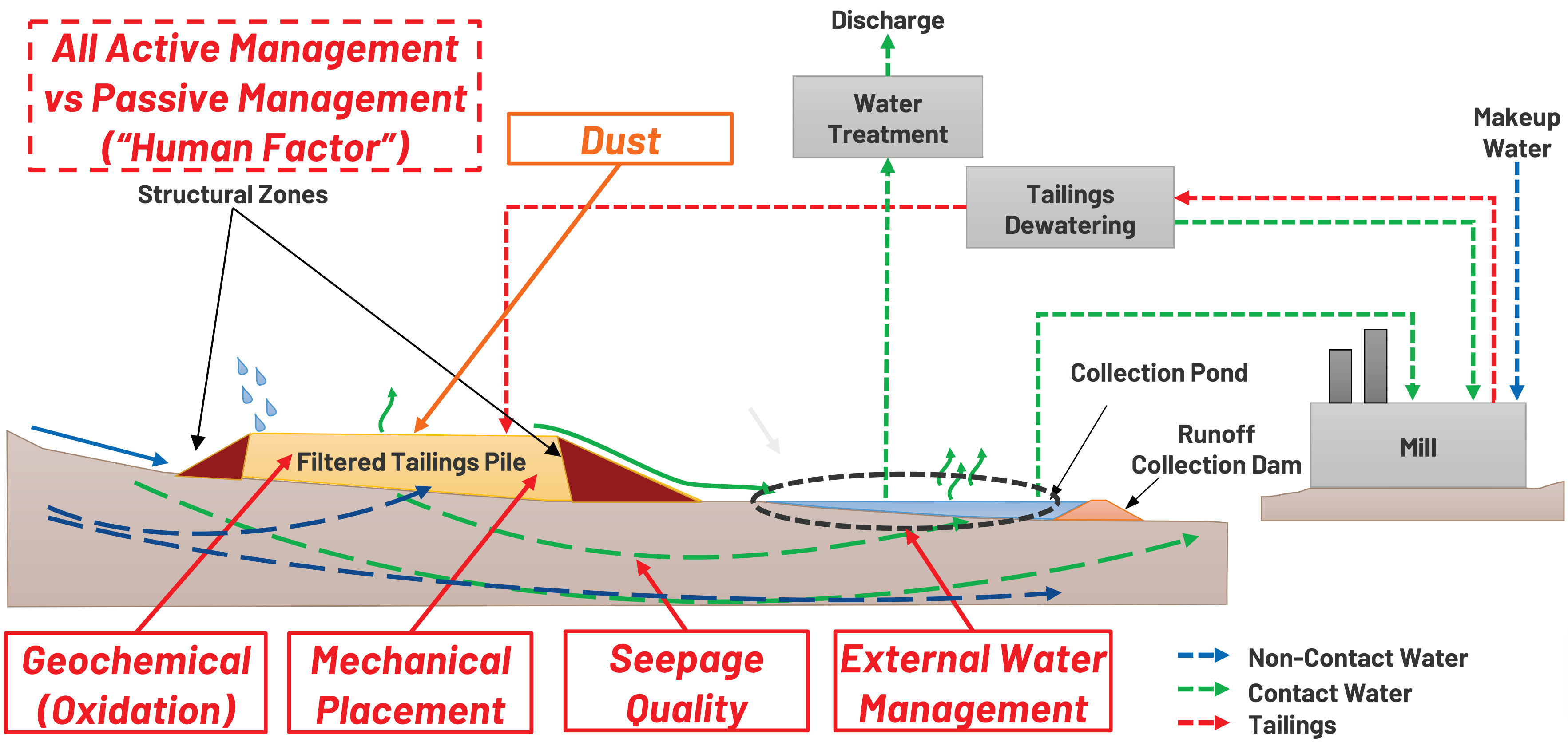
Surface Tailings Facility Types – Filtered

Advantages and Risk Mitigation



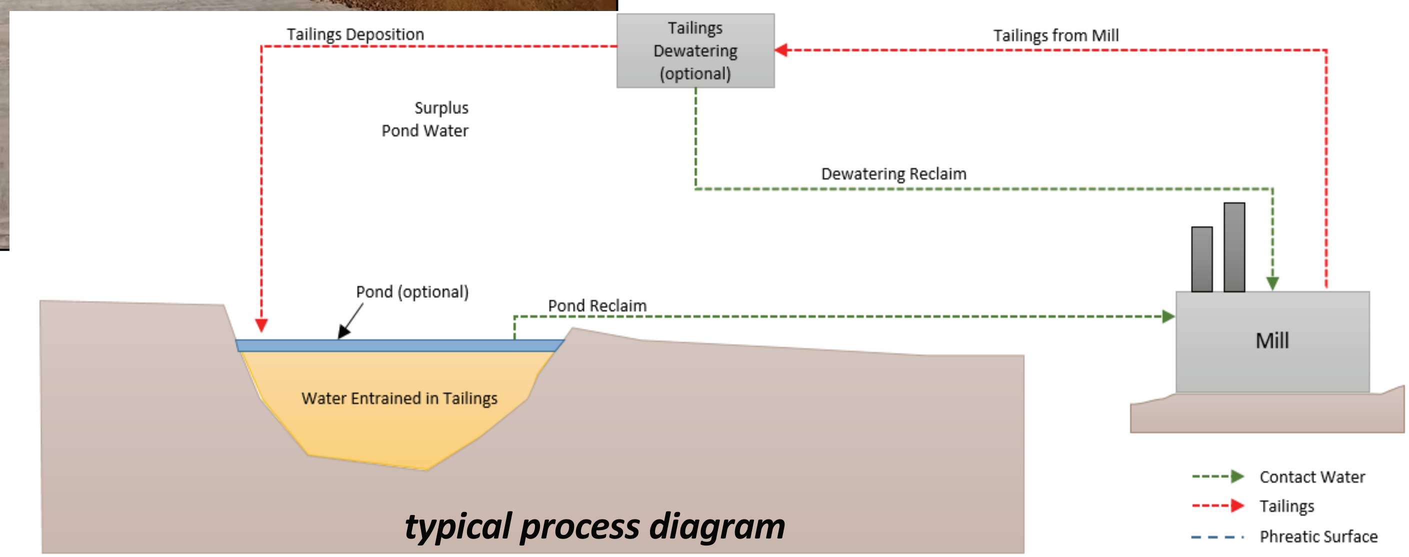
Surface Tailings Facility Types – Filtered

Disadvantages and Risks



Types of Alternative Tailings Facility – Pit Backfill

Source: Marlin Mine
Goldcorp 2015 (Video still)



Type of Alternative Tailings Facility – Waste Rock Co-disposal

Types:

- Co-mingling
- Zonation

Considerations:

- Material handling
- Ratio of rock to tailings
- Stability
- Geochemistry
- Water Management
- Precedents

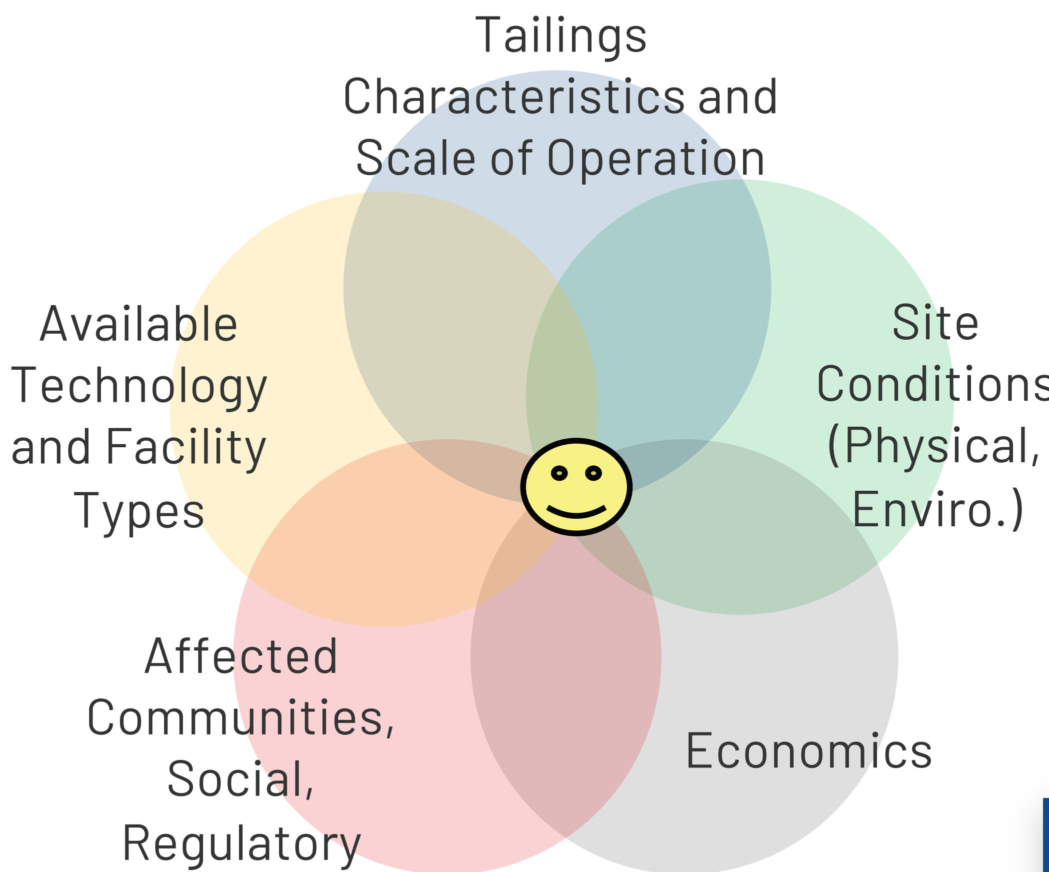
Other Management Techniques

- Multiple Streams of Tailings for Separate Management
  - Sulfide flotation – separate high S and low S streams
  - Hydrocycloning – separate coarse and fines
- Additives to "troublesome" tailings to achieve desired properties
  - Inline flocculation (settling/drainage characteristics)
  - Lime amendments (geochemical characteristics)
  - Polymers
- In-situ dewatering
  - Dewatering wells / drainage
  - Mud-farming or Air Fines Drying (use of climate to reduce moisture content prior to ultimate storage)

Note that segregation of S by flotation doesn't often result in a low S tailings stream that is NPAG.

How Do We Select a Tailings Management Strategy?

There is **NO one-size-fits-all** tailings management strategy. Need to consider all of the following to identify the best strategy for the project.



Risk-Informed Design
Develop a ROBUST DESIGN that integrates the *Knowledge Base* and Minimizes the Risk of Failure to People and the Environment for all phases of the Tailings Facility Lifecycle, including Closure and Post-Closure

Global International Standard on Tailings Management (GISTM)

3. Risk Assessment

Can There Be Risk Free Tailings Facilities?

Risk Identification

Risk Avoidance

Risk Controls

Identification of Residual Risks

Monitoring/ TARPs

Risk Reduction

Obviously no but striving to Risk Reduction!

TARP – Trigger Action Response Plan

Very subjective; not many mining houses have a good approach to this yet

Go through some examples of client approaches; Vale use a likelihood of 10-5 per annum etc

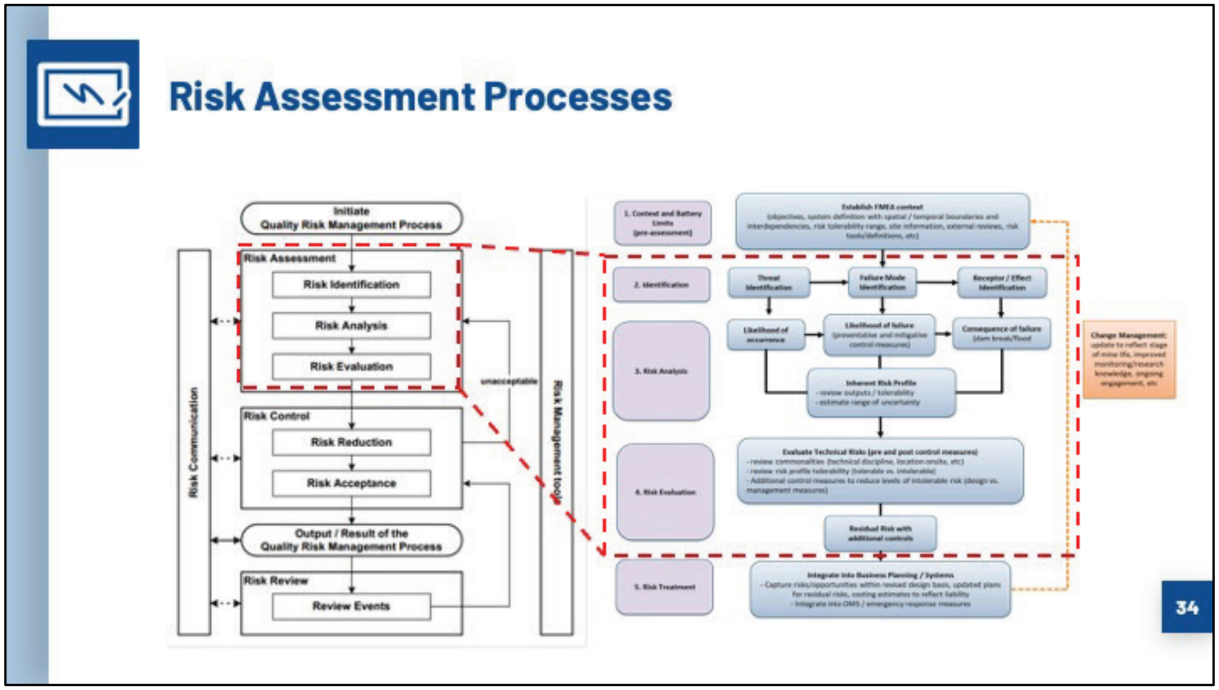
Risk-informed Approach to Tailings Management

Planning, designing, operating, and closing tailings facilities in a manner that is informed by risk assessment; includes:

- Site Characterization
- Decision Analysis
- Managing uncertainty
- Performance-based design
- Surveillance and TARPs
- Adaptation

Figure 8: Framework for a risk-informed approach for tailings management

ICMM Tailings Management Good Practice Guide



- **Risk Identification**
  - Hazard identification
  - Failure mode identification
  - Estimation of consequences (e.g., tailings dam breach study)
- **Risk Analysis**
  - Hazard -> Failure Mode:
    - Consequence, Likelihood
    - Risk control measures (e.g., design of operational mitigations)
  - Types:
    - Qualitative, Semi-quantitative, Quantitative
    - Failure Modes and Effect Analysis (FMEA)
  - Support from: Fault Tree Analysis (FTA) or Event Tree Analysis (ETA)
- **Risk Evaluation**
  - Risk evaluation comprises examining and judging the significance of the risk presented by the TSF and deciding whether – and which – risk control measures should be implemented.

Types of Hazards/Risks to Consider

- Extreme precipitation - *water is a major driver of dam failures: erosion, seepage/piping, overtopping*
- Seismic - *Failures in Chile in 1960s; banned upstream dams*
- Geohazards (e.g., landslides) – *can cause foundation failure or overtopping failure*
- Geomorphology (e.g., rivers) – *historical geomorphology is important to understanding potential foundation issues, but also river systems can be a risk during flood or meandering events*
- Foundation conditions (e.g., weak soils) - *Mount Polley; Cadia failures*
- Human interference – *deliberate or by accident, human interference can lead to tailings dam failure*
- Steep terrain - *limits the types of tailings disposal methodology, results in very high dams*
- Tailings geochemical properties – *what conditions promote or limit geochemical processes from occurring.*
- TSF pond water quality – *what process reagents are being used, what other inputs are expected to the TSF.*
- Groundwater interactions – *how does the quantity or quality of groundwater affect or is affected by the TSF.*
- Infrastructure and maintenance issues – *is the mill down and affecting the water balance, less people on site to operate pumps, power failure, etc.*

Risk informed design does not mean accepting risks, rather understanding vulnerabilities
PNG has a unique amount of risk; rainfall; weak soils; earthquake, steep terrain

Potential Failure Modes Assessment

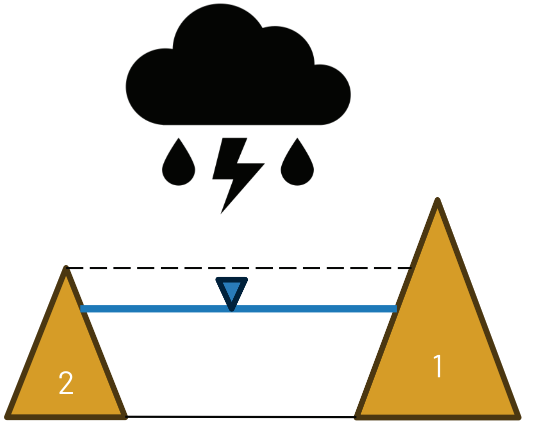
A failure mode is the way or means by which failure occurs.

A failure mode requires **an initiating event** (e.g., earthquake, flood, construction load, etc.), that leads to a **failure mechanism**, and the failure of the system (or **loss of function**).

The assumed failure mode that the consequence is based on should be **physically possible**, no matter how low the likelihood of failure.

– ICOLD Bulletin 194

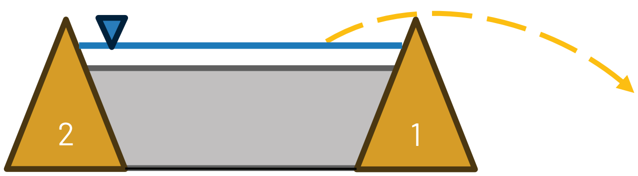
***Example:** Overtopping is NOT credible (i.e., not physically possible) for Dam #1, because Dam #2 will overtop first*



Potential Failure Modes Assessment

Acute

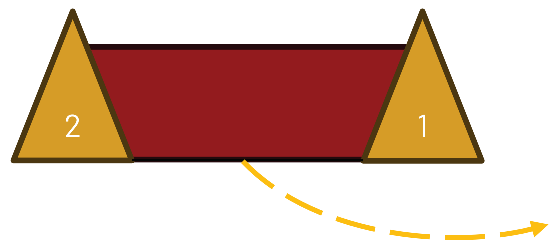
Example: *Storm event causes a power failure resulting in water requiring discharge without treatment.*



To be ***credible*** *the storm event has to be significant to overcome the environmental design flood (EDF).*

Chronic

Example: *Acidic seepage slowly degrades the foundation bedrock resulting in a fugitive groundwater plume.*



To be ***credible*** *the seepage has to have the potential to be acidic* ***and*** *the foundation has to be susceptible to degradation (e.g. limestone/karst).*

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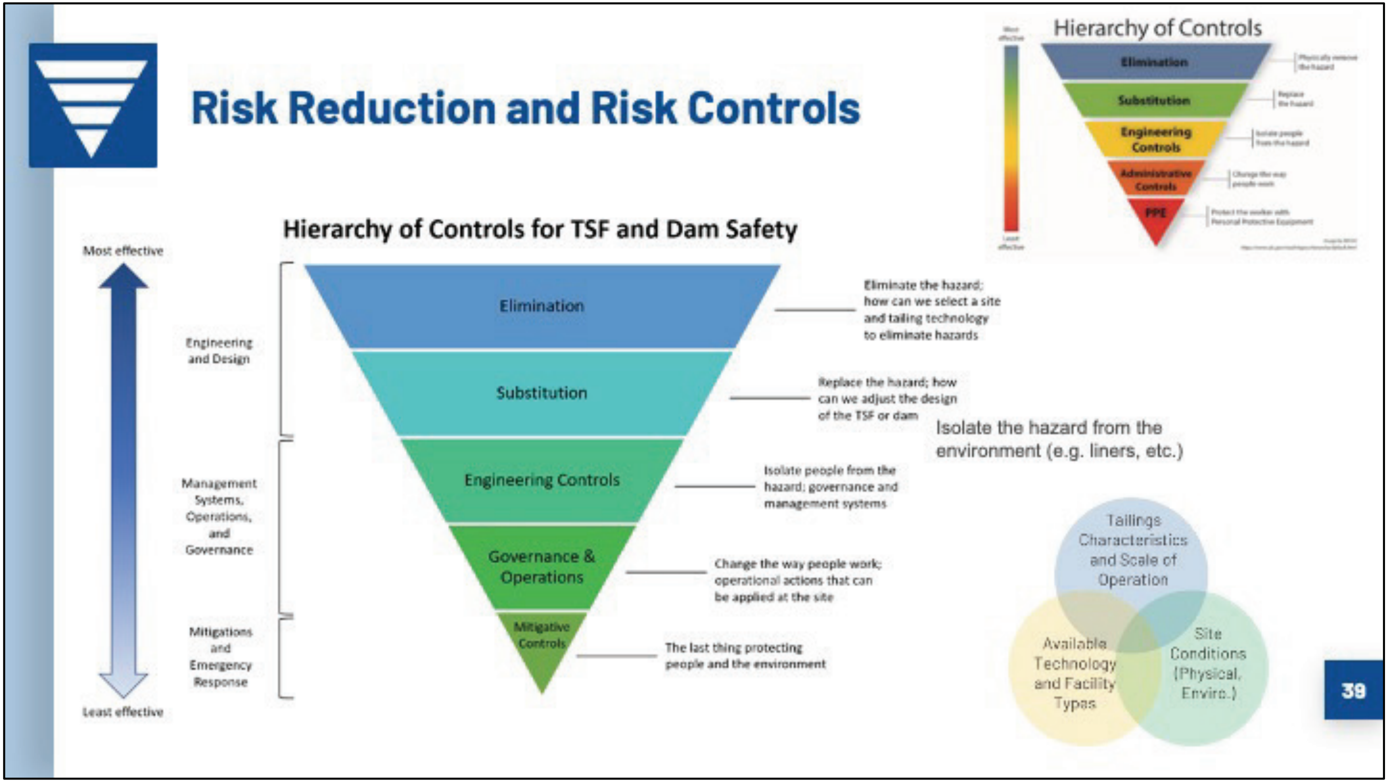
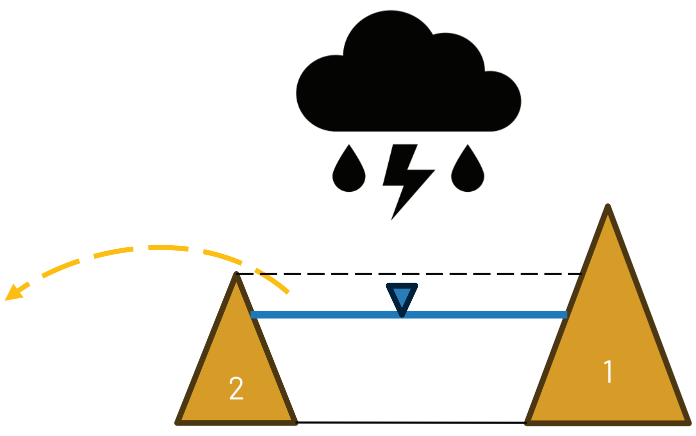


Very subjective; not many mining houses have a good approach to this yet

Go through some examples of client approaches; Vale use a likelihood of 10-5 per annum etc

Risk Reduction and Risk Controls

Overtopping



Dam Failure or Release of Untreated Water

Change TSF design so water storage is external to reduce the likelihood of an overtopping failure (this might increase the environmental consequences of the facility).

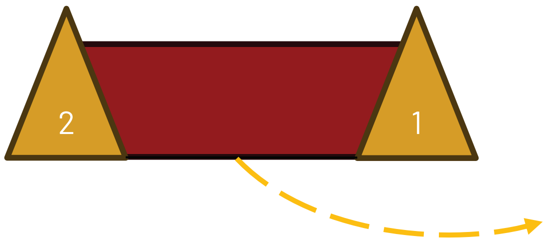
Construct the facility so that overtopping occurs in one direction only to reduce the consequence.

Robust EDF and inflow design flood (IDF) to reduce the likelihood.

Clear TARPs for when water is discharged without treatment (reduces the likelihood of overtopping but causes the consequence of water release).

Risk Reduction and Risk Controls

Fugitive Seepage



Groundwater Plume or Weakened Dam Foundation

Change facility siting so that the failure mode is not credible.

Manage TSF pond and pore water to reduce metal leaching and acid rock drainage and likelihood of failure.

Line the facility to reduce the porewater/foundation interaction and likelihood of failure.

~~*Monitor the downstream seepage/ groundwater quality.*~~

Monitoring is an important part of a risk management plan (verification activity), but it is not a RISK CONTROL!

Risk Communication Tools – The Risk matrix

Risk	Risk Rating	Criteria and Decision-Making Guide
Non-Credible	-	To be considered credible, the failure mode assessed had to identify an initiating event and consider the credibility that that initiating event has a probability of occurrence greater than zero. Review annually to confirm the risk remains non-credible.
Acceptable	0 - 3	Risk is acceptable. Review annually and monitor as part of management controls.
ALARP	3 - 10	Risk is tolerable, ALARP. Review practicable additional control measures to further reduce risk to acceptable level.
High	12 – 20	Risk is considered high and not tolerable. Additional preventative controls are required *within 1 year* to reduce risk to tolerable risk range.
Intolerable	21 – 35	Risk is considered intolerable. Additional preventative controls are required *immediately* to reduce risk to a tolerable risk range.

Impacts of TSF Failure Mode

(determined by tailings dam breach assessment)

(estimate PAR, PLL, etc.)

Likelihood of TSF Failure Mode

Qualitative to Quantitative

E.g., Event Trees

Likelihood Rating	Factor	Current Risk (Risk With Existing Preventative and Mitigative Controls) Existing risk of the facility with implementing operational, maintenance, surveillance dam safety controls (e.g., OMS/EPRP practices)				
Almost Certain	7	7	14	21	28	35
Likely	6	6	12	18	24	30
Possible	5	5	10	15	20	25
Unlikely	4	4	8	12	16	20
Rare	3	3	6	9	12	15
Very rare	2	2	4	6	8	10
Close to non-credible	1	1	2	3	4	5
	Factor	1	2	3	4	5
	Rating	Slight	Minor	Moderate	Major	Severe
		Consequence				

Intolerable Risk (immediate preventative/mitigative controls required to ALARP)

High Risk (preventative/mitigative controls required to ALARP)

Tolerable, ALARP Risk

Acceptable Risk

Current risk (without operational controls)

Current risks

Residual risk (with additional controls)

Risk Communication Tools – The Bow-tie

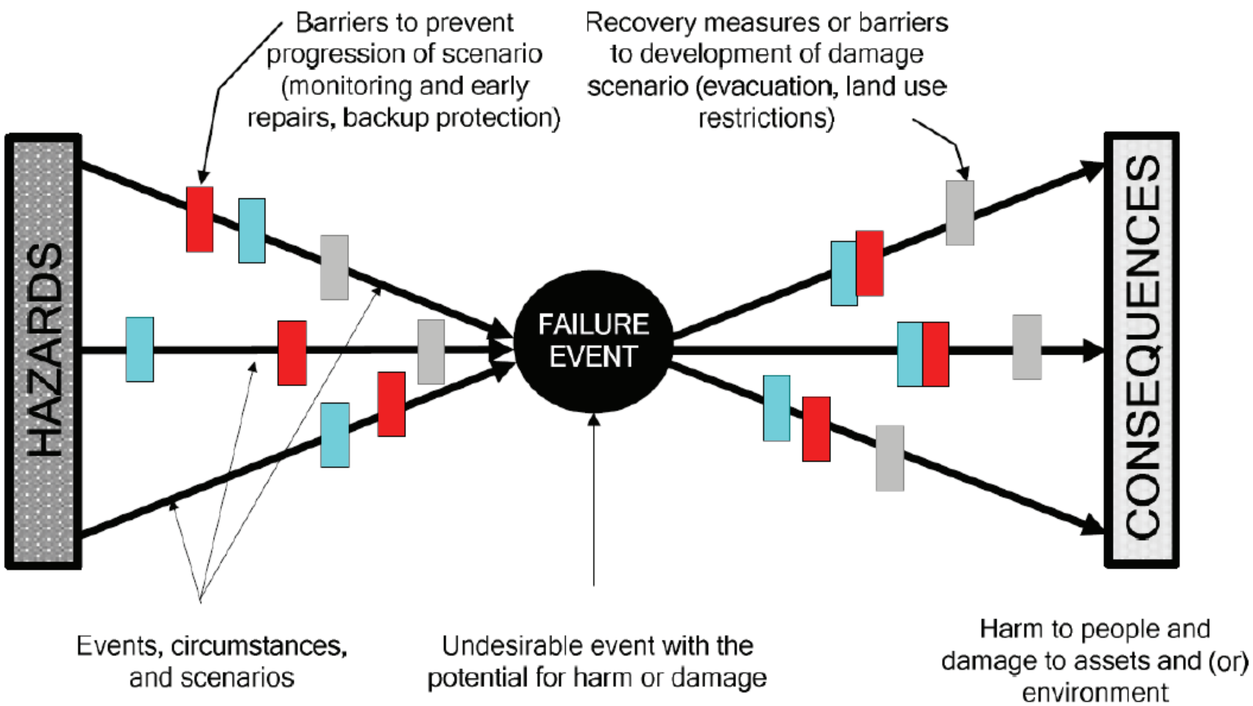


Figure 1: Bow-Tie Risk Management Model (CDA, 2007)

Bow-tie is underpinned by FMEA and/or event trees

Understanding Risks

Need to also acknowledge the confidence in risk controls

- Continual improvement is key.
- Good risk management includes risk reduction.
- A robust risk assessment may require more than one method of evaluation.

Very subjective; not many mining houses have a good approach to this yet
Go through some examples of client approaches; Vale use a likelihood of 10-5 per annum etc

Risk Tolerability

- Evolving approaches in the industry
- Basic principle is risk tolerability:
  - Zone of acceptable risk
  - Zone of intolerable risk
  - Zone of "As Low As Reasonably Practicable" or ALARP
- Reduce risk to ALARP
  - A risk reduction measure is generally considered reasonably practicable if it can be controlled, management and verified by the owner and the sacrifice for such measure is not grossly disproportionate to the benefit of the risk reduction gained
- Different perspectives have very different thresholds e.g., Owners, regulators, IGOs, local communities, stakeholders, NGOs

Very subjective; not many mining houses have a good approach to this yet
Go through some examples of client approaches; Vale use a likelihood of 10-5 per annum etc

Risk Informed Decision Making

Considers risks in the decision-making process

For design, operations, surveillance, maintenance.

All life phases

Many other factors inform the decision

Risk assessments can be used to provide input

ICOLD Bulletin 154: Dam Safety Management: Operational Phase of the Dam Lifecycle

Key Take Aways

There is no “one size fits all” solution to tailings management

Tailings management has risks, no matter what we do

There are good, established processes out there for assessing risks

There are good, established processes out there for effective decision making for tailings management

A good process for risk assessment and decision making is multi-disciplinary

Thank you

Any questions?

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