Tailings Storage Facilities Insights - Types, Failures, and Management Guidelines Update

52nd IMIA Conference
19th to 23rd October 2019
Hotel Savoyen, Vienna, Austria

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Director International Forensics
Jensen Hughes UK Ltd.

21 October 2019
OVERVIEW

• Tailings and Processing
• Tailings Storage Facilities Overview
• Failure History Dashboard
• Mount Polley, Samarco, Newcrest, Brumandinho (Feijão)
• Upgrading Guidelines or Practices Towards Zero Failure
MY BACKGROUND

• B.Ap.Sc. (Civil) UBC: 1987
• Klohn Leonoff Ltd. 1987 to 1990
• AMEC Inc.: 1993 to 1993
• GWA then Golder Associates (HK): 1996-2001
• London Business School: 2001 to 2003
• Golder Associates Ltd. 2003-2006
• Giffin Koerth then -30- Inc. 2006-2017
• Jensen Hughes UK Ltd. 2017
• P.Eng. (Canada), CEng., FICE (UK)
SUMMARY PROCEDURES IN MINING PRODUCTION

Ore

Grinding

Leaching

Concentration

Dewatering

Concentrate Emulsion Product

Waste Tailings

Heating
TAILINGS DEWATERING RANGE AND CONSISTENCY

<table>
<thead>
<tr>
<th>Tailings Type</th>
<th>Consistency</th>
<th>Non-Pumpable</th>
<th>Pumpable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Filtered Tailings</td>
<td>Moist Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet Filtered Tailings</td>
<td>Wet Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paste Tailings</td>
<td>Thin Milk Shake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickened Tailings</td>
<td>Sandy Yogurt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailings Slurry</td>
<td>Water with Sand/Silt/Clay</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Unsaturated**
  - Likely lowest operating cost
  - Least efficient water conservation
  - Containment dams required
  - Potential seepage issues
  - Water management considerations

- **Saturated**
  - Water conservation
  - Negligible seepage
  - Progressive reclamation
  - More stable tailings mass
  - Minimal containment berms
  - Simpler water management
  - High operating costs

Decreasing Water Content
AN ILLUSTRATION OF TAILINGS VOLUMES - GOLD
VOLUME OF TAILINGS PRODUCED FOR GOLD IN 2018

• 1 g/gold/metric tonne of rock (on average)
• 2018, 3,260 metric tonnes of gold = 3.3B metric tonnes of rock mined
• Rock density of 2.6 g/cm$^3$, bulking factor of 1.6, ►2B m$^3$ of tailings
OPEN PIT DISPOSAL

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DAMS PLUS TOPOGRAPHIC RELIEF
Mildred Lake Tailings Pond
18 km circumference
40 m (avg) to 88 m (max) high
THICKENED TAILINGS DISPOSAL

Ref.: Thickened Tailings Disposal at Xstrata Copper Canada, Kidd Metallurgical Site
Shiu Kam, David Yaschyshyn, Michael Patterson and David Scott
PASTE TAILINGS – SURFACE & UNDERGROUND

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FURTHER DEWATERING THROUGH DRY STACKING
CO-DISPOSAL OF TAILINGS WITH WASTE ROCK
PROGRESSION IN DEWATERING TECHNIQUES

Most filtered facilities ≤ 6,500 tpd emphasis within arid climates

## RANGE OF PROCESSING & INITIAL STORAGE COST

<table>
<thead>
<tr>
<th>Dewatering Technology</th>
<th>Typical Processing &amp; Transport Cost ($/t)</th>
<th>Typical Dam &amp; Water Management Cost ($/t)</th>
<th>Typical Total ($/t)</th>
<th>Range of Cost ($/t)</th>
<th>Relative Increase in Typical Total Compared to Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unthickened (conventional)</td>
<td>$0.20</td>
<td>$1.00</td>
<td>$1.20</td>
<td>$0.50 to $2.50</td>
<td>100%</td>
</tr>
<tr>
<td>Thickened</td>
<td>$0.30</td>
<td>$1.00</td>
<td>$1.30</td>
<td>$0.50 to $2.50</td>
<td>110%</td>
</tr>
<tr>
<td>High density thickened</td>
<td>$0.50</td>
<td>$0.90</td>
<td>$1.50</td>
<td>$0.75 to $2.50</td>
<td>125%</td>
</tr>
<tr>
<td>Paste</td>
<td>$1.50</td>
<td>$0.50</td>
<td>$2.00</td>
<td>$2.00 to $8.00</td>
<td>170%</td>
</tr>
<tr>
<td>Filtered</td>
<td>$5.00</td>
<td>$0.20</td>
<td>$5.20</td>
<td>$4.00 to $12.00</td>
<td>430%</td>
</tr>
</tbody>
</table>

Notes:
1. Costs are site and project specific and are indicative only
2. Cost per tonne typically decrease with increased tonnage due to economies of scale
3. Capital and closure costs not included.

“No universally ideal tailings dewatering technology or facility types…the ideal solution will depend on the tailings properties, production scale, site characteristics, available technologies and facility types.”

Ref.: Mining Environment Neutral Drainage, October 2017
Embankment Construction

• Constructed to full height prior to deposition, likely under 1 contract/contractor
• Good permanent water storage suitability
• Any type of tailings
• Good seismic resistance
• Requires natural soil
• Relatively high embankment cost

Downstream Construction

- Constructed progressively using tailings, mine waste, or natural borrow materials
- Good permanent water storage suitability
- Any type of tailings
- Good seismic resistance
- Relatively high embankment cost *(compared to centerline & upstream methods)* spread over life of facility

Centerline Construction

- Constructed progressively using tailings, mine waste, or natural borrow materials
- Good temporary water storage ability
- Sands or low plasticity silts
- Acceptable seismic resistance
- Raising rate restrictions may apply
- Moderate embankment cost (less than downstream methods) spread over life of facility
TAILINGS DAMS – FOUR MAIN APPROACHES

Upstream Construction

- Constructed progressively using tailings, mine waste, or natural borrow materials
- Majority of all tailings dams worldwide
- Lowest embankment cost compared to above methods
- Sand requirements of 40% to 60%
- Not suitable for significant water storage
- Poor seismic resistance
- Raising rate restrictions of 15 -30 ft (4.6-9.1m) per year may apply

TAILINGS DAMS’ RELATIVE EMBANKMENT VOLUMES

Upstream Construction

Centerline Construction

Downstream Construction

Area A1

Area A2 = 2A1

Area A3 = 3A1

GROWTH AND EVOLUTION WITH TIME – LL DAM 1988

1988: 120 m tall
1,100 m Crest
Circa 2010: 180 m tall 2,500 m Crest
GROWTH AND EVOLUTION WITH TIME – LL DAM 45 YEARS OLD AND GROWING
TAILINGS DAMS ARE/CAN BE COMPLEX STRUCTURES

Ref.: ITRB Report on Mount Polley Tailings Storage Facility Breach, 30 January 2015
ACCIDENTS AND FAILURE EVENTS OVER TIME

3500 tailings operating dams in 2000
- 1:1,000 Failure Frequency
- 1:100 Event Frequency

By Comparison:
For earthfill and rockfill dams in the U.S. constructed after 1960 (H 15 m to 90 m), estimated annual failure frequency is 1:10,000 (Martin & Davies 2000)
- Greatest proportion of failures through Overtopping, Spillway, and Erosion
REPORTED CAUSE OF FAILURE

Ref.: Conclusions From Evaluation of Tailings Dam Incidents, Strachan, C., and Van, R., USSD April 2018
VOLUME RELEASED VS STORED VOLUME

VOLUME RELEASED VS RUNOUT DISTANCE

EVENT AND CUMULATIVE VOLUME AND LIVES LOST

>2,280 Reported Dead or Missing

MOUNT POLLEY 4 AUG 2014

Ref.: ITRB Report on Mount Polley Tailings Storage Facility Breach, 30 January 2015
MOUNT POLLEY - LAYOUT AND CROSS-SECTIONS

Ref.: ITRB Report on Mount Polley Tailings Storage Facility Breach, 30 January 2015
MOUNT POLLEY TAILINGS TRAVEL DISTANCE

≈22 km from breach
“The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation. As a result, foundation investigations and associated site characterization failed to identify a continuous Glaciolacustrine (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.”
Fundão Tailings Dam Review Panel

Report on the Immediate Causes of the Failure of the Fundão Dam

Panel:
Norbert R. Morganstein, Chairman
Steven G. Vick
Olavo R. Viane
Bryan E. Wells

August 25, 2016

FUNDÃO TSF DESIGN INTENT

**Slimes (30%)**
10% fine sand, 70% silt, 20% clay

**Sand Tailings (70%)**
40% to 60% fine sand, 40% to 60% silt, <4% clay

FUNDÃO TSF SAND TO SLIMES RATIO

FUNDÃO TSF – MAY 2013
FUNDÃO TSF – AUG 2014
FUNDÃO TSF – JULY 2015
FUNDÃO TSF DYKE 1 FAILURE – APRIL 2009

• Failure 4 months following sand tailings deposition, ± 10 month following slimes deposition
• Dyke 1A constructed u/s to investigate
• Gross construction defects with respect to foundation drains
• Foundation drains abandoned
• Replaced with blanket drain at El. 826 m

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Overflow Channel Operational Period:

- February 2011 – July 2012 (18 Months)
- July 2013 – December 2013 (6 Months)
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FUNDÃO TSF SLIMES MIGRATION

Ref.: Fundão Tailings Dam Review Panel Report on the Immediate Causes of the Failure of the Fundão Dam, 25 August 2016,
FUNDÃO TSF FROM RIGHT ABUTMENT NOV 2015

Ref.: Fundão Tailings Dam Review Panel Report on the Immediate Causes of the Failure of the Fundão Dam, 25 August 2016,
FUNDÃO TSF FROM RIGHT ABUTMENT POST FAILURE

Ref.: www.theguardian.com/world/2018/
FUNDÃO TSF FROM LEFT ABUTMENT PRE & DURING FAILURE

Ref.: Fundão Tailings Dam Review Panel Report on the Immediate Causes of the Failure of the Fundão Dam, 25 August 2016,
FUNDÃO TSF FAILURE ORIGINATING FROM LEFT ABUTMENT - VIDEO

Ref.: Fundão Tailings Dam Review Panel Report on the Immediate Causes of the Failure of the Fundão Dam, 25 August 2016,

Reduction in Confining Stress on Loose, Saturated Contractive Tailings….Causing Collapse
FUNDÃO TSF DOWNSTREAM IMPACT

FUNDÃO TSF DOWNSTREAM IMPACT – SANTAREM DAM
• 35 Mm3 of Tailings Evacuated
• 20 Mm3 of Tailings Remained
• 19 Lives Lost
• 600 People Displaced
• Samarco’s Operations Suspended Now For 3 Years (PD $MM, BI $B)
• 22 Criminal Indictments

650 KM IN 17 DAYS

November 22, 2015
NTSF PRIOR TO FAILURE

- 91 m maximum embankment height
- 3,900 m crest length
- 9 m crest width
- 450 ha area
- 160 Mm³ tailings stored
- 170 Mm³ tailings capacity

CADIA NTSF REPORTED EVENTS PRIOR TO FAILURE

8 March 2018:
• M2.7 Earthquake occurred

9 March 2018:
• Cracking (morning), then embankment slumped (19:00)
• Tailings deposition stopped

10 March 2018:
• Suspension of all mining and processing operations
• Geotechnical monitoring including radar and cameras established

“Prior to slump”
• Relocated residents of 2 houses
• Briefed landholders below tailings dams and requested restricted access
CADIA NTSF FAILURE DIMENSIONS AND CONTAINMENT

Dimensions Reported/Estimated:
- \( \approx 270 \) m wide
- \( \approx 60 \) to 90 m high
- \( \approx 100 \) m u/s
- \( \approx 200 \) m d/s
- \( \approx 1.3 \) Mm\(^3\) of soil

- Limited flow liquefaction propagation
- Construction of 2 km of containment bunds/berms
- Mining resumed 17 days after slump, processing resumed 22 days after slump

CADIA NTSF PRECURSOR DEFORMATION (DEC 2017 to MAR 2018)
CADIA NTSF PRECURSOR DEFORMATION (9 MAR 2018)

Starter dyke material has displaced and partially raveled downslope.

Horizontal lips reflect previous upstream constructed lifts from starter dyke or upstream raises.

Tailings initially contained by slumped starter dyke material.

Progressive upstream construction from starter ring dyke.

CADIA NTSF CROSS-SECTION

1998-2000

2005-2016

2000-2005

2016-Dec 2017

Dec 2017-Failure

- Stage 10 Completed in Area of Collapse by 31 July 2017
- Buttress 1 Installed In Area of Collapse 15 Dec 2017 to 5 March 2018 – 4 days before failure
- Buttress 2 Not Installed In Area of Collapse Prior to Failure
- 2007 Initiated Buttress Not Installed in Area of Collapse
- Estimated Toe Excavation in Area of Collapse in January 2018 and Left Open

1. **Progressive failure in the foundation soils** as upstream raises cause outward horizontal movement in the foundation.

2. **Foundation movements reduce the lateral support to the tailings** while increasing yielding (deformation) in the tailings.

3. When yielding in the tailings progresses to the instability locus or point of collapse, the **tailings behavior reverts from a drained to an undrained strength**, causing a rapid approximately $\frac{2}{3}$ reduction in their strength.

4. The **loss of strength in the loose saturated tailings** due to their liquefaction resulted in a further increase in the lateral load to the dam wall, causing accelerated and larger scale movements.
BRUMANDINHO - CÓRREGO DE FEIJÃO – DAM 1
CÓRREGO DE FEIJÃO – DAM 1

• Initial Starter Dyke 18 m high constructed in 1976

• Ten (10) upstream lifts in various stages, reaching a height of 86 m by 2013

• Stopped receiving tailings in 2016

• Undergoing reclamation at time of failure

• Failure on 25 January 2019
CÓRREGO DE FEIJÃO – DAM 1 – 25 JAN 2019 - VIDEO
CÓRREGO DE FEIJÃO – DAM 1

High resolution image: 18th January 2019
High resolution image: 29th January 2019
RUSSIAN MINING DAM FAILURE - 19 OCT 2019

“At least 15 people have died and 13 others are missing after a dam collapse at a gold mine in Siberia.”

The dam, on the Seiba river in the region of Krasnoyarsk, burst after heavy rain on Saturday, flooding cabins where workers lived.

"The hydro-technical facility was self-constructed and, I believe, all rules I can and cannot think of were violated," Yuri Lapshin, the head of the Krasnoyarsk regional government, was quoted by RIA news agency as saying.
LEADING INTERNATIONAL STANDARDS & GUIDELINES

Canadian Dam Association (CDA)
- CDA Dam Safety Guidelines

Mining Association of Canada (MAC)
- A Guide to the Management of Tailings Facilities

International Congress on Large Dams (ICOLD)
- Bulletins Specific to Tailings and TSF: 44A, 45, 74, 97, 98, 101, 103, 104, 106, 121, 139, 159

Australian National Committee on Large Dams (ANCOLD)
- ANCOLD Guidelines on Tailings Dams

European Commission
- BAT for Management of Tailings and Waste-Rock in Mining Activities

South African National Standards (SANS)
- SANS Code of Practice – Mine Residue

US Federal Emergency Management Agency (FEMA) & US Army Corp of Engineers (USACE)
ICMM COMMISSIONED REPORT (2016) FOUND:

• Best of currently available national and international guidance documents all provide excellent good practice guidance and provide foundation for good practice in company guidance documents.

• Based upon the three recent failures, they concluded that:

  …if one were to focus on these and other such case histories through consideration of a greater number of failures and investigation results over the last 20 or so years, and ask the question is there anything missing from existing standards and guidance documentation that if known and applied could have forestalled such events, then the answer might be as follows:

**Existing published guidance and standards documentation fully embrace the knowledge required to prevent such failures. The shortcoming lies not in the state of knowledge, but rather in the efficacy with which that knowledge is applied.** Therefore, efforts moving forward should focus on improved implementation and verification of controls, rather than restatement of them.
10 Guiding Principals For Preventing Catastrophic TSF Failures, with the following Commitments:

- **Accountabilities**, responsibilities and associated competencies are defined to support appropriate identification and management of tailings storage facilities risk.

- The **financial and human resources** needed to support continued tailings storage facility management and governance are maintained throughout a facility’s life cycle.

- **Risk management** associated with tailings storage facilities, including risk identification, an appropriate control regime and the verification of control performance.

- **Risks** associated with potential changes are assessed, controlled and communicated to avoid inadvertently compromising facility integrity.

- **Processes** are in place to recognize and respond to impending failure of facilities and mitigate the potential impacts arising from a potentially catastrophic failure.

- **Internal and external review** and assurance processes are in place so that controls for facilities risks can be comprehensively assessed and continually improved.
Third Edition Included New Guiding Principals:

- **Risk-Based Approach** for managing physical and chemical stability considering:
  - Rigorous risk assessment and transparent decision making
  - Best Available Technologies (BAT)
  - Best Available Processes (BAP)

- **Critical Controls** for identification, implementation and performance monitoring to manage high-consequence risks

- **Engineer of Record (EOR)** with the owner having responsibility to identify and retain for design, construction and performance monitoring throughout lifecycle

- **Objective independent third-party independent review** on behalf of owner of all aspects from planning, design, construction, operation, maintenance

“This new Guide provides an outstanding document to influence the organization and governance protocols needed to ensure safe tailings management from the conceptual stages through to closure.” (Morgenstern 2018)

9 September 2019: Brazil Instituto Brasileiro de Mineração (IBRAM), announced that it will adopt the Towards Sustainable Mining (TSM) initiative, a corporate social responsibility program developed by the Mining Association of Canada (MAC). IBRAM joins six other mining associations around the world, including the second in Latin America, in adopting TSM, an increasingly internationally recognized standard for responsible mining.
27 March 2019:

ICMM, UN Environment Programme and Principles for Responsible Investment Agree to Co-convene Mine Tailings Storage Facilities Review

London, UK – The International Council on Mining & Metals (ICMM), the United Nations Environment Programme (UNEP) and the Principles for Responsible Investment (PRI), today announced that they will co-convene an independent review that will establish an international standard on tailings storage facilities.

While the standard would become an ICMM company member commitment, the co-convening partners will encourage others to join in advocating for it to be accepted more broadly.

This initiative is in response to the recent tragedy at Brumadinho and will be informed by evidence and lessons from earlier mine tailings dam failures. The aim is to complete this work by the end of the year.

The PRI will be represented by the Church of England Pensions Board and the Council of Ethics of the Swedish National Pension Funds, who are both PRI signatories.

As a next step the co-convenors will jointly appoint an independent chair and a multi-stakeholder advisory panel. There will be a further update once the chair has been appointed.
“To this end, it is recommended for any specific project that the operator be required to develop, for regulatory approval and subsequent execution, a tailings management system for Performance-Based, Risk-Informed Safe Design Construction Operation and Closure of the proposed tailings storage facility (PBRISD). Many single elements combined in PBRISD have been identified before, but the required integration presented in the following is perceived as necessary to impose more rigorous direction, supported by critical levels of review at various stages of the process.”

- **Stage 1 (Conceptual)** involving a qualified operator, established independent review board, uncertainty assessment, potential problem analysis (PPA), and multiple account analysis (MAA)
- **Stage 2 (Feasibility)** involving engineer of record (EOR), designer, design basis memorandum (DBM), risk assessment, quality management, documentation
- **Stage 3 (Construction and Operation)** involving safe construction and operations dictated by the operation, maintenance and surveillance manual (OMS)
- **Stage 4 (Closure)** planning considered during all previous stages, with increasing levels of detail with time

“Instead, the underlying principle for the tailings management system advocated here (PBRISD) is accountability. This is achieved by multiple layers of review, recurrent risk assessment, and performance-based validation from construction through closure.”
SOME FINAL COMMENTS

- Major **failure rates of 2 events/year** unlikely to lessen in short term
- **Various innovations** in dewatering and storage of tailings reducing risk of collapse and downstream consequences (mobility)
- **Lessons are being learned** from major failures such as Mount Polley, Samarco, Cadia, and Feijão (technically, operationally and managerially – reduce risks and consequences)
- Available **national and international** guidance documents provide excellent **good practice guidance** in design, construction, operation, and closure
- Guidelines being upgraded with support of ICMM, UN, and PRI, which are being informed based upon Performance-Based, Risk-Informed Safe Design Construction Operation and Closure
- “Tailings dams are **complex systems** that have evolved over the years. They are also **unforgiving systems**, in terms of the **number of things that have to go right**. Their reliability is contingent on **consistently flawless execution** from concept to completion.” (Mount Polley Expert Panel Report)
>1250 Engineers, Consultants, Scientists, and Professionals providing innovative solutions

>100 Countries we’ve worked in, providing comprehensive safety, security and risk-based engineering and scientific solutions

>70 Global office locations located in key metropolitan areas to better serve our clients

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Building Design + Construction (BD+C) Top Engineering Firms:
Ranked #3 out of 60

Consulting-Specifying Engineer (CSE) MEP Giants:
Ranked #6 out of 400

Engineering News Record (ENR) Top Design Firms:
Ranked #105 out of 500