# Tailings Dam Monitoring to Reduce Risk of Failures

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# Constraints Under Which Surface TSFs Must Operate

- Climatic, topographic and seismic settings
- Nature of tailings, particularly sulfidic minerals and presence of clay minerals
- Tailings production rate and % solids on deposition
- Dam foundation conditions and borrow materials
- Need to maximise tailings settled dry density and strength
- Mitigating risk of a (sudden) spill of water and/or tailings
- Need to manage, store, and recycle process water
- Need to meet discharge water quality licence conditions
- Need to rehabilitate TSF in perpetuity

***People, infrastructure and environment downstream are key risks***

# Conventional Tailings Disposal and Storage

***Commonly held perception, supported by NPV approach, is that transporting tailings as a slurry to a dam is most economic***

- Dewatering tailings to a paste or by filtration is perceived to be too expensive
- Reduced storage volume occupied by tailings paste or filter cake, and relative ease of capping are discounted, as is potential for a higher level future land use
- Cost of rehabilitating resulting soft and wet tailings is discounted and not considered to be significant
- Few TSFs have been rehabilitated, due to difficulty and expense of capping “slurry-like” tailings, particularly at a time when mine is no longer producing revenue

# Key Causes of Tailings Dam Failures and Industry Threats

- Most tailings dams that fail have marginal stability
- Most tailings dam failures involve "water", making drainage, clay cores and water management of key importance
- Many tailings are potentially liquefiable
- Another cause can be a weak (often unidentified, possibly moving from over- to normally-consolidated on progressive raising) foundation layer
- Industry threats are coming from:
  - Investors; e.g., Church of England
  - Insurers
  - Regulators; e.g., outlawing upstream construction, which happened in Chile following earthquake-induced failures in 1965, and will follow in Brazil (wet climate and failures)

# Susceptibility of Tailings to Liquefaction

- Earthquake-induced liquefaction susceptibility:
  - Fine-grained sandy or silty sand tailings **–** √
  - Loose (brittle [collapse beyond peak], contractive [more so at higher stress]) state **–** √
  - Near-saturated **–** √
  - Earthquake magnitude > 5.5 and peak ground acceleration >0.13g **– ?** Static or flow liquefaction, triggered by:
  - Loss of containment due to dam/upstream raise instability
  - Overtopping and erosion of dam/upstream raise
  - Rise in phreatic surface due to heavy rainfall or fresh tailings

  } Undrained unloading

  - Pore water pressure increase due to dam raise, recharge or blocked drains – Undrained loading

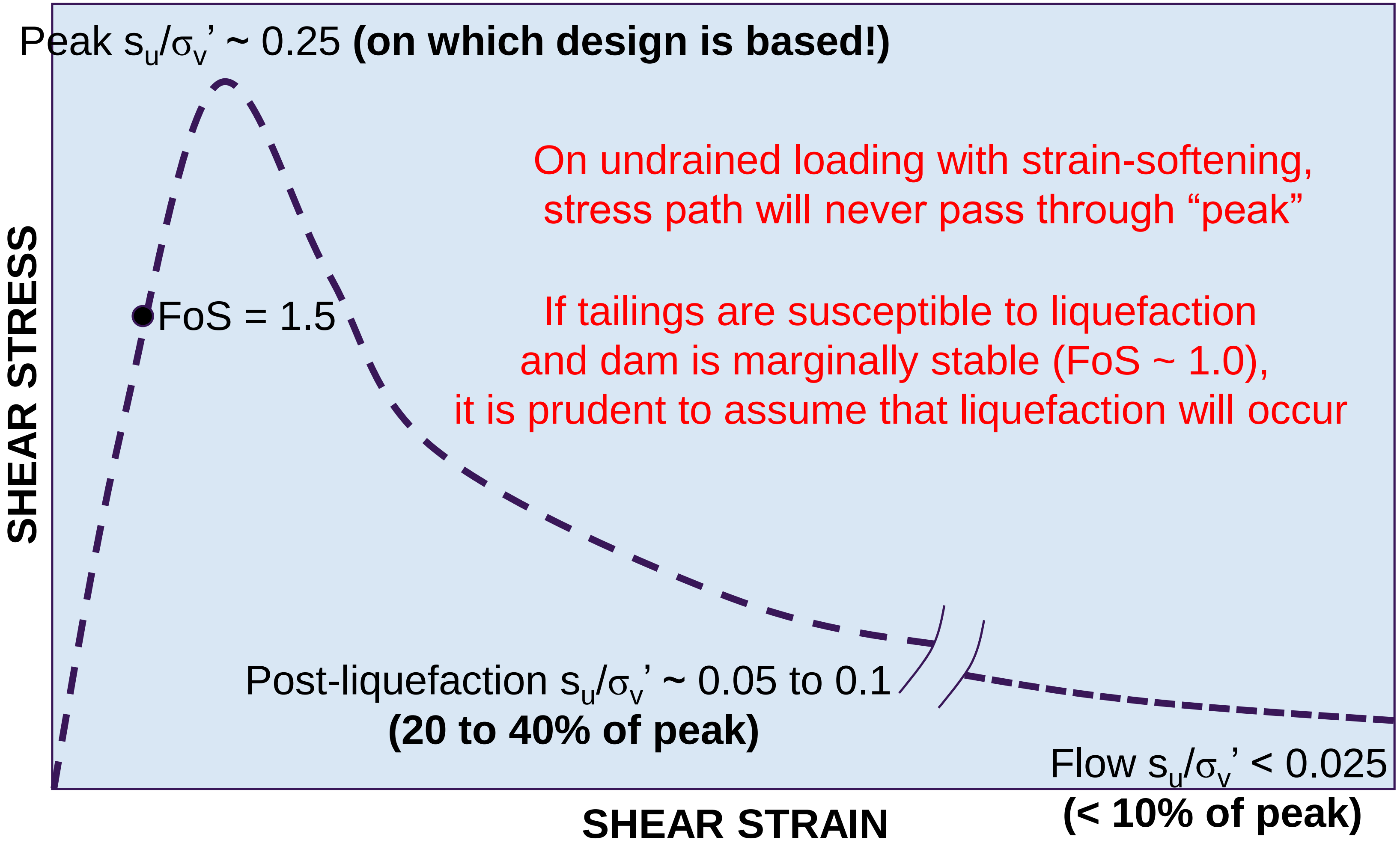
***Susceptible tailings can behave in an undrained, contractive, strain-softening manner, and liquefy or flow***

# Susceptibility of Tailings to Liquefaction

- Moisture content << Liquid Limit suggest that tailings will not liquefy
- However, tailings state (loose or dense) *in situ* is difficult to determine, particularly if tailings are loose:
  - They can't be sampled at their *in situ* state, if at all (an indicator of liquefaction)
  - CPTu data plot in bottom left-hand corner of log-log SBT Chart, where few correlation data exist
  - Some use is made of SPT, with difficulty
  - Some use is made of "simple shear" testing, but samples may not be at *in situ* state

***In absence of laboratory test data, liquefaction susceptibility and post-liquefaction shear strength may be estimated based on correlations between liquefaction case histories (notably mainly in natural, uncemented soils) and CPT cone resistance***

# Relative Peak, Post-Liquefaction and Flow Shear Strengths of Tailings



On undrained loading with strain-softening, stress path will never pass through “peak”

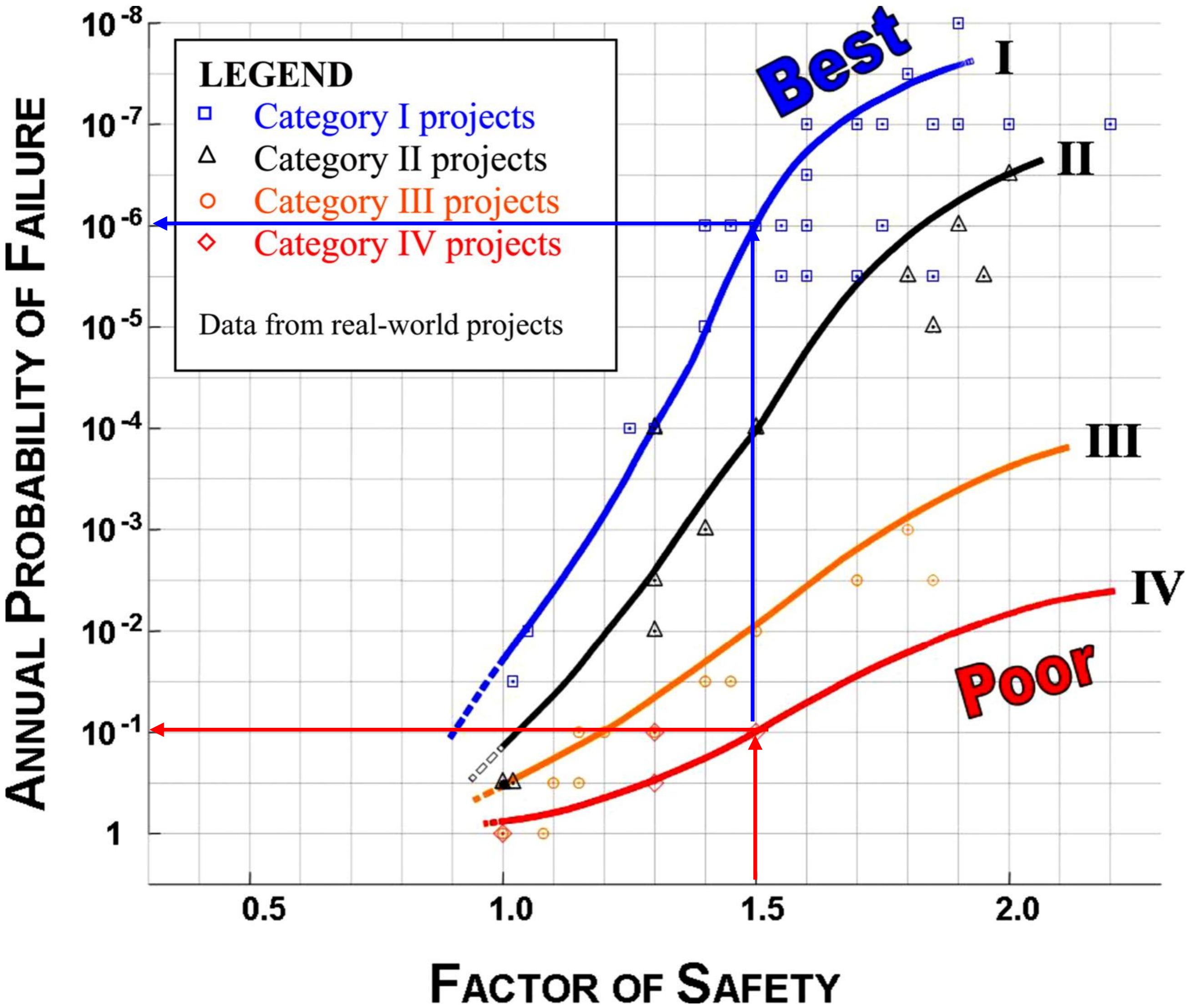
If tailings are susceptible to liquefaction and dam is marginally stable (FoS ~ 1.0), it is prudent to assume that liquefaction will occur

# Commentary on Geotechnical Design Parameters

| PARAMETER | TYPICAL RANGE |
|---|---|
| Angle of repose of waste rock | 37± 3° (depending on weathering and durability) |
| Annual Rainfall | ± 50% of average annual rainfall |
| Design peak ground acceleration | Perhaps ± 20% for operations to ± 50% for closure? |
| | |
| Undrained cohesion | ± 50% |
| Undrained shear strength ratios:<br>Peak<br>Residual | <br>0.25<br>0.05 to 0.10, or lower |
| Drained cohesion | Often assumed = 0, but suction on desiccation will induce some apparent cohesion |
| Drained friction angle | ± 3° (~ 6° higher than angle of repose, implying a Factor of Safety = 1.24) |
| Unit weight | ± 10% (typically has little impact) |
| | |
| Erosion loss | ± 100% or greater? |

What are error bars on calculated Factor of Safety? – Certainly >> 1 decimal place!

# Annual $P_f$ versus FoS (Silva, Lambe and Marr, 2008)



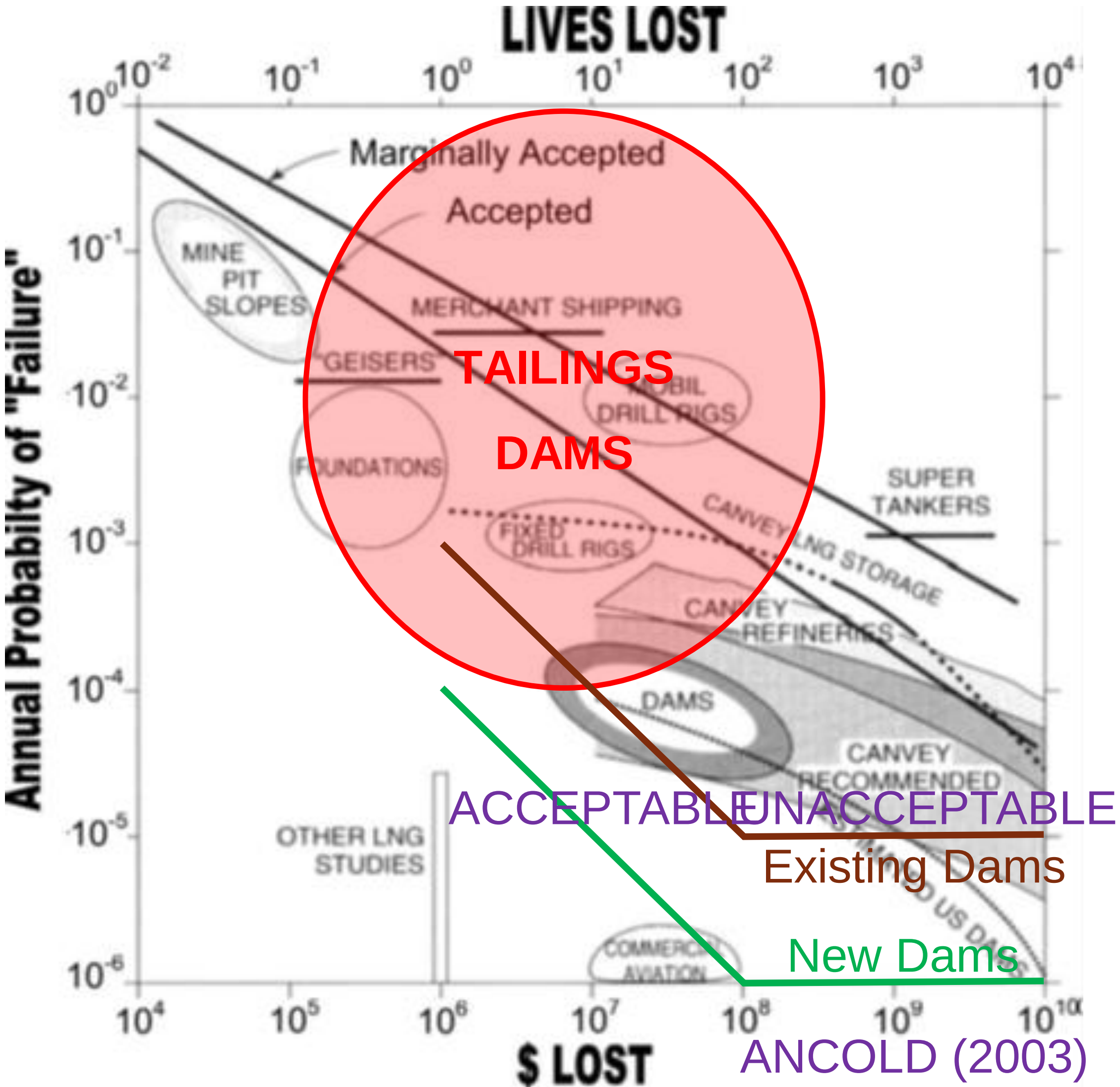
Design and Construction

Design and Construction

# Way Forward

- Risk assessments of tailings dams are common-place
- Defining what is an ***"acceptable"*** risk level is difficult
- Ongoing rate of tailings dam failures is ***unacceptable*** (100 x that of water dams!)
- Approaches to tailings management need to improve
- Tailings minimisation and dewatering need to be pursued
- Design, construction, operation and closure of TSFs need > reliability & resilience
- Monitoring and interpretation of tailings dams needs to be more comprehensive, and in real-time, linked to triggers:
  - Green, for safe operation
  - Amber, requiring assessment by a Geotechnical Engineer
  - Red, initiating Emergency Response Plan

# Acceptability of Tailings Dam Risk? (After Silva, Lambe and Marr, 2008)



ANCOLD (2003)

# Emerging Tailings Dam Surveillance Methods

| METHOD | COMMENTS |
|---|---|
| Drone surveillance | Aiding visual inspection and LiDAR |
| Nested VW Piezometers | Recording and analysing phreatic surface and hydraulic gradient in real-time |
| V-notch weirs for monitoring flows | Recording and analysing flows in real-time |
| Settlement monuments and inclinometers | For correlation with Radar and InSAR – Must be high resolution |
| LiDAR (above water) and bathymetry (below water) | For density estimation, and evaporation estimation |
| Slope Stability Radar | Potential “noise” issues due to short wavelength, rapid scanning, and lack of visible targets can reduce reliability |
| Satellite InSAR | Fortnightly/weekly fly-over for line-of-sight deformations (potentially to ±3 mm/year), wet spots and vegetation |
| Environmental monitoring | For water quantity and quality |
| Future “Smart” geofabrics | In tailings beach, or under upstream raises |

# Radar Frequencies and Wavelengths (Source: GroundProbe)

<table>
<tr><th>PARAMETER/BAND</th><th>L-BAND</th><th>S-BAND</th><th>C-BAND</th><th>X-BAND</th><th>Ku-BAND</th></tr>
<tr><td>FREQUENCY (GHz)</td><td>1-2</td><td>2-4</td><td>4-8</td><td>8-12</td><td>12-18</td></tr>
<tr><td>WAVELENGTH (cm)</td><td>30-15</td><td>15-7.5</td><td>7.5-3.75</td><td>3.75-2.5</td><td>2.5-1.67</td></tr>
<tr><td>COMMON USES</td><td>Radio/Mobile communications</td><td>Airport surveillance</td><td>Satellite communications</td><td>Wireless communications</td><td>Microwaves, affected by moisture</td></tr>
<tr><td rowspan="2">InSAR; e.g.</td><td>JERS<br>ALOS PALSAR<br>ALOS2</td><td></td><td>ESA Sentinel<br>RADARSAT1/2</td><td>TerraSAR-XCOSMO-SkyMed</td><td rowspan="2"></td></tr>
<tr><td colspan="2">Not much used for InSAR</td><td colspan="2">Long-term, large area deformation</td></tr>
<tr><td rowspan="2">GROUND-BASED</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td>GBRAR (Real)</td><td>GBSAR (Synthetic)</td></tr>
<tr><td colspan="2">Rapid, targeted scanning; e.g., of pits<br>Application to tailings dams affected by moisture, vegetation and rapid scanning</td></tr>
</table>

# Monitoring to Provide Adequate Stability and Warning of Failure

***Above all, design, operate and close a tailings dam ensuring an adequate FoS against geotechnical failure***

- Avoid, where possible, people at risk downstream of a tailings dam
- Aim to provide at least 24 hours warning to evacuate any people downstream of a tailings dam
- Install redundant monitoring systems, recorded and analysed in real-time, and linked to triggers and responses, including:
  - Daily inspections for wet spots, cracking, deformation, etc., aided by drones
  - Phreatic surface and hydraulic gradient – Nested VW Piezometers confirmed by regular CPTu
  - Deformation – Combination of automated total station prisms, inclinometers, Radar (long wavelength), and InSAR
  - Flows and water quality monitoring – Automated V-notch weirs and sampling

# Lessons Learned from Recent Tailings Dam Failures

- Common Threads:
  - Fatal tailings dam failures are more likely in developing countries
  - Most past and recent tailings dam failures involve dams constructed upstream
  - Split of failures is roughly equal between closed and operational dams
  - Split of liquefaction failures is roughly equal between seismic and static liquefaction
  - About half of recent tailings dam failures involve weak foundations
  - Cementation and suction provide apparent cohesion, which can be lost
  - A closed or inactive dam should not be considered safe unless monitoring indicates unsaturated conditions (i.e., drain down on cessation of tailings deposition, which would be expected in a dry climate, but may not occur in a wet climate)
  - Tailings dam failures occur very rapidly, with little or no warning
  - While mechanisms of failure can usually be identified retrospectively, triggers are more difficult to identify

# Some Upcoming Meetings and Conferences

ANCOLD – **Considering Liquefaction of Tailings Workshop** – 12 November 2019 Perth – https://www.ancold.org.au/?p=15322

**10th Australian Workshop on Acid and Metalliferous Drainage (AMD) 2020** – 23-26 March 2020, Dubbo – https://amdworkshop.com.au/home

**Mine Waste and Tailings (MWT) 2020** – 28-30 July 2020 in Brisbane – https://tailings.ausimm.com/ – Call for Abstracts open till end October 2019

**International Conference on Acid Rock Drainage (ICARD) 2021** – 30 August to 3 September 2021, Brisbane – https://www.inap.com.au/icard/