FGI Webinar: Lessons Learned from Tailings Dam Failures

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Introduction

Tailings dam failures represent catastrophic events with significant loss of life and environmental impacts, exposing critical weaknesses in design, construction, and operational practices. This webinar examined major failures including El Cobre (Chile), Mount Polley (Canada), Fundão and Brumadinho (Brazil), and Cadia (Australia), analyzing technical causes, regulatory responses, and lessons learned. The presentation integrated geotechnical stability principles with governance considerations including bias, liquefaction risks, and evolution toward the Global Industry Standard on Tailings Management (GISTM).

Liquefaction: The Fundamental Challenge

Liquefaction represents the most critical technical challenge in tailings dam stability. Dr. Ishihara advised avoiding liquefiable materials entirely, as water dams would never be built on such substrates. Dr. Morgenstern emphasized that susceptible tailings should be assumed to fail at some stage. Laboratory data shows liquefaction triggering strengths approaching zero pascals—fluid behavior—rather than the commonly assumed 20% of peak strength. Data from failures and flood mitigation structures confirm post-liquefaction residual strengths measured in pascals, contradicting retained strength assumptions in stability analyses.

El Cobre, Chile: Industry-Led Transformation

Pre-failure calculations consistently overestimate stability. Mount Polley's design factor of safety was 1.43; actual construction yielded approximately 1.1 with no required undrained analysis despite liquefaction risk. Cadia presumed 1.5 but back-calculated to 1.15. Fundão calculated 1.09 with liquefaction dismissed, yet failed by flow liquefaction. The only certain factor of safety for any failed structure is 1.0; all other values represent uncertain calculations.

The El Cobre failure (pre-1965) killed 250-350 people when an upstream-raised dam failed through the village. This catalyzed fundamental transformation in Chile's seismic environment.

Critically, the industry developed solutions before regulatory mandates: upstream raising was banned, downstream slopes were flattened by half, centerline/downstream construction replaced upstream methods, sand-slimes separation enabled competent downstream sand dams, and upstream geomembranes limited water infiltration. Performance has been exemplary since, demonstrating industry capacity for change. Regulators took five years to formalize these practices, showing that industry leadership drives meaningful safety improvements.

Mount Polley, Canada: Foundation Weakness and Construction Deviation

The Mount Polley failure (2014) released tailings and water down Hazeltine Creek into Polley Lake with no fatalities but significant environmental impact and operational disruption. Technical causes identified by the independent expert panel centered on an unknown weak glaciolacustrine foundation layer beneath the embankment. This foundation material, though slightly overconsolidated, became normally consolidated when loaded beyond preconsolidation stress by embankment weight addition, reducing stiffness approximately tenfold and increasing deformations proportionally. Foundation investigation failed to identify this critical weakness despite its predictable behavior under loading. The downstream rockfill buttress was constructed at 1.3H:1V (angle of repose from end-dumping) rather than the designed 2H:1V, eliminating planned stability margin. Construction methodology—end-dumping from the crest rather than controlled placement and compaction—guaranteed steeper slopes. The critical combination of weak foundation and reduced buttress effectiveness created marginal stability. Tailings, water, and slimes positioned against the embankment section that failed enabled overtopping erosion and catastrophic runout once embankment height was lost, with materials flowing down Hazeltine Creek to Polley Lake approximately 10 kilometers distant.

Mitigation recommendations addressed governance improvements including enhanced corporate design responsibility and independent tailings review boards (ITRBs), catalyzing adoption of Engineer of Record and Responsible Tailings Facility Engineer designations with clear accountability. Technology recommendations included filtered/thickened tailings and reduced reliance on water storage, though governance changes proved easier to implement than operational modifications. The failure demonstrated that changing governance structures occurs more rapidly than transforming fundamental tailings management approaches, with the former providing incremental safety improvements while the latter offers potential for dramatic risk reduction.

Fundão, Brazil: Rate of Rise and Foundation Extrusion

The Fundão failure (2019) liquefied in seconds, killing 19 people and releasing tailings 600 kilometers downstream to the Atlantic Ocean, with fine sediments remaining visible in the ocean as suspended load. The facility operated within a larger complex including the heavily buttressed Germano Dam in the Germano Valley and the smaller Fundão Valley separated by a ridge. Original planning envisioned raising Germano Dam to the ridge elevation before engaging Fundão storage, creating a large combined impoundment. Inadequate advance permitting prevented Germano raising, forcing entire tailings production into the much smaller Fundão

Valley. The resulting rate of rise reached 2-3 meters per month during peak production periods—over ten times typical Australian practice of 2-3 meters per year—while processing relatively low-grade iron ore generated massive tailings volumes. This exceptional rate of rise prevented adequate consolidation and strength gain in deposited slimes.

Technical failure causes identified by the expert panel included the original starter dam, rapid slimes deposition particularly near the embankment, concrete drain failure at the left abutment, subsequent setback raising over deposited slimes rather than beach sands, progressive damage and lateral extrusion (squeezing) of slimes beneath embankment loading. Lateral extrusion—a term borrowed from metallurgy and geology rather than geotechnical engineering—described foundation material displacement under rapid loading without sufficient drainage time for consolidation. The setback raising practice, common in Latin America to reduce overall slope angles, positioned embankments on wetter, softer slimes further down the beach, inevitably degrading stability compared to raising directly on competent beach sands near the crest. Three small closely-timed earthquakes (largest magnitude 2.6) occurred approximately one kilometer from the dam 30 minutes before failure. While individually below the magnitude 4-5 threshold typically required for liquefaction triggering, the rapid succession (approximately 10-minute intervals) prevented excess pore pressure dissipation between events, potentially creating cumulative effects equivalent to a larger single event. The marginally stable setback experienced likely lateral extrusion from rapid rise rates, with small sequential earthquakes providing the final trigger for flow liquefaction failure.

Brazilian Regulatory Evolution Post-Fundão

Prior to Fundão (pre-2019), Brazilian law mandated only drained geotechnical stability analysis. Drained parameters (friction angles) exhibit relatively narrow variability (±3 degrees) and produce generally favorable factors of safety, making drained analysis non-critical for most tailings facilities. Undrained and seismic stability—typically the critical cases—were not legally required despite representing the failure modes observed in practice. This created a fundamental disconnect between regulatory requirements and actual failure mechanisms. Latin American design follows prescriptive legal mandates ("you must do X") rather than the guideline-based approaches ("you should consider X") common in English-speaking countries following ANCOLD, ICOLD, or similar frameworks.

Following Fundão (2017 forward), Brazilian law changed to require drained, undrained, and post-seismic analyses. This created immediate challenges for Brazilian practitioners unaccustomed to determining reliable undrained strengths, which vary significantly more than friction angles depending on consolidation history, density, structure, and testing methodology. Different consultants produced different undrained strength values, yielding different factors of safety for identical projects and creating confusion about acceptable outcomes. If any calculated factor of safety falls below required minimums, deformation analysis is now mandated to evaluate strain potential and consequences. This regulatory evolution demonstrates reactive rather than proactive safety improvements, with fundamental analysis requirements only mandated after catastrophic failure rather than being incorporated from first principles of geotechnical engineering practice.

Cadia, Australia: Unexpected Foundation and Loading Sequence

The Cadia failure (2018) involved the northern embankment releasing into the southern tailings storage facility, contained entirely within the overall facility footprint with no fatalities or injuries despite significant operational impact. The northern embankment section that failed coincided with a persistent wet spot visible in aerial photography—the highest point along the embankment crest where wet conditions indicated seepage or poor drainage. Prior to 2003, no southern impoundment existed; subsequent construction created the storage area immediately adjacent to the northern embankment toe.

Technical causes centered on loading at the crest (upstream raising) combined with loading at the toe (southern facility filling), eliminating the stabilizing influence of competent downstream foundation support. A relatively weak glaciolacustrine foundation layer—again, unidentified during investigation—underlay the failure section. The highest point along the embankment crest experienced the most critical loading conditions. High phreatic surface elevation at the time of failure indicated poor drainage or excessive seepage. Upstream raising methodology and excavation at the crest for the Mainstream Storage expansion further destabilized the section. Construction of an upper buttress for stabilization preceded placement of lower buttresses—a critical sequencing error. For a typical circular failure surface centered upgradient of the embankment, material placed on the downslope side of the center (the upper buttress location) contributes to the driving moment rather than resisting moment, worsening stability. Lower buttresses positioned further downslope would have provided actual resistance, but were not constructed until after the upper buttress. Following upper buttress construction, excavation for the southern facility foundation exposed weak foundation conditions and removed lateral support at the downstream toe. This combination—adding load upslope of the critical failure circle center while removing support downslope—guaranteed instability.

Feijão (Brumadinho), Brazil: Creep, Strength Loss, and Climate

The Feijão dam at Brumadinho (2019) liquefied in seconds, killing 272 people in Brazil's deadliest mining disaster. The embankment stood approximately 80 meters high with an extremely high proportion of that height comprising tailings rather than competent engineered fill—essentially a marginally stable structure dependent on tailings for support. The expert panel found failure resulted from a critical combination of ongoing internal strain accumulation (creep) and strength reduction due to wetting of the unsaturated zone during wet season rainfall. The wet season preceding failure was not the wettest on record but represented a continuation of progressively wetter conditions over approximately 60 years, potentially making failure a matter of time rather than requiring an extraordinary triggering event. The facility had been closed for several years, eliminating operational factors and making the dam entirely dependent on climate conditions and internal processes rather than external loading changes.

Limit equilibrium stability analysis assumes all points on a potential failure surface exist at the same stress state simultaneously. This assumption fails for marginally stable structures where portions of the potential failure surface may already have exceeded peak strength and entered post-peak softening while other portions remain pre-peak. This creates a progressive failure mechanism not captured by conventional factor of safety calculations assuming simultaneous mobilization. The Brumadinho tailings exhibited brittle bonded behavior due to iron-rich composition; iron oxidation created cementation that provided apparent cohesion, but once broken through strain accumulation or strength reduction, materials lost strength rapidly. The combination of ongoing creep deformation (even at rates as low as 30 millimeters per year with seasonal fluctuation) and strength reduction from wetting created conditions where progressive portions of the failure surface exceeded peak strength, redistributing stresses to adjacent regions in a cascading mechanism.

Rainfall infiltration during wet seasons saturated the unsaturated zone above the phreatic surface without necessarily raising the water table significantly, as moisture was absorbed into previously unsaturated materials. This process eliminated matric suction—negative pore pressures providing apparent cohesion—reducing shear strength without changing effective stress conditions measured by piezometers monitoring positive pore pressures. Conventional instrumentation using vibrating wire piezometers measures positive pressures but not negative pressures (suction), creating a blind spot in monitoring programs that fail to detect strength reduction in unsaturated zones above the phreatic surface. Post-closure facilities lacking active management to control water through deposition, drainage, or operational intervention become entirely dependent on climate conditions, with wet years progressively degrading strength in unsaturated zones while creep continues independently, together driving structures toward failure.

Global Industry Standard on Tailings Management (GISTM)

Brumadinho catalyzed development of the Global Industry Standard on Tailings Management (GISTM) with the aspirational goal of zero harm to people and environment from tailings facilities. GISTM mandates extreme consequence classification with 10,000-year return period design floods and earthquakes for all facilities. However, this creates a mismatch with existing design standards: current practice typically designs for probable maximum flood (PMF) and maximum credible earthquake (MCE) at closure but significantly lesser events (1-in-100 to 1-in-1,000 year) during operations. The 10,000-year return period actually matches ANCOLD and CDA guidelines for closure conditions but exceeds operational requirements. Climate change considerations suggest designing for PMF and MCE from the start of operations rather than deferring to closure, but GISTM implementation focuses primarily on new facilities with limited retrofitting of existing structures.

The practical outcome of GISTM has been substantial improvement to governance structures—ITRBs, Engineers of Record, Responsible Tailings Facility Engineers, enhanced corporate accountability, improved monitoring and reporting—without proportional improvement to fundamental tailings management practices or design standards. Companies claim near-100% GISTM compliance based primarily on governance checklist completion, creating perception that "GISTM is done" despite minimal change to actual tailings handling, storage methodologies, or design conservatism. The industry interprets compliance through documentation and organizational structure rather than transformative operational change. Future GISTM evolution must address the disconnect between aspirational 10,000-year safety standards and continued design/operation at lesser criteria, potentially requiring adoption of PMF/MCE as operational standards rather than closure standards, though economic and technical feasibility concerns impede this transition.

Typical Versus Optimal Construction Sequencing

Conventional tailings dam construction follows an inefficient evolutionary sequence. Initial starter dams are followed by one or two downstream raises while economically feasible, then transition to upstream raising when downstream material volumes become prohibitive, potentially adding buttresses when upstream failure concerns emerge. At closure, design objectives demand a stable post-closure landform requiring substantial additional fill to achieve acceptable downstream slopes. The total volume of material placed through this evolutionary sequence dramatically exceeds the volume required if the stable post-closure configuration had been constructed initially.

Economic objections claim upfront costs prohibit initial construction of stable final configurations. However, if closure requirements mandate stable post-closure landforms regardless, the obligation exists whether acknowledged at outset or deferred. Current practice defers the inevitable at higher total cost through interim configurations requiring eventual reconstruction. Water dams are designed and constructed to final stable configurations from the start; tailings dams should adopt identical philosophy. The fundamental question: why not build a stable dam from the beginning if stability represents the mandatory end-state? Whole-of-life accounting rather than net-present-value accounting reveals that deferred stability costs more in total material, construction effort, and long-term liability while providing less safety during operational life.

Key Conclusions and Path Forward

Tailings dams that fail demonstrate marginal stability regardless of calculated factors of safety, revealing limitations in predictive analysis. Failures typically result from combinations of causes with water content being the critical common factor—both as stored tailings moisture and as operational/climate-introduced saturation. Catastrophic failures can drive industry transformation when lessons are internalized: El Cobre revolutionized Chilean tailings practice through industry-led changes that preceded regulatory mandates by five years, demonstrating that leadership rather than compliance drives safety culture. Brumadinho catalyzed GISTM adoption with zero-harm aspirations, but implementation has focused on governance improvements rather than fundamental operational change. Companies claiming near-100% compliance based primarily on governance structure completion believe "GISTM is done" without transforming tailings management practices.

Alternatives to repeating historical approaches include widespread adoption of thickened, paste, and filtered tailings; integrated waste rock and tailings co-disposal; and fundamental separation of stable containment structures from optimized tailings storage rather than conflating the two objectives. The industry cannot continue constructing structural zones that are essentially upstream geometries dependent on deposited tailings for support and label them as safe alternatives. Regulators in Latin America recognize that "stacks" (filtered tailings) claiming stability while relying on underlying tailings for support represent marginally different configurations of the same fundamental vulnerability as upstream dams. Stable tailings containment must be separated conceptually and physically from optimal tailings storage and dewatering, with the two systems designed independently then integrated to work together.

Recovery of community confidence and trust—largely lost and extremely difficult to restore—demands demonstrable commitment to fundamentally safer approaches rather than incremental governance improvements. The mining industry must move beyond doing what has always been done while hoping for better outcomes, acknowledge the role of bias and ego in perpetuating unsafe practices, and embrace transformative change in tailings management philosophy, design standards, and operational practices to achieve meaningful risk reduction aligned with GISTM's aspirational zero-harm goal.