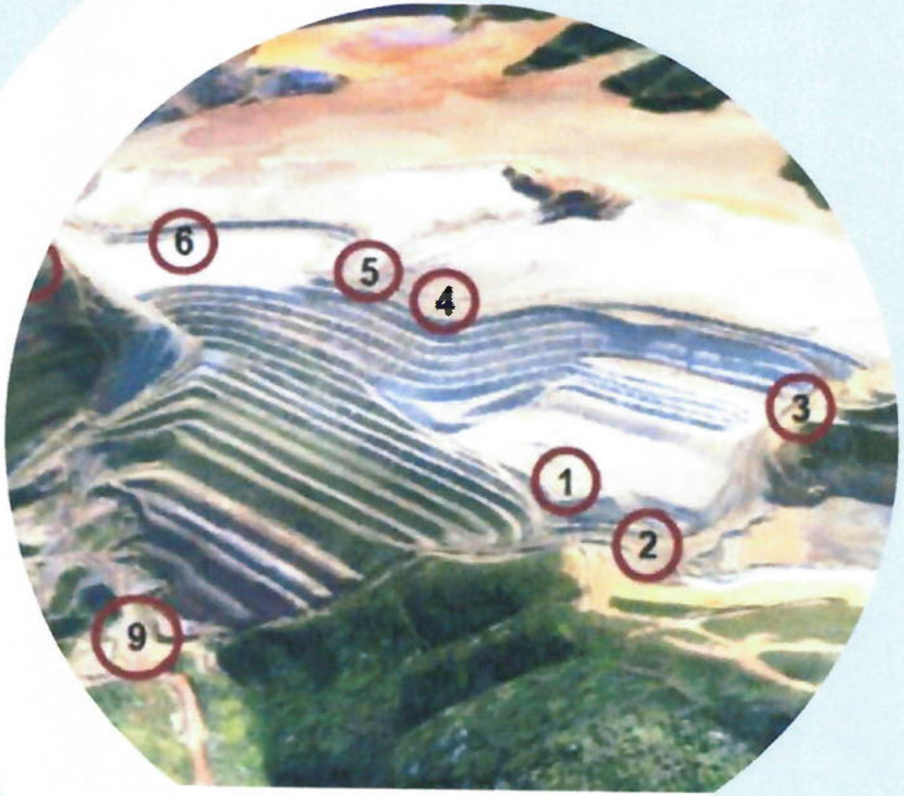
Appendix No 8

WHY MINE WASTE IMPOUNDMENTS EXPERIENCE STABILITY FAILURES September 5, 2019. W. Allen Marr Founder and CEO of Geocomp NAE, PE, PhD, ASCE Fellow Board Certified in Geotechnical Engineering Committee on Geological and Geotechnical Engineering Board on Earth Sciences and Resources National Academies of Sciences, Engineering, and Medicine.

Third Party Planning Appeal of the decision by Meath County Council to grant planning permission for development Planning Reference Number: 22331 Meath CoCo.

Planning Application Reference: 22331 Meath County Council
Development Address: Randalstown, Simonstown and Sillogue, Navan, Co Meath
Applicant: Boliden Tara Mines DAC,
Agent: John Callaghan, Civil Engineer, 10 The Cloisters, Oldcastle Road, Kells, Co Meath A82C9Y7
Agent's Address: John Callaghan, Civil Engineer, 10 The Cloisters, Oldcastle Road, Kells, Co Meath A82C9Y7
Appellant: Sustainability 2050, Care of John Callaghan, 10The Cloisters, Oldcastle Road, Kells, Co Meath A82C9Y7
Appellant Address: Sustainability 2050, Care of John Callaghan, 10The Cloisters, Oldcastle Road, Kells, Co Meath A82C9Y7
Address for correspondence: John Callaghan, 10 The Cloisters, Oldcastle Road, Kells, Co Meath A82C9Y7



WHY MINE WASTE IMPOUNDMENTS EXPERIENCE STABILITY FAILURES

Committee on Geological and Geotechnical Engineering
Board on Earth Sciences and Resources
National Academies of Sciences, Engineering, and Medicine

September 5, 2019

W. Allen Marr
Founder and CEO of Geocomp
NAE, PE, PhD, ASCE Fellow
Board Certified in Geotechnical Engineering

Outline of presentation

- Brief review of some significant failures of tailings dams
- Some characteristics of tailings dam failures
- Key aspects of geotechnical failures in tailings dams
- Shear strength concepts for granular materials
- Some design goals
- Summary

Note this presentation does not address seismic factors.
Contents are work by W. Allen Marr and do not reflect any position of COGGE or NAE.

Scope

- Barriers made of earthen or waste materials that retain particulate wastes placed by sluicing at high water content.
- Barriers – dams, impoundments, ponds
- Particulate materials – tailings, washings, ashes, slags, chemical by products like gypsum
  - Placement varies by industry. Mechanical and physical properties can vary widely even within same stack

Cities Service, FL, USA (1971)

Date:	Dec 3, 1971, sudden, no warning
Type:	15 m homogenous earthen embankment, retaining clay slimes for phosphate mine
Failure Mode:	Stability failure of the dam <u>due to uncontrolled flow through the dam</u>
Volume Spilled:	9 million cubic meters of clay tailings
Consequences:	Clay tailings traveled 120 km downstream in Peace River, large fish kill First use by courts in FL of strict liability doctrine for hazardous use of land. Led to implementation of design regulations for dams in FL

Buffalo Creek, West Virginia, USA (1972)

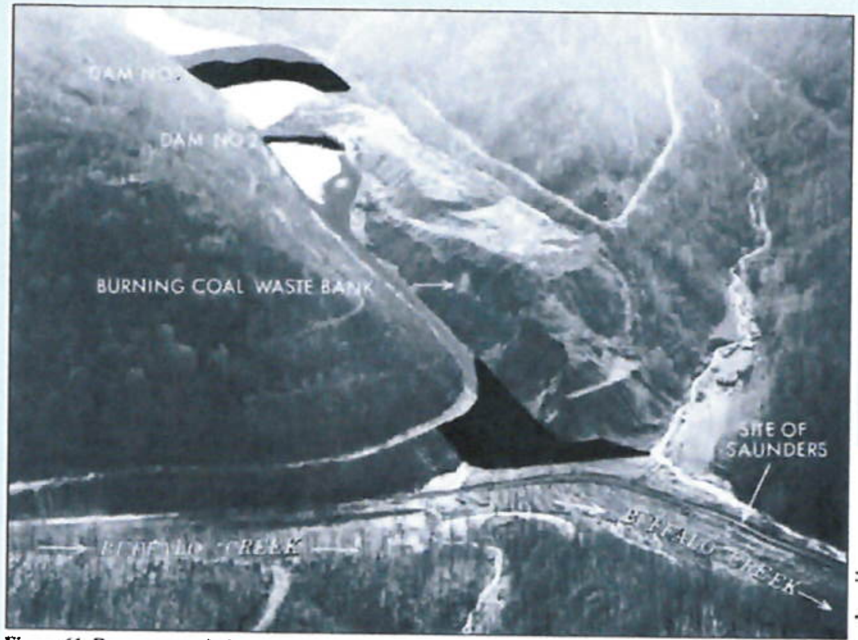


Figure 61. Reconstructed view of the damsite.
Source: U.S. Geological Survey, Circular 667

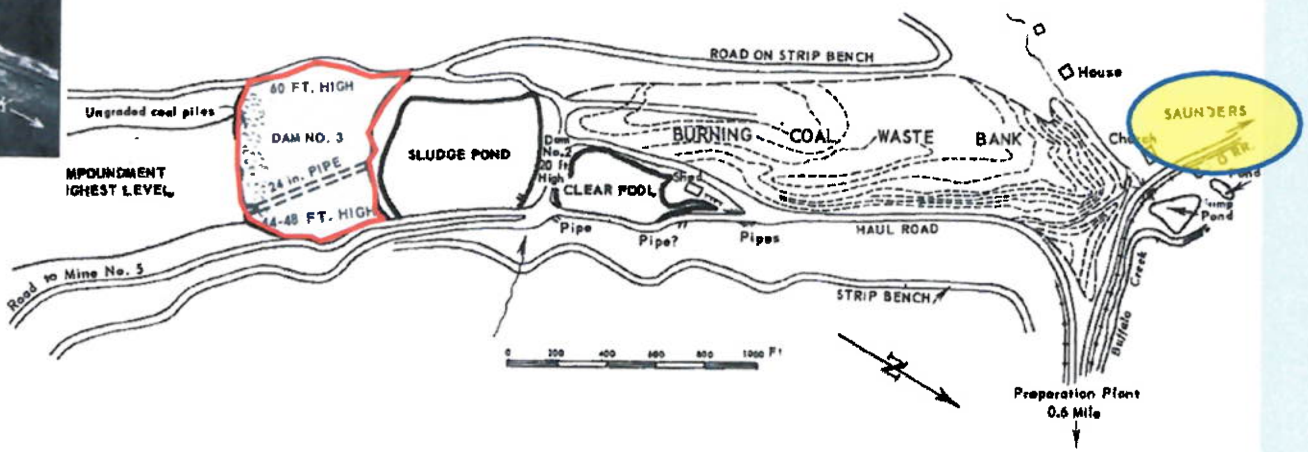
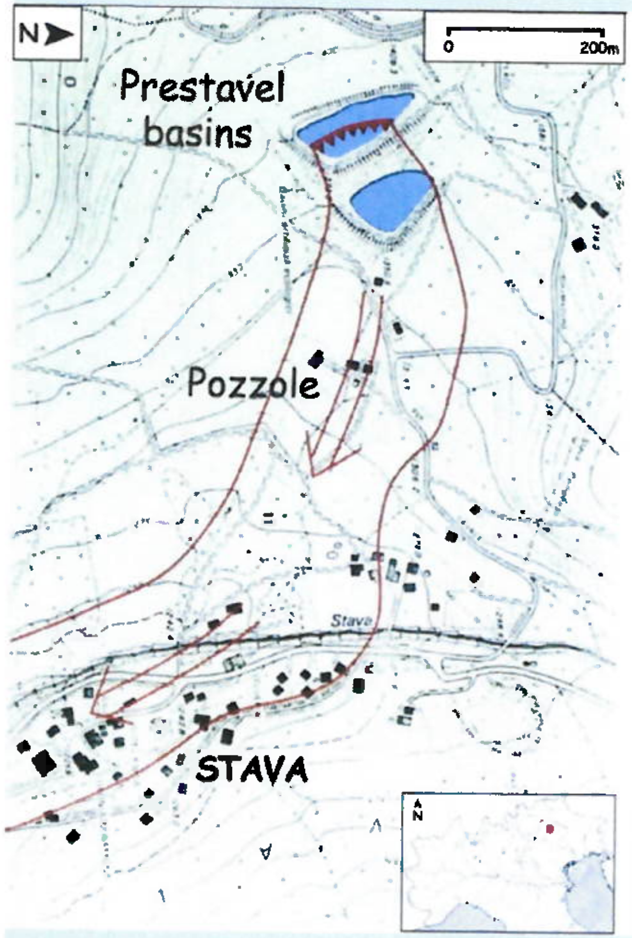


FIGURE 3.—Sketch map of Middle Fork, February 1972, before dam broke.

Buffalo Creek, West Virginia, USA (1972)

Date:	Feb 26, 1972, sudden, no warning
Type:	14 m embankment of coal waste built on coal refuse slurry retaining coal wash tailings for coal mine
Failure Mode:	Collapse of dam by slumping and sliding of downstream after heavy rain (<u>water flow through the dam</u>)
Volume Spilled:	500,000 cubic meters
Consequences:	Tailings traveled 27 km downstream average 2 m/sec, 125 people died, 1121 injuries , 507 homes destroyed, 30 businesses. Property and highway damage exceeded $65 million. Led to US Dam Safety Act giving US Army Corps of Engineers responsibility to conduct nationwide safety inspections of dams.

Stavia Mudflow, Trento, Italy (1985)



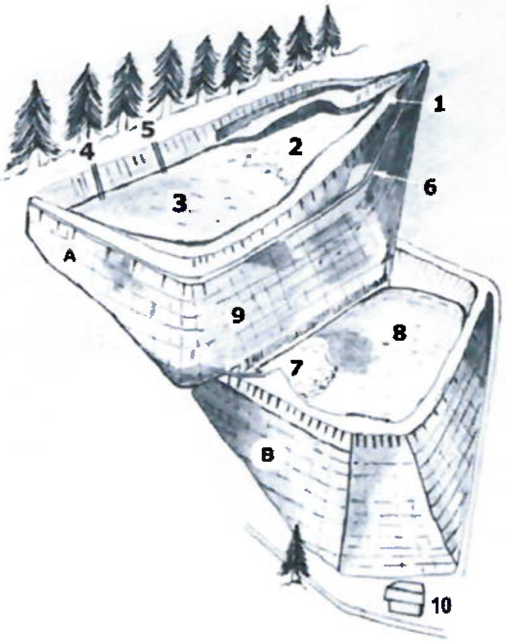


Fig. 2. Graphical representation of the Prestavel basins: **(A)** upper basin; **(B)** lower basin; (1) cyclone, (2) sandy deposit, (3) silty deposit, (4) drainage service, (5) emergency drainage,(6) service road, (7) sand cone, (8) silty deposit, (9) drainage from the upper basin, (10) caretaker's house.

Fig. 13. Before and after the passage of the mudflow in the Tesero village at section 20 in Fig. 8 (postcard – Foto Trettel, P., edited by: Artesan, Tesero).

From Luino, F. and DeGraff, J.V., 2012

Tailings Pond #3, Tyrone, NM, USA (1980)

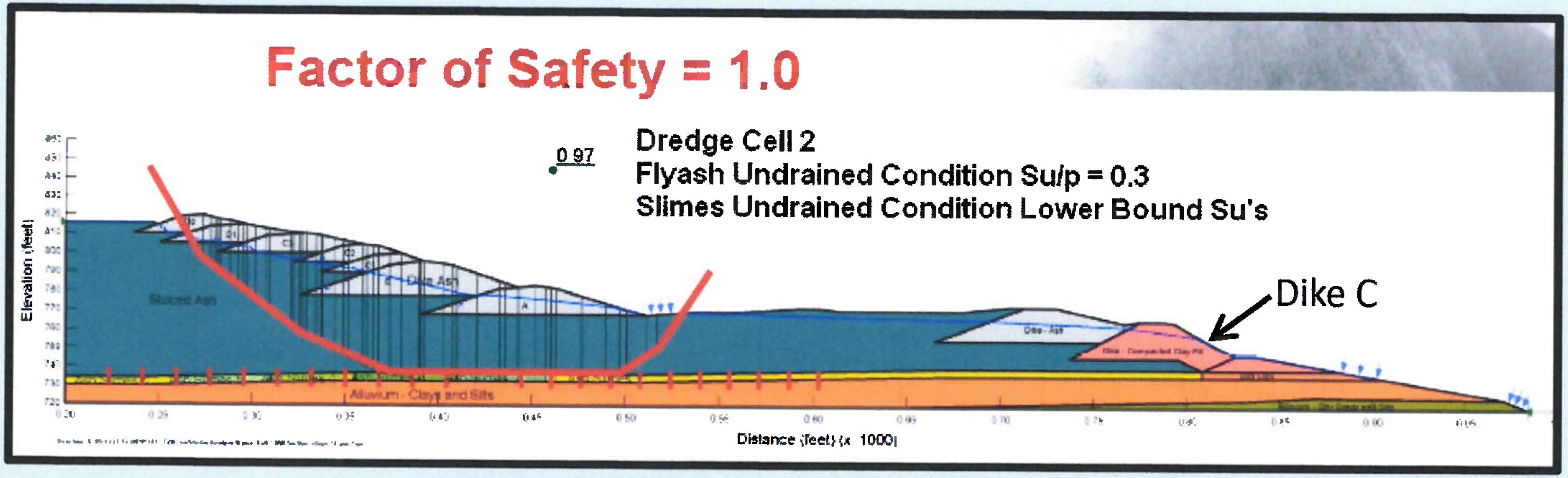
Date:	Oct 13, 1980, sudden, no warning
Type:	66 m upstream method, 443 acres, tailings for copper mine
Failure Mode:	Stability failure through dam and tailings due to rapid increase in tailings height causing <u>high internal pore pressure in tailings from rapid filling</u>.
Volume Spilled:	2,000,000 cubic meters into Mangas Valley
Consequence:	Tailings flowed 8 km downstream and inundated farmland

Stavia Mudflow, Trento, Italy (1985)

Date:	July 19, 1985, sudden, no warning
Type:	30 m upstream tailings dam for fluorite mine
Failure Mode:	Failure through silt foundation followed by mud flow
Volume Spilled:	200,000 cubic meters of liquefied tailings flowed 4.2 km at 25 m/sec
Consequence:	Mud flows killed 268 people, destroyed 82 buildings

From Luino, F. and DeGraff, J.V., 2012

Kingston, TN, USA (2008)



Undrained creep shear failure of 6" layer of interbedded silt, clay and slimes at high water content with load being added. Triggered shear slide then liquefaction of the sluiced ash tailings.

Kingston Ash Flow, TN, USA (2008)

Date:	Dec 22, 2008 sudden no warning, inspected day before
Type:	30 m upstream method dam for coal ash at power plant
Failure Mode:	<u>Undrained failure through thin weak foundation layer</u>, leading to liquefaction of stored ash, followed by mud flow
Volume Spilled:	4.1 million cubic meters of liquefied ash flowed 7 km, initially at ??? m/sec
Consequence:	Mud flows >180 properties damaged $1.2+ Billions of dollars paid by TVA in cleanup, unknown other damage payments

Mount Polly, BC, Canada (2014)

Mount Polly, BC, Canada (2014)

E 4.1.1: SIMPLIFIED CROSS-SECTION OF THE MOUNT POLLEY DAM

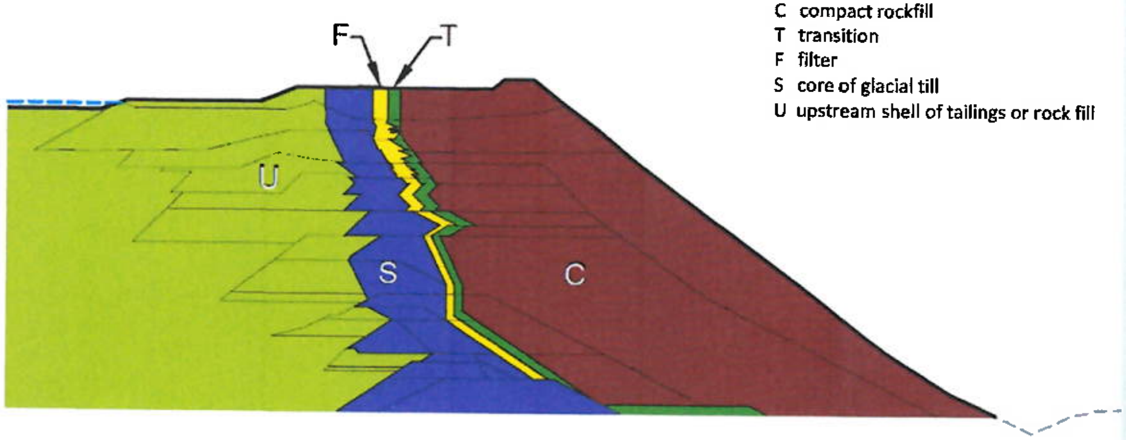
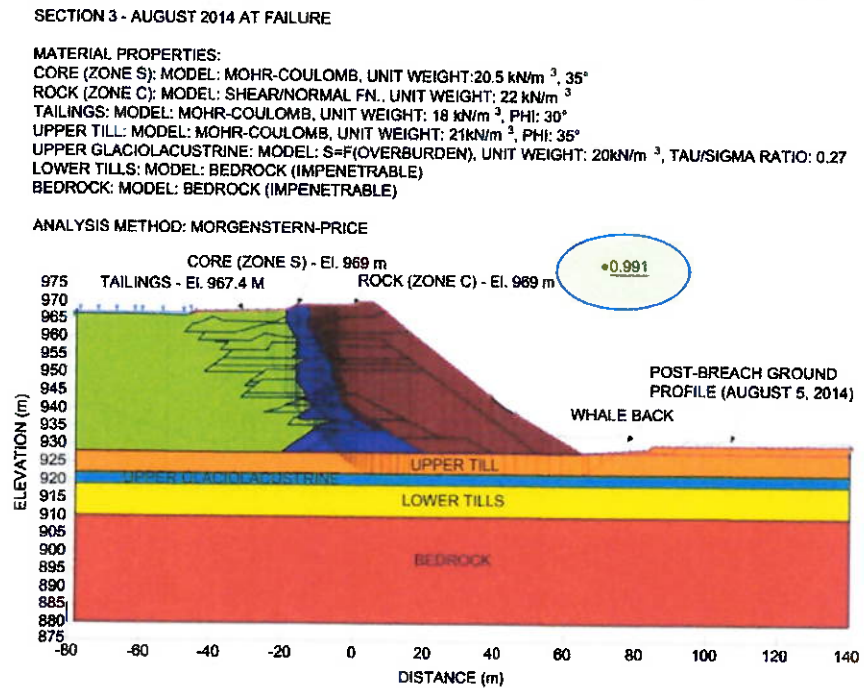


FIGURE 6.2.1: DETAILED SECTION USED FOR LIMIT EQUILIBRIUM ANALYSIS (HIGH WATER TABLE, UNDRAINED STRENGTH RATIO 0.27)



bile Connect | t Engineering Investigation and Review Panel | January 30, 2015

Piezometer types were not able to measure undrained pore pressures induced by shearing during the last stage.

- *...indicate that the foundation [GLU] was brought to failure under fully drained conditions, until the undrained strength was reached...*

Mount Polly, BC, Canada (2014)

Date:	Aug 4, 2014, sudden failure, no warning
Type:	40 m modified centerline dam for tailings from gold and copper mine
Failure Mode:	<u>Undrained stability failure through foundation</u> of containment dam built over varved clay, leading to liquefaction of stored tailings, followed by mud flow
Volume Spilled:	24.4 million cubic meters of liquefied tailings and water flowed into 600 km long Frasier River over 4 days
Consequences:	Mud flows created one of the biggest environmental disasters in modern Canadian history Estimated $68 million in clean up cost. >100 jobs lost. Design engineering firms paid $108 million to settle out. APEGBC charged the responsible engineers with negligence or unprofessional conduct.

Information from expert report by Norbert R. Morgenstern (Chair), Steven G. Vick, Dirk Van Zyl

Fundäo, Brazil (2015)

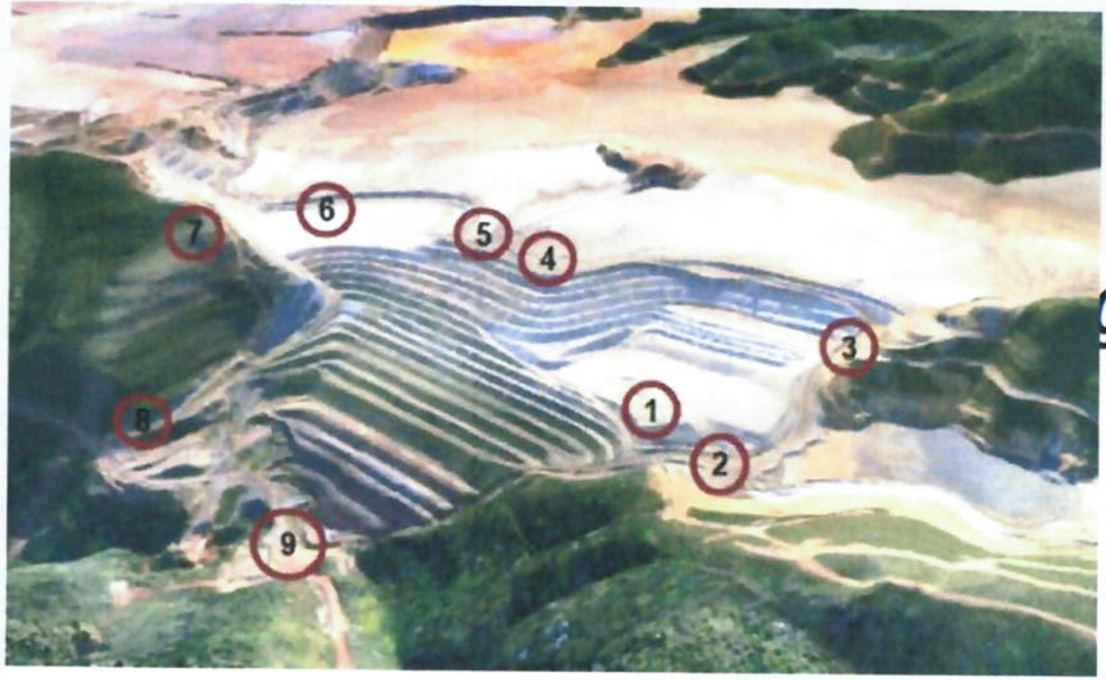
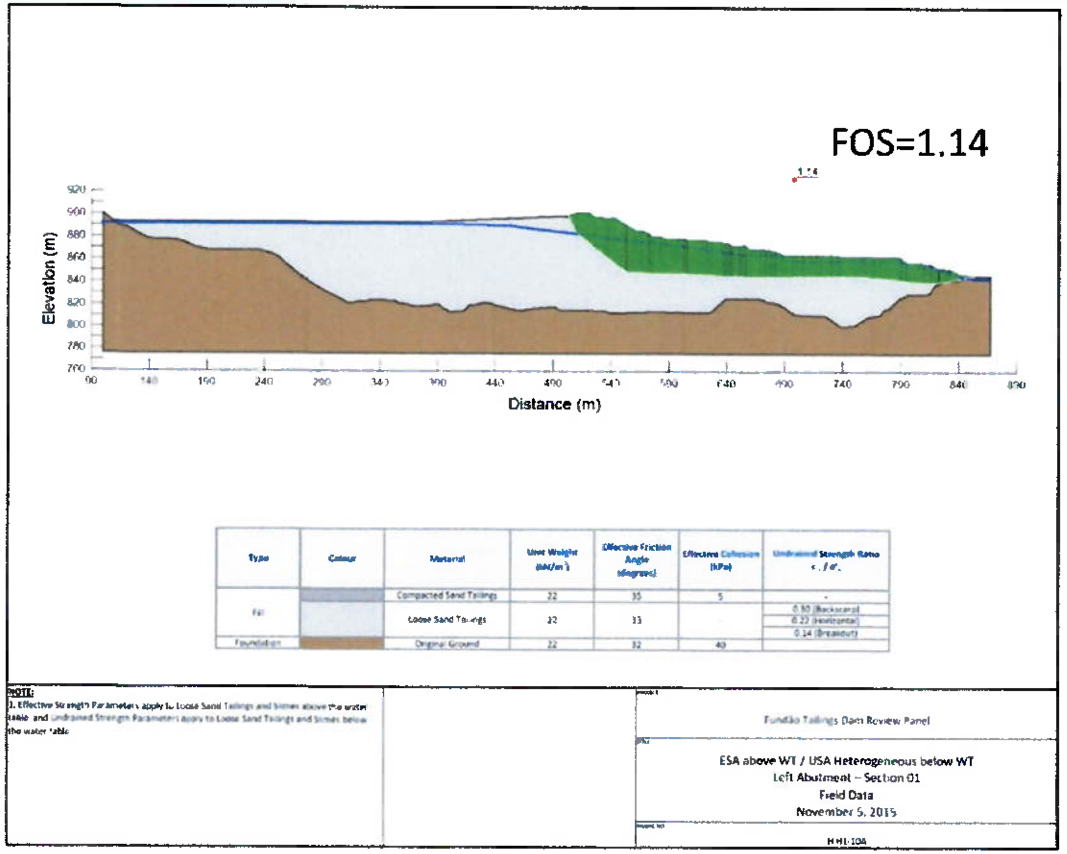
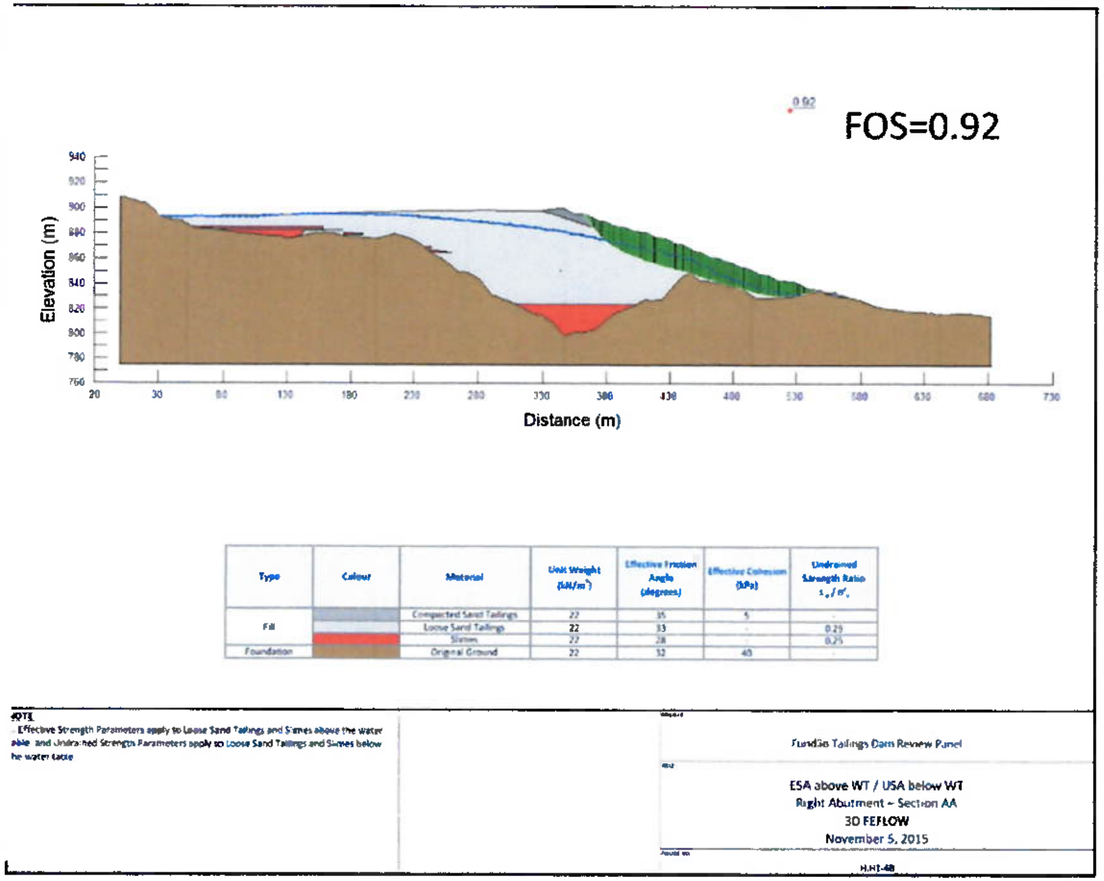


Figure 2-17 Eyewitness locations on the afternoon of November 5, 2015

Fundäo expert report

High pore pressures in the tailings from filling lowered the stability of the dam





Fundäo Mudflow, Brazil

Date:	Nov 15, 2015 sudden no warning, inspected shortly before
Type:	39-100 m upstream method dam tailings from iron ore
Failure Mode:	Undrained failure of containment dam built over tailings from rapid filling, leading to liquefaction of stored tailings, followed by mud flow
Volume Spilled:	43.7 million cubic meters of liquefied tailings flowed 620 km, initially at 11 m/sec
Consequence:	Mud flows killed 19 people, destroyed 375 homes, other structures. Worst environmental disaster in Brazilian history to that time. Damages and lawsuits of billions of dollars against owners.

Information from Norbert R. Morgenstern (Chair), Steven G. Vick, Cássio B. Viotti, and Bryan D. Watts. ; Wikipedia; Samarco 2015-2016 biannual report

Brumadinho Tailings Dam, Brazil

700 m long, 86 m high

248+ deaths; 22+ missing; >$5 billion damages??

Brumadinho Tailings Dam, Brazil (2019)

Date:	Jan 22, 2019, sudden, no warning
Type:	86 m upstream method tailings dam for iron mine, no filling for 3 years prior to failure
Failure Mode:	--to be determined--
Volume Spilled:	12 million cubic meters of liquefied tailings flowed 5 miles to Paraopeda River at average rate of 1 m/sec
Consequences:	Mud flow killed 248+ people, 22 missing, financial consequences will be in billions of dollars, individuals arrested. Owner stock valuation fell $19 Billion in single day

Some characteristics of failures of tailings dams

- Failure can occur quite suddenly will little to no warning.
- Generally, something triggers a failure within the barrier dam or the foundation which results in loss of containment of tailings. This triggers the stored tailings to liquefy.
- Liquefied tailings can flow very fast for long distances and present great risk to downstream people and environment
- Little time to warn and evacuate people within a few km below the dam.
- Visual inspections may not reveal the threat of imminent failure.
- Most monitoring systems will not give adequate warning.
- These characteristics should be strongly considered in the design and operation of a tailings dam.

Risk comparative chart for relative assessments

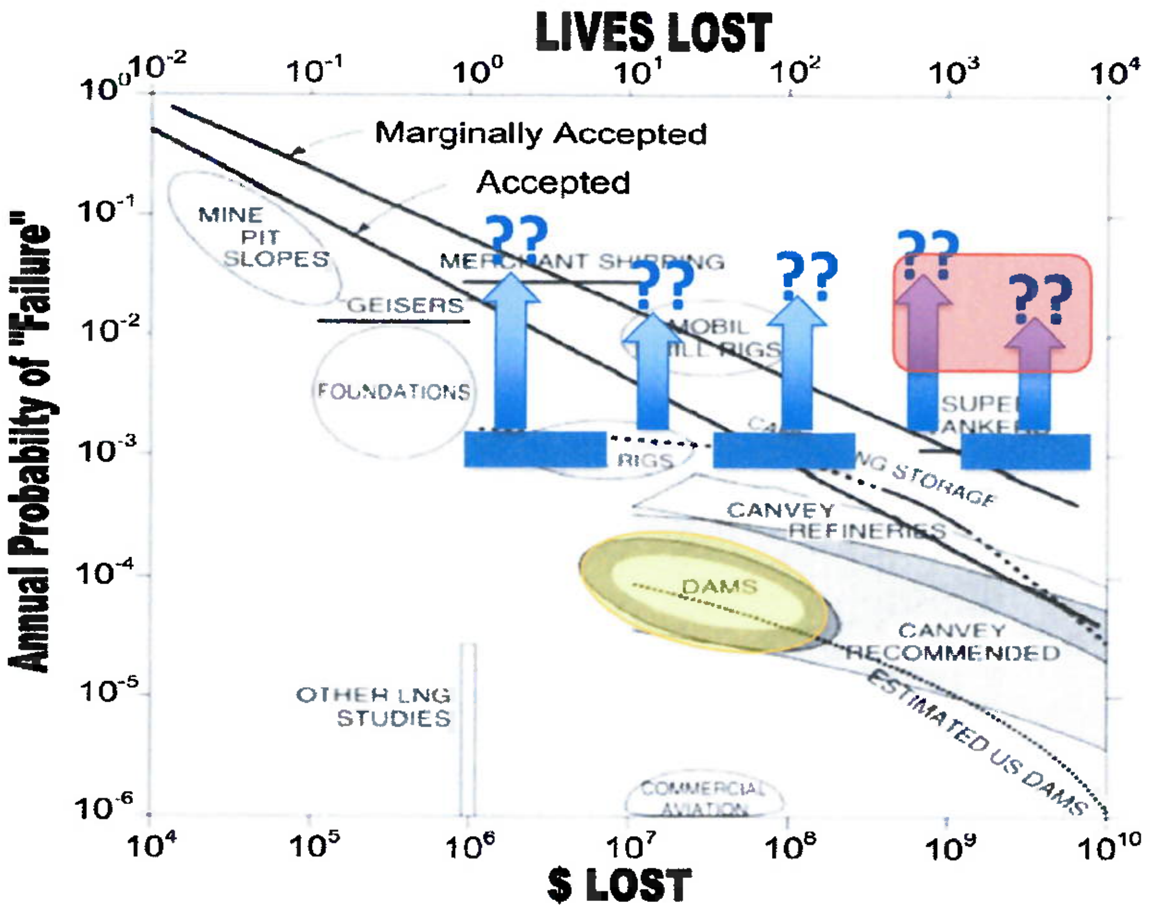


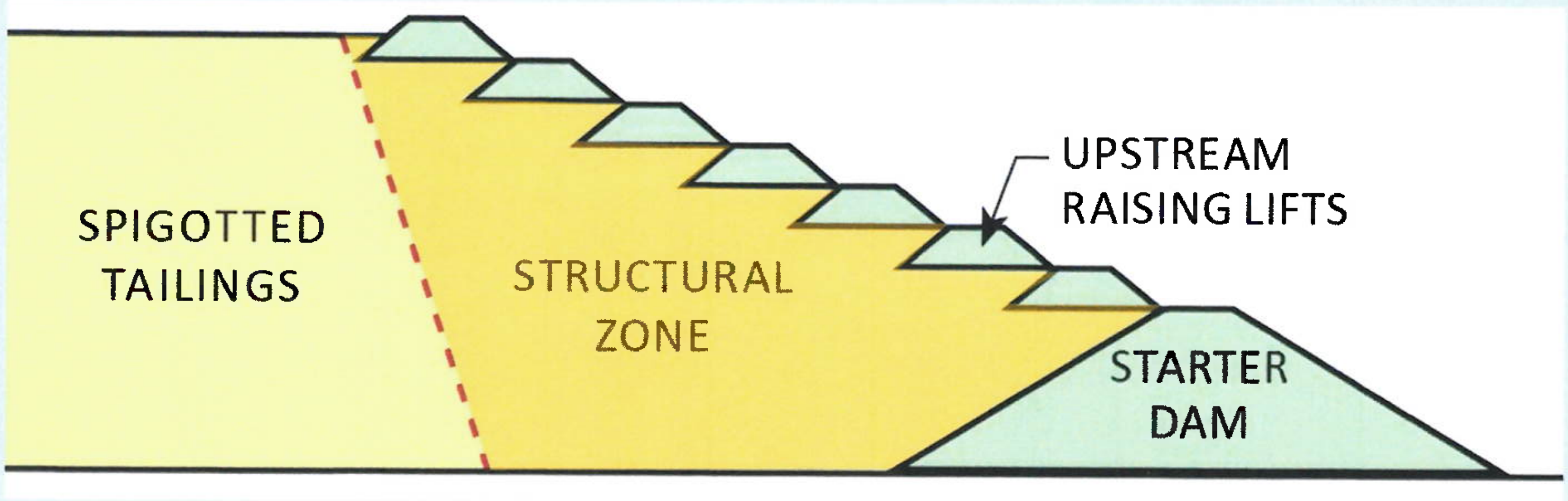
Fig. 5. Tolerable levels of risk (adapted from T. W. Lambe and Associates 1982, 1989, with permission)

Average annual failure rates
-modern earth dams 1 in 10,000
-tailings dams 1 in 1,000

Possible risk for a large tailings dam not using good practices

Base Figure from R.V. Whitman Terzaghi lecture "EVALUATING CALCULATED RISK IN GEOTECHNICAL ENGINEERING" ASCE Journal of Geotechnical Engineering, Volume: 110 Issue Number: 2 ISSN: 0733-9410

Upstream method - lowest cost to construct



https://www.klohn.com/blog/best-practices-for-tailings-dam-design/

Construction methods for tailings dams

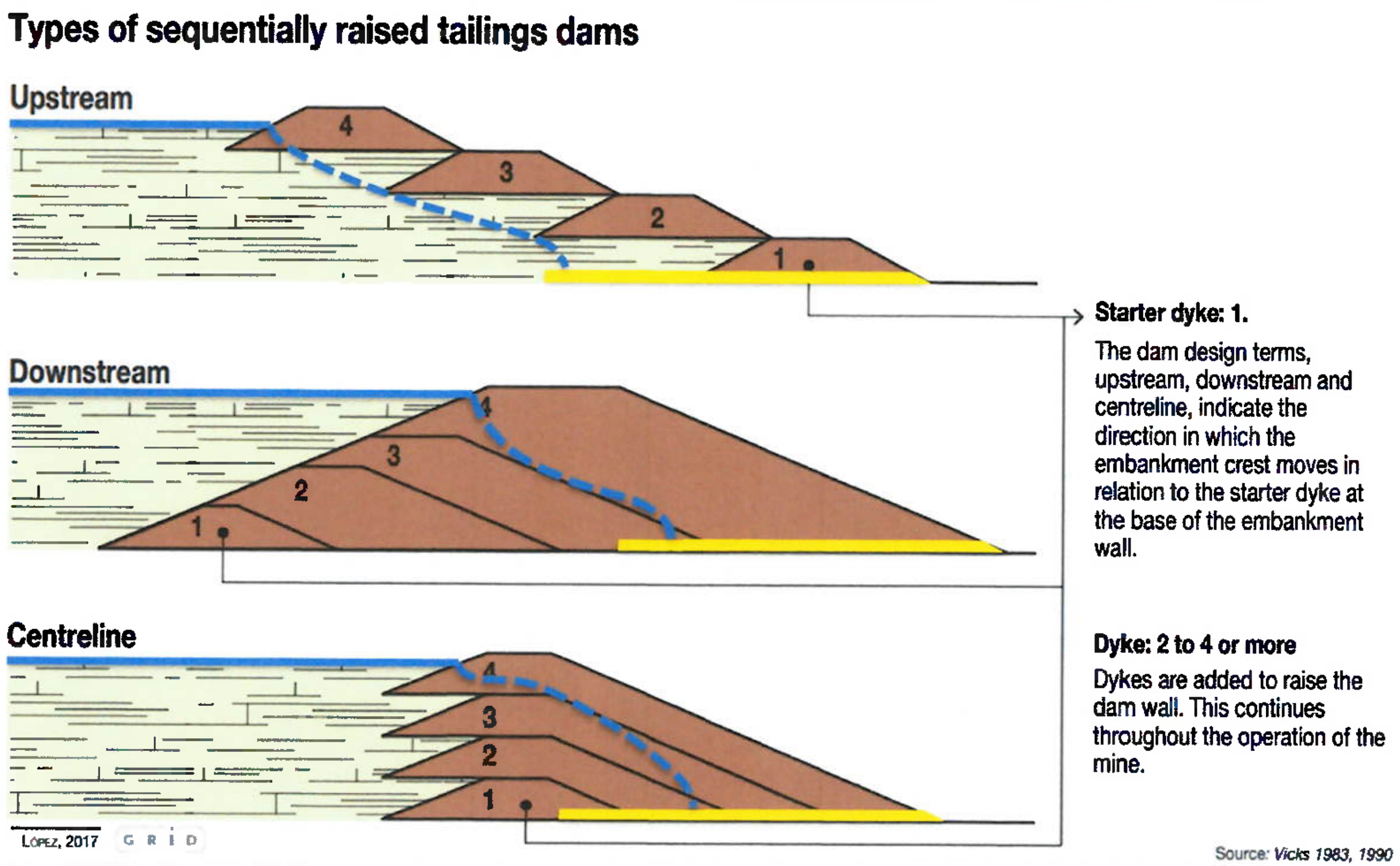


Figure 9. Dam building methods

Characteristics of particulate wastes placed by hydraulic methods that make them complicated materials

- Placed in loose state without compaction and with few controls on placement
- Have high water content (low solids content)
- Large fraction is saturated (makes incompressible)
- May be highly variable in composition with alternating layers of different gradations and plasticity
- May be chemically altered, "weathered" and/or aged
- Once something triggers shear strain, they can switch from drained to undrained shear behavior and lose strength.
- Almost no strain occurs before they switch to undrained behavior, lose strength and liquefy → they are very brittle materials

Key geotechnical factors affecting stability of tailings dams

- Geometry - slope and toe conditions
- Subsurface profile – horizontal layers of weak materials in tailings, in dam, in foundation
- Pore pressures within dam, foundation and stored tailings

  complicated due to anisotropic, nonhomogeneous materials and excess pore pressure from loading
- Strength – drained and undrained; contractive or dilative; cohesive or non-cohesive

Basic strength concepts for granular materials

- **Drained** – rate of loading/shearing is slow so water can flow into and out of element to keep excess pore pressures at zero.
- **Undrained** – rate of loading/shearing is fast so water cannot flow into or out of the element and excess pore pressures develop.

- **Contractive** – when strained the element tends to decrease in volume which if undrained creates a positive excess pore pressure and decreases strength.
- **Dilative** – when strained the element tends to increase in volume which if undrained creates a negative excess pore pressure and increases strength.
- Warning: textbook classifications of sands as "drained" for stability can be terribly misleading!

Some sources of geotechnical problems where failures have occurred

1. Underestimated potential consequences of poor performance.
2. Missed weak layer or permeable layer in the foundation
3. Missed source of high pore pressure in the foundation
4. Material properties used in analysis(strength, permeability) not representative of field conditions (layering, anisotropy, stress levels, poor samples, poor testing)
5. Flawed analysis type (drained versus undrained stability)
6. Errors in analyses (incomplete search, critical failure surface not identified)
7. What gets constructed does not adhere to design or design intent
8. Placed materials do not have the properties considered in the design
9. Actual performance deviates from that considered in the design (flow through the dam or foundation or abutments differs from design assumptions)
10. Operations or weather cause overtopping and erosion of the dam
11. Instrumentation does not give useful indication of poor performance, or does not work, or is not used.
12. People don’t interpret warning signs correctly or take appropriate actions in time.

Factor of Safety for global instability failure

$$Factor\ of\ Safety \approx \frac{Shear\ Strength}{Shear\ Stress}$$

-decrease in shear strength

mostly from increase in pore pressure due to water flow through the dam

-increase in shear stress

adding load, removing toe area, increasing pore pressure, external forces (earthquake, blasting, loads, collapse from piping or dissolution)

Strength of granular materials

- Drained and undrained strength depend on effective normal stress which depends on the pore pressure.
- Drained strength for friction angle of 30 to 40 degrees
  - $S_D/\sigma'_{nc} = \tan(\phi') = 0.58$ to 0.84
- Undrained Strength for many contractive soils
  - $S_U/\sigma'_{nc} = 0.2$ to 0.3
- Undrained strength can be about ½ to ⅓ of the drained strength for contractive soils.
- A comprehensive stability assessment should consider both drained and undrained loading.
  - If material is Dilative, drained condition will usually be the more critical
  - If material is Contractive, undrained condition will usually be the more critical

Most important design requirement for all dams

- Do not lose containment of the contents of the dam!

  (water, tailings, wastes)

  - No stability failures
  - No piping failures
  - No overtopping
  - No uncontrollable erosion of the dam
  - No washouts around hard structures (pipes, concrete works, etc.)

Design Goals Simplified

- Ensure foundation has enough strength for all possible load cases.
- Have all materials that comprise the dam be dilative.
- Control internal water pressures with internal drains to keep FoS for drained and undrained conditions > 1.5 for all possible load cases.
- Prevent overtopping.
- Control internal and external erosion
- Other requirements in seismically active regions

- Many existing tailings impoundments do not meet these goals.
- What to do?

Requirements for monitoring of tailings dam

- Detect lateral movements in the foundation beneath the outer slope of the dam.
- Detect changes in flow rates from internal seepage.
- Have sufficient locations with pore pressure measurements to establish flow pattern through the dam at several sections so minimum FoS can be determined with confidence .
- Be reliable and redundant.
- Be automated with readings taken several times per day.
- Be complemented with visual inspections by trained persons.
- Have a team that knows how to evaluate the measured data and interpret what it means.
- Have an action plan triggered by validated exceedances of Action Levels.
- Warning: monitoring of deformations in contractive tailings may not provide warning because these materials are brittle and can lose strength suddenly.

Summing up

- We know how to design and build tailings dams that are safe.
- Problem enters when designers don't use what we know and builders don't build what designers design.
- Problem is compounded by the many existing tailings dams that were not designed or built using what we know is required for a dam to be safe.
- Tailings dams can fail after they are retired from service.
- Average failure rate of tailings dams is too high (1 in 1000) when compared to water retention dams (1 in 10,000). And half of those are even higher.
- Risks from failure of tailings dams are higher than that from other industries.
- Seems logical that steps are needed to reduce these risks by at least an order of magnitude below the present state.
  - (Reduce probability of failure, reduce potential consequences.)

Ask questions by clicking Q&A Box
on the tool bar at the bottom of the Zoom screen.
We will read your questions as time permits

Conclusions and recommendations presented by Dr. Marr are his own and do not represent recommendations of COGGE or the National Academies of Sciences, Engineering, and Medicine

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