

A recent tailings dam failure and the future of waste dam construction

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Lessons Learned in Geotechnical Engineering
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Why talk about Brumadinho?

- Bajo Llojeta, La Paz, Bolivia landslide (4/30/19)



<https://www.youtube.com/watch?v=3myeSQbQSW4>



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Why talk about Brumadinho?

- Dam I, Feijao mine, Brumadinho, Brazil (1/25/19)



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Why talk about Brumadinho?

- Many more dams like Dam I in Brazil
- No official count, but estimated 3,500 tailings dams worldwide



By Scott Reinhard | Source: Agência Nacional de Mineração



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Overview

- What is a tailings/waste storage facility (TSF)?
- How do TSFs fail?
- What happened at Feijao mine?
- Is the failure at Feijao a unique occurrence?
- What does the future hold for TSFs?
- Final remarks



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Tailings/waste storage facilities (TSF)

- Several industries produce solid wastes after use of valuable fraction of materials
 - Metal/mineral mine tailings (tails, slimes, reject)
 - Coal ash (fly ash, coal combustion residue)
 - Oil sands



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Tailings/waste storage facilities (TSF)

- Several industries produce solid wastes after use of valuable fraction of materials
 - Metal/mineral mine tailings (tails, slimes, reject)
 - Coal ash (fly ash, coal combustion residue)
 - Oil sands
- Historically, waste pumped via pipeline to TSF (i.e., a tailings dam)
 - Embankment dam constructed of natural soils, waste (overburden) rock, or coarser fraction of tailings/waste

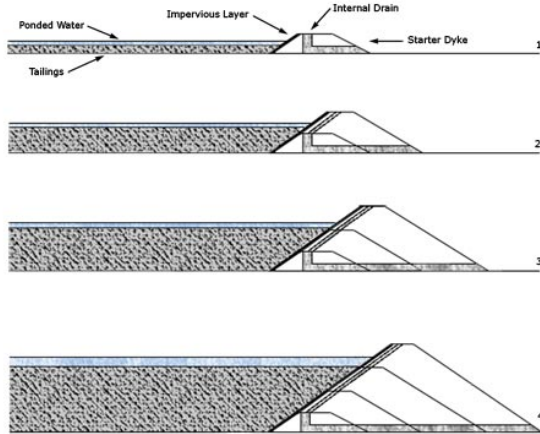


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TSF construction

- Downstream (D/S)



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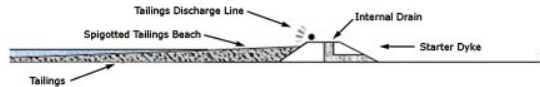


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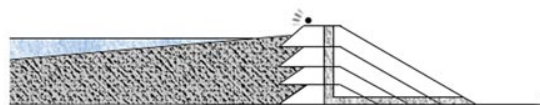
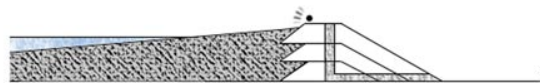
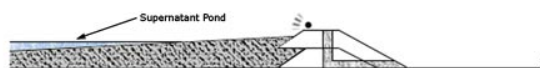


TSF construction

- Downstream (D/S)



- Centerline (C/L)



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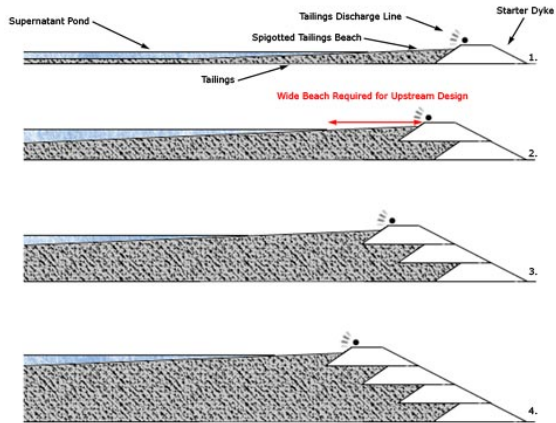


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TSF construction

- Downstream (D/S)
- Centerline (C/L)
- Upstream (U/S)



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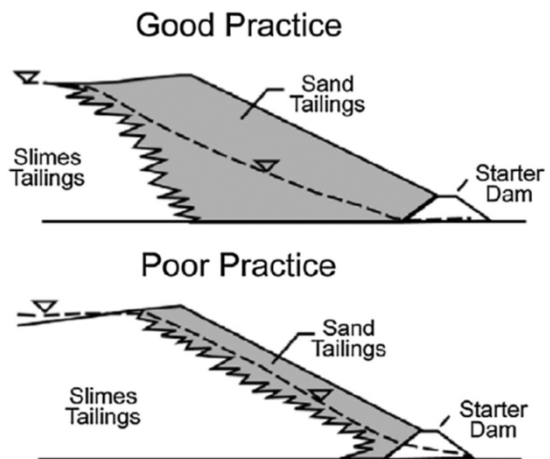


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TSF construction

- Downstream (D/S)
- Centerline (C/L)
- Upstream (U/S)



Martin and McRoberts (1999)

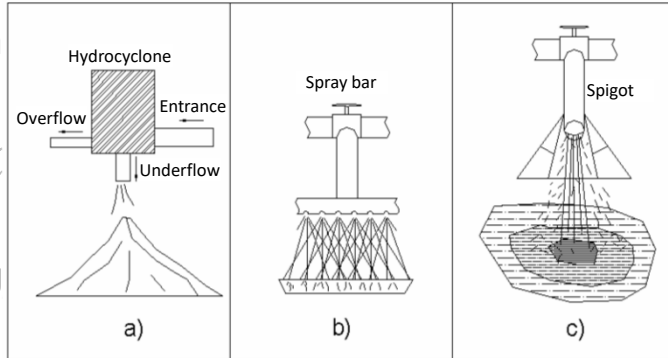


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TSF construction

- Downstream
- Centerline (C)
- Upstream (U)
- Placement
 - Cyclone



Mendes (2007)



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TSF construction

- Downstream
- Centerline (C)
- Upstream (U)
- Placement
 - Cyclone



Courtesy of W. Pirete



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TSF construction

- Downstream
- Centerline (C)
- Upstream (U)
- Placement
 - Spray bar



Courtesy of W. Pirete



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TSF construction

- Downstream
- Centerline (C)
- Upstream (U)
- Placement
 - Spigot

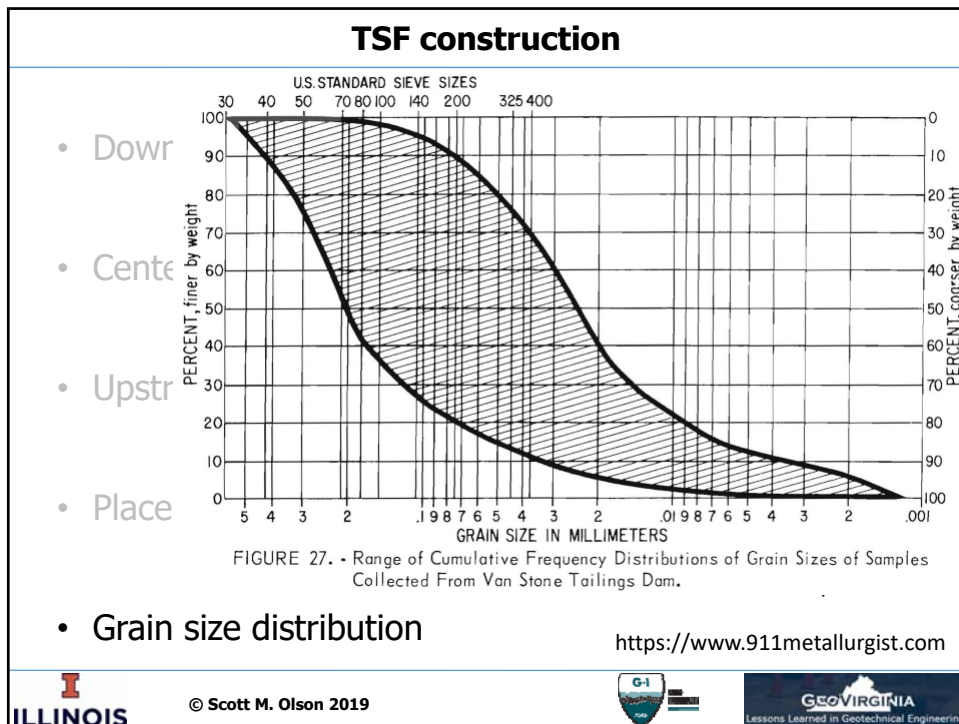


Courtesy of W. Pirete



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Mechanisms that can trigger liquefaction failure

- Rapid placement of fill, tailings, or perimeter dikes
- Failure/excessive deformation of foundation soils, thin soft layers, or shell materials
- Seismic or dynamic loading
- Rapid or excessive rise of the phreatic surface
- Overtopping of the dam crest
- Piping



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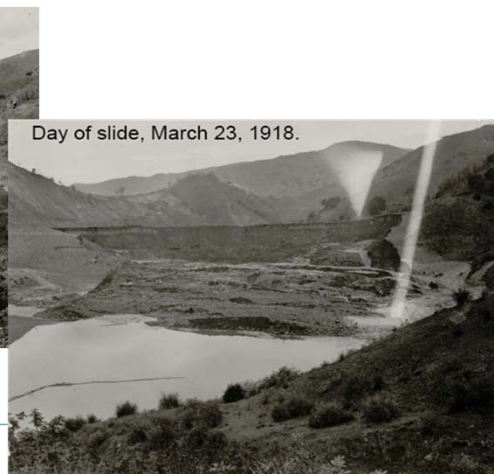


Failure resulting from rapid fill placement

- Rapid placement of hydraulic fill triggered failure of Calaveras dam during construction in 1918
- Hazen (1920) first coined the term "liquefied" after failure



Day before slide, March 22, 1918



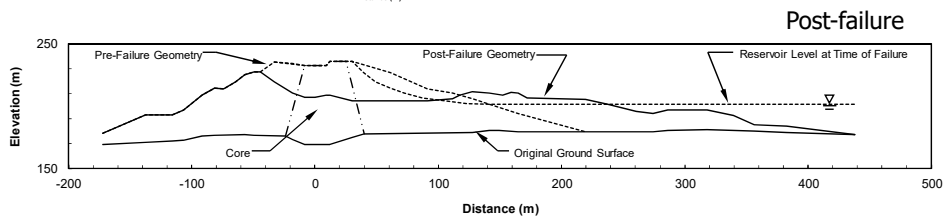
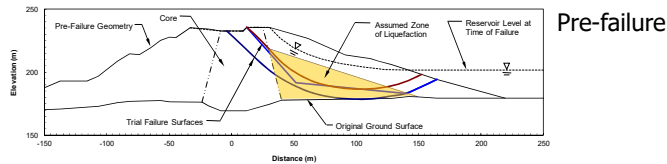
Day of slide, March 23, 1918.

<http://damsafetyca.blogspot.com/2008/05/42-4-calaveras-dam.html>



Failure resulting from rapid fill placement

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Failure of foundation materials

- Best known example: Fort Peck Dam
- Failure along Bearpaw shale foundation layer triggered liquefaction in sluiced fill materials



www.fortpeckdam.com

SEPT. 22, 1933
PARTIAL FAILURE OF FORT PECK DAM AS SEEN FROM THE AIR.

303
CULE BRIDGE
PRICE-PLATE

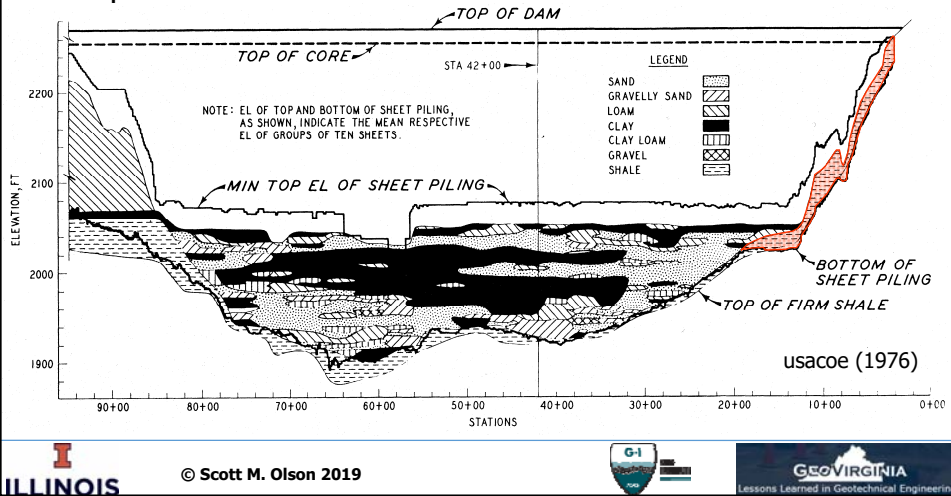


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Seismic loading-induced failure

- Best known example: Lower San Fernando Dam
- Hydraulic fill liquefied in 1971 San Fernando earthquake (M 6.6); dam failed ~60 seconds after shaking ceased



<http://www.gf.uns.ac.rs/~wus/wus07/web4/liquefaction.html>



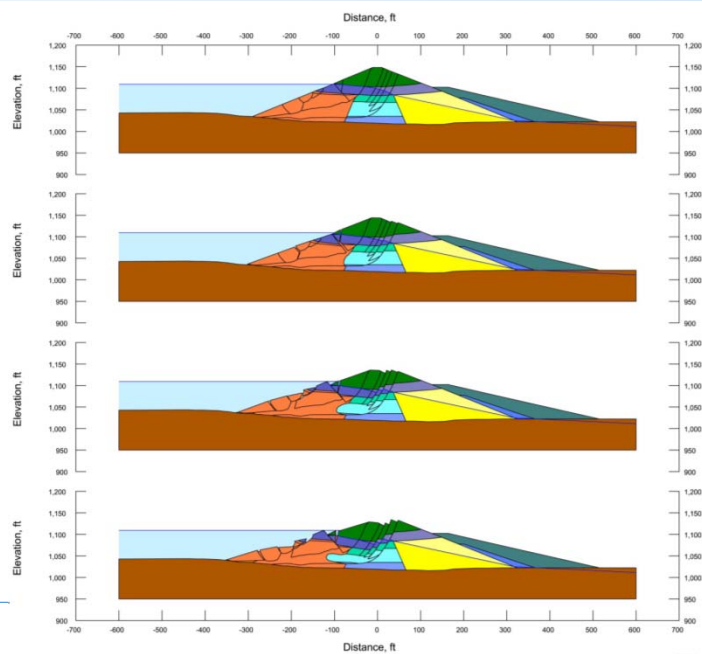
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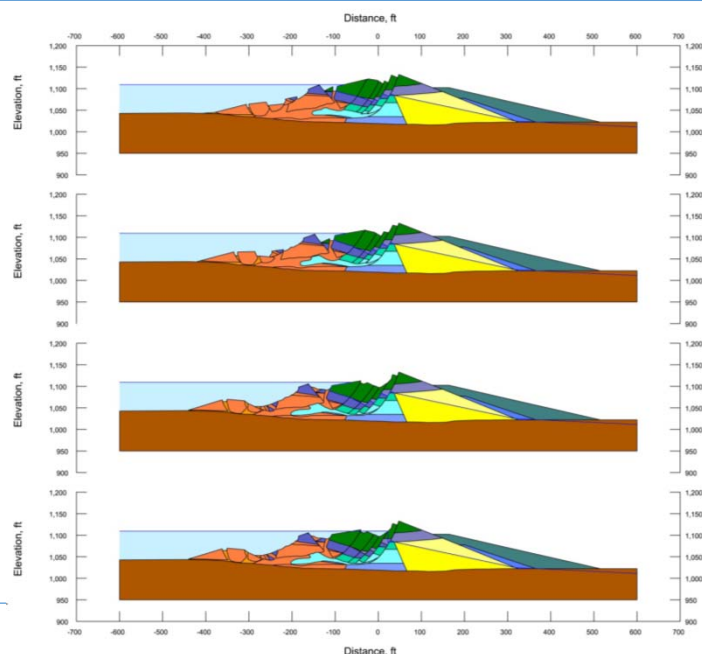
Weber (2015)



Seismic loading-induced failure

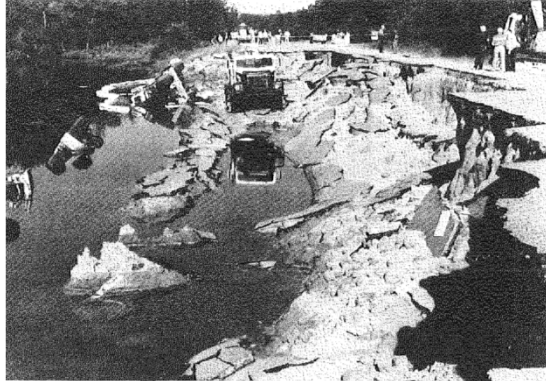
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Weber (2015)



Dynamic loading-induced failure

- Dynamic loading can include dynamic compaction, railroad traffic, geophysical surveys, among others
- Best known case: dumped fill embankment along Lake Ackermann, Michigan, USA



Hryciw et al. (1990)



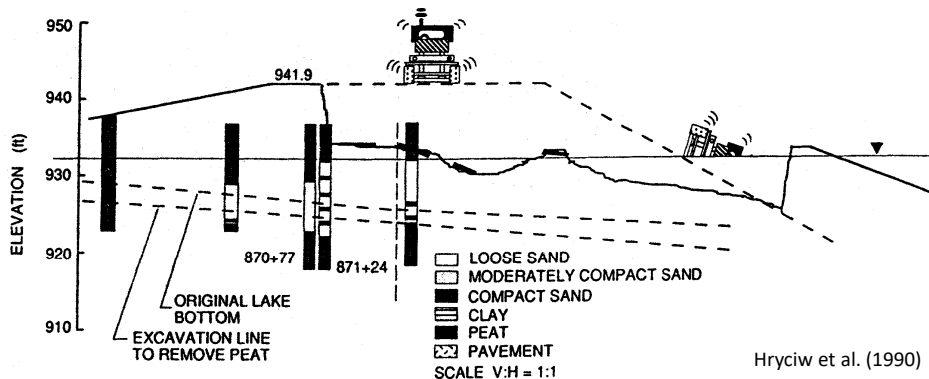
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Lessons Learned in Geotechnical Engineering

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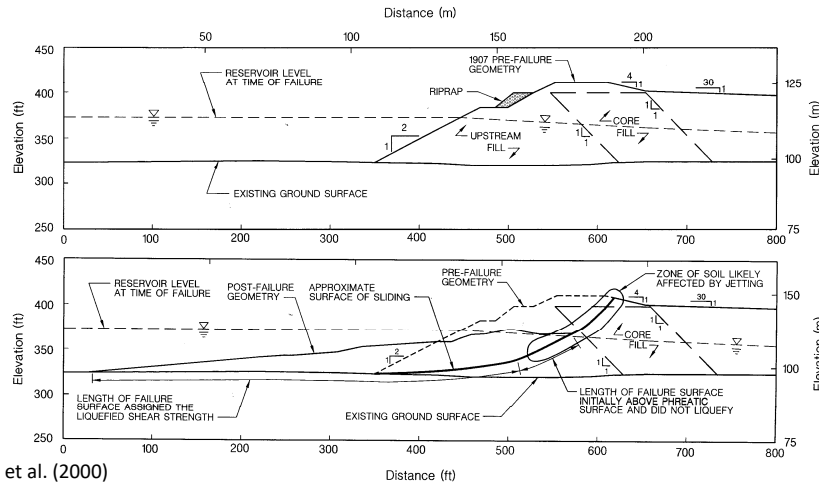
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Failure resulting from rapid rise of phreatic surface

- Dumped fill used to create North Dike of Wachusett Dam in 1907 failed during first reservoir filling



Olson et al. (2000)

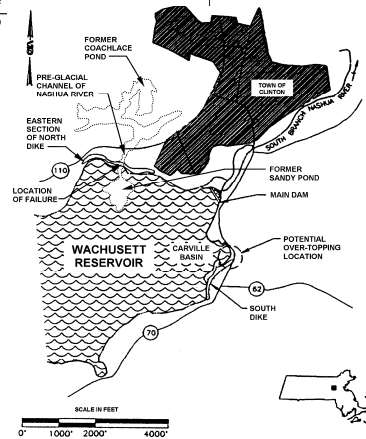
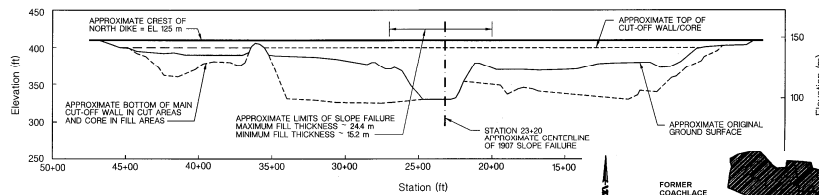


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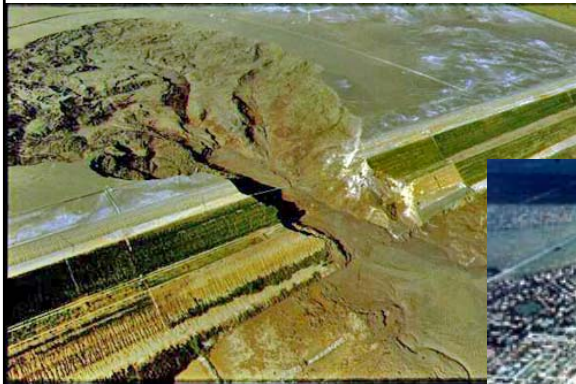


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Failure resulting from crest overtopping

- Merriespruit (South Africa) gold mine tailings failure in 1994



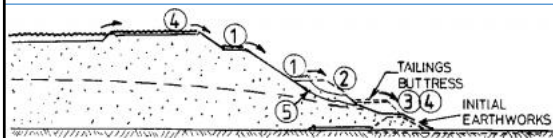
tailings.info



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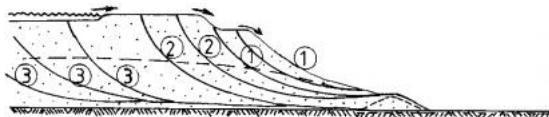
Failure resulting from crest overtopping



- Merriespruit (South Africa) gold-mine tailings failure in 1994

- Berms overtop after thunderstorm
- Loose tailings infill to earlier failures on lower slope erodes
- Tailings buttress starts to fail
- Pool commences overtopping and erodes slopes and buttress
- Unstable lower slope fails and failed material is washed away

Critical section of North wall during early stages of failure



- Lower slopes fail and are washed away
- Domino effect of local slope failures which are washed or flow away
- Major slope failures with massive flow of liquid tailings

Fourie et al. (2001)

Critical section of North wall during failure



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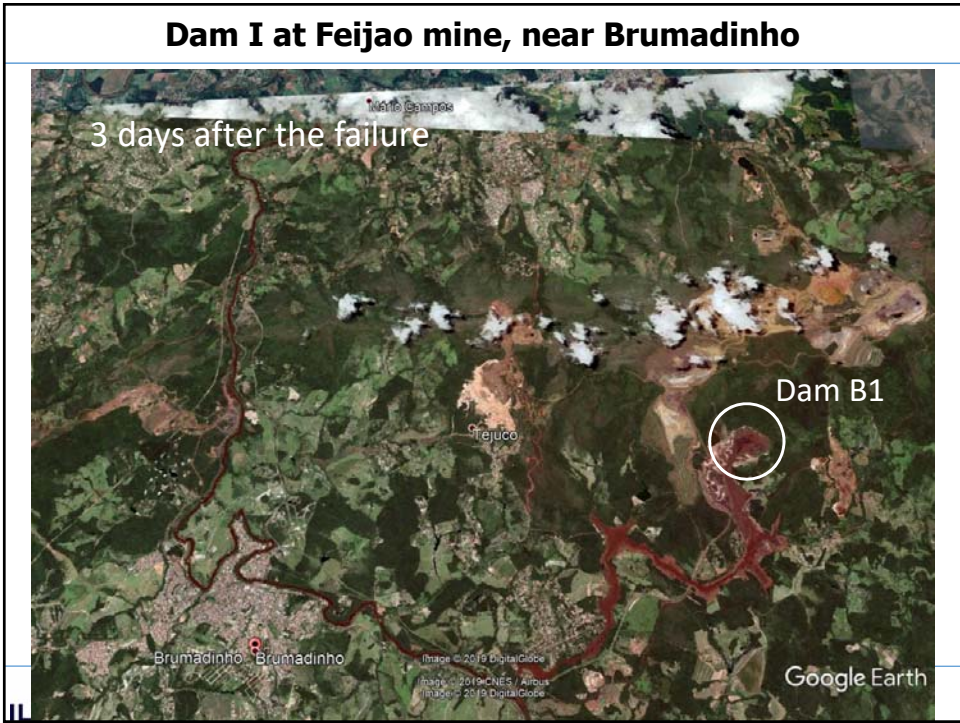


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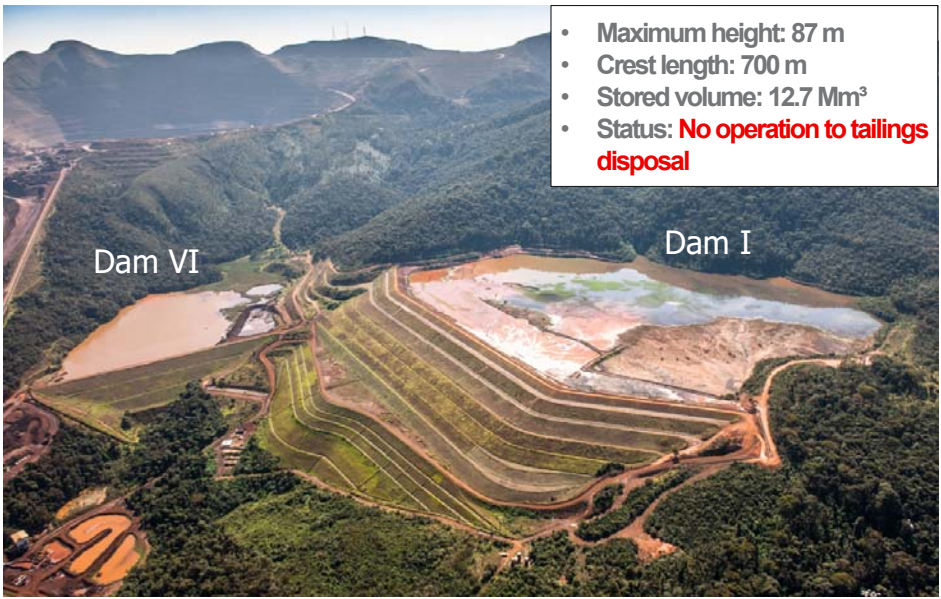


Dam I at Feijao mine, near Brumadinho







Dam I at Feijao mine, near Brumadinho




- Maximum height: 87 m
- Crest length: 700 m
- Stored volume: 12.7 Mm³
- Status: **No operation to tailings disposal**

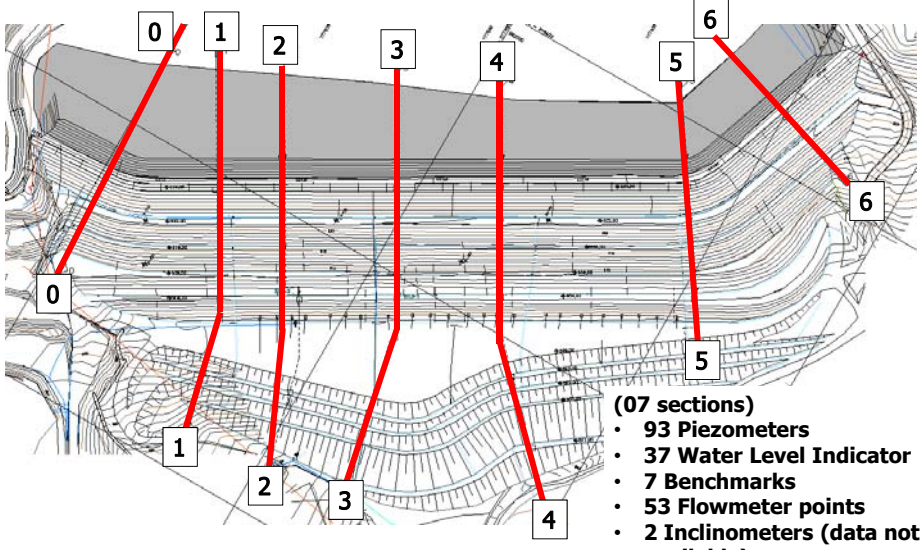


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Dam I – Cross-sections evaluated by others





(07 sections)

- 93 Piezometers
- 37 Water Level Indicator
- 7 Benchmarks
- 53 Flowmeter points
- 2 Inclinerometers (data not available)



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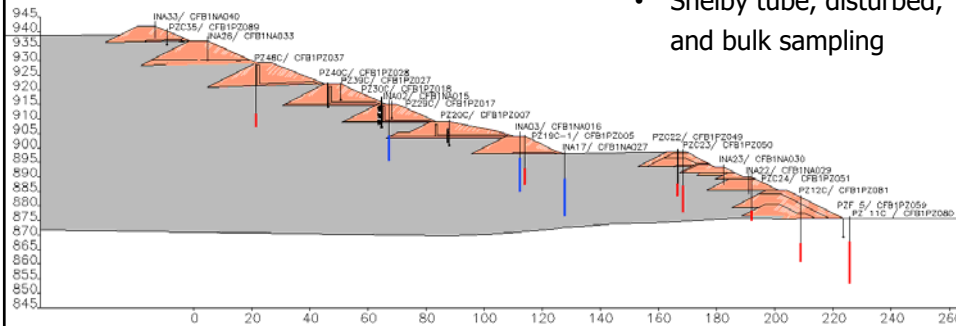




Dam I – Cross-sections evaluated by others

Two field campaigns

- 17 CPTu soundings
- 8 borings w/FVSTs
- 38 borings w/SPTs
- Shelby tube, disturbed, and bulk sampling



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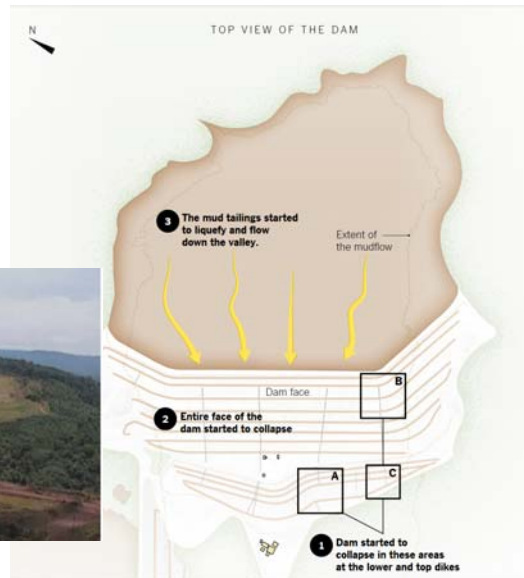


Dam I at Feijao mine, near Brumadinho

- Clearly, something triggered liquefaction
- International panel investigating the failure



New York Times (2019)



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Is the failure at Feijao mine unique?

- No, not in Brazil...



Vista da barragem por jusante após a ruptura.



Vista aérea da barragem e do talvegue a jusante, após a ruptura.



Is the failure at Feijao mine unique?

- No, not in Brazil...even recently (November 2015)



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Is the failure at Feijao mine unique?

- No, not in Brazil...even recently (November 5, 2015)



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Is the failure at Feijao mine unique?

- No, not elsewhere in the world either

<http://www.wise-uranium.org/mdaf.html>

Date	Location	Parent company	Ore type	Type of Incident	Release	Impacts
July 2019 Peru	Peru	Dese Ban Perú S.R.L.	copper	tailings dam failure	67,488 m ³ of tailings	tailings covered an area of 41,574 m ² and reached Mantazo River
April 2019 Myanmar	Myanmar	Shwe Nagar Koe Kaung Gems Co. Ltd., Myanmar Thura Gems Co. Ltd.	jade	waste heap failure	?	3 workers killed, 54 workers are missing
April 2019 India	India	Sakco Industries India	bauxite	failure of red mud tailings pond	?	spill of red mud over 35 acres and a nearby railway line, number of casualties still unclear
March 2019 Brazil	Brazil	Mining Mineração S.A. S.A.	tin	failure of inactive tailings dam after heavy rain	?	tailings spill damaged seven bridges, leaving 100 families isolated; no deaths or injuries reported
January 2019 Brazil	Brazil	Vale SA	iron	failure of tailings dam No. 1 (View details)	12 million m ³ -> View: video of dam failure and flow slide (Globe)	The tailings wave devastated the mine's loading station, its administrative area, and two smaller sediment retention basins (B4 and B4A); it then traveled approx. 7 km downhill until reaching Rio Parapoíba, thereby destroying a bridge of the mine's railway branch, and spreading to parts of the local community Vila Ferteosa, near the town of Brumadinho; the slurry was then carried further by Rio Parapoíba; 248 people were killed, and 22 are reported missing. (View details)
June 2018 Mexico	Mexico	Minera Rio Tinto Carter Mining de Basham A.C.	gold, silver	tailings dam failure	249,000 m ³ of tailings and 190,000 m ³ of embankment material	Dam failure results in tailings release travelling 29 km downstream; most of the tailings have been deposited along the course of the Cahitas River. The Federal Attorney's Office for Environmental Protection (PROFEPA) says that the tailings don't contain cyanide or any heavy metals. Three workers were killed, two wounded, and four are reported missing.
May 2018, Australia	Australia	Newcrest Mining Ltd.	gold, copper	tailings dam failure, mainly due to the existence of a low-density foundation layer in the vicinity of the slump. -> Download: Independent Technical Review Board report > Apr. 17, 2019 (27-6MB-PDF) -> View: video (Youtube)	1.33 million m ³ of tailings	Embankment failure results in "limited breakthrough" of tailings material from the northern to the southern tailings dam. The breakthrough has been contained within the southern tailings dam.

ILLINOIS

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LESSONS LEARNED IN GEOTECHNICAL ENGINEERING

Is the failure at Feijao mine unique?

- Cadia gold mine, Australia (March 9, 2018)

Newcrest Mining Ltd. (2018)



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LESSONS LEARNED IN GEOTECHNICAL ENGINEERING

Is the failure at Feijao mine unique?

- Mount Polley, Canada (August 4, 2014)

cbc.ca



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Is the failure at Feijao mine unique?

- Bingham Canyon, USA (April 2013)



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Is the failure at Feijao mine unique?

- Bingham Canyon, USA (April 2013)



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Is the failure at Feijao mine unique?

- Las Palmas, Chile (February 27, 2010)

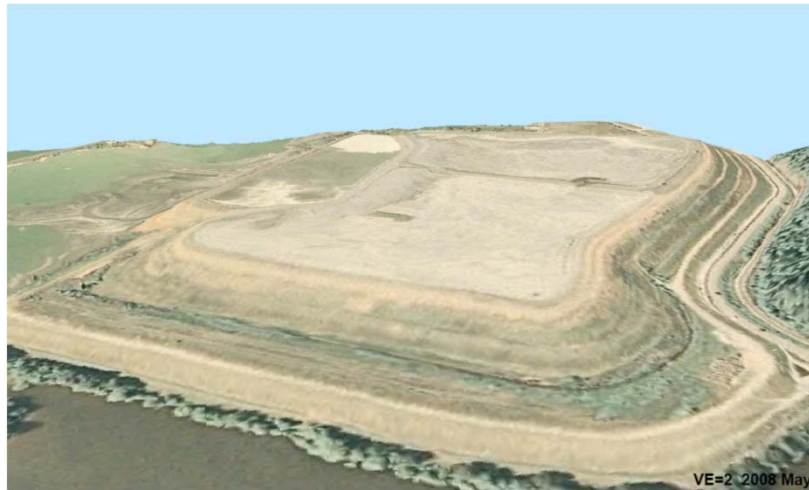


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Is the failure at Feijao mine unique?

- Kingston fossil plant, USA (December 22, 2008)



[Slide courtesy of W. Walton (AECOM)]



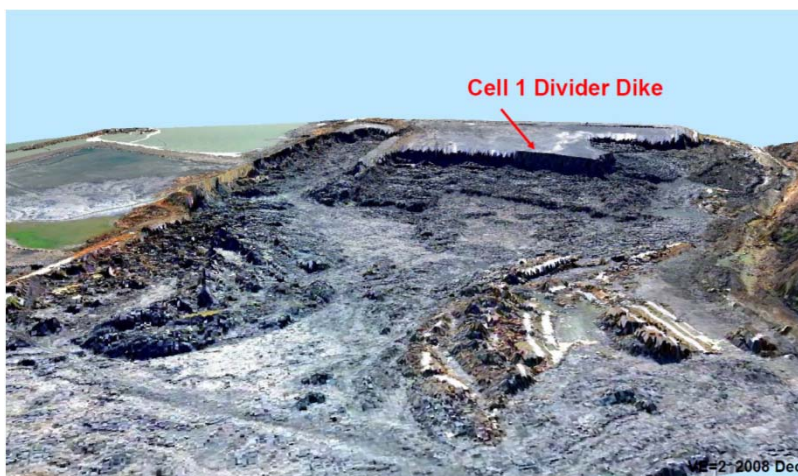
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[Slide courtesy of W. Walton (AECOM)]



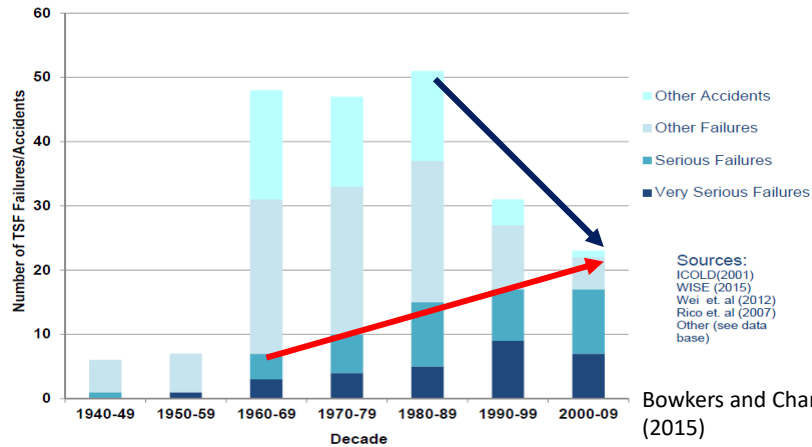
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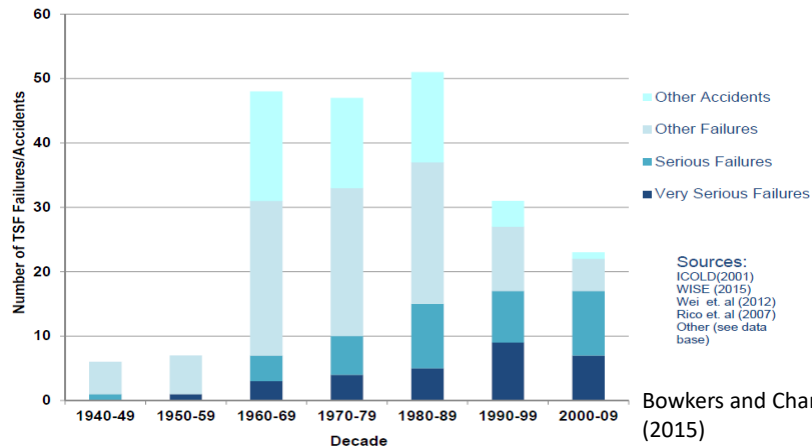
Is the failure at Feijao mine unique?

- 128 reported serious failures since 1960, but undoubtedly many more unreported



Is the failure at Feijao mine unique?

- Failure rate \sim 1:700 to 1:1750 (compared to water-retaining dams at \sim 1:10,000) (Davies 2001)



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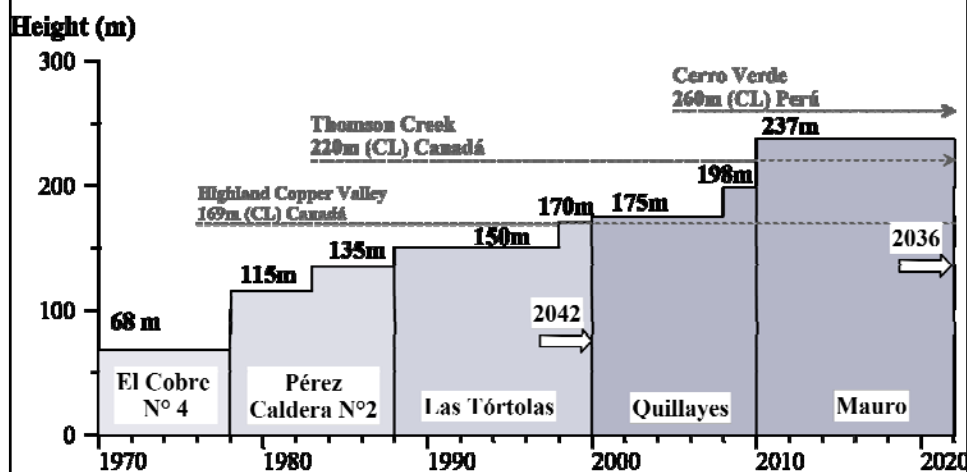


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What does the future hold?

- Despite the failures, TSFs keep getting bigger



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Should we construct upstream TSFs?

- New upstream tailings dams already outlawed in many seismically-active countries (e.g., Chile)
- All upstream tailings dams in state of Minas Gerais, Brazil must be decommissioned (deconstructed)
- Some planned upstream raises in the US being reconsidered/re-permitted
- Mining companies (e.g., Vale, ArcelorMittal, Anglo American, PolyMet, BHP, Cliffs, Rio Tinto) are re-evaluating or decommissioning



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What are the alternatives?

- Downstream construction
- High density thickened tailings (HDTT)
- Surface paste tailings
- Dry stack/filtered tailings
- Co-disposal



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High density thickened tailings (HDTT)

- Tailings are mechanically dewatered to a concentrated slurry using thickeners or filter presses
- Advantages:
 - ▶ Starter dike not needed
 - ▶ Little or no ponded water
 - ▶ Slurry can be modified using binders or bentonite
- Disadvantages:
 - ▶ Higher initial costs
 - ▶ Lack of experience



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Surface paste tailings

- Tailings dewatered such that they do not readily flow and produce no bleed water
- Advantages:
 - ▶ Steeper depositional slopes
 - ▶ Less likely to liquefy
 - ▶ Desiccation promotes interlocking between layers
- Disadvantages:
 - ▶ High initial costs
 - ▶ Need positive displacement pumps for transport – limits transport



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Dry stack/filtered tailings

- Tailings dewatered more than paste to create filtered wet cake (saturated) or dry cake (unsaturated)
- Advantages:
 - ▶ Conserves water
 - ▶ No liquefaction
 - ▶ Faster placement
- Disadvantages:
 - ▶ High cost!
 - ▶ Low volume
 - ▶ Truck or conveyor transport

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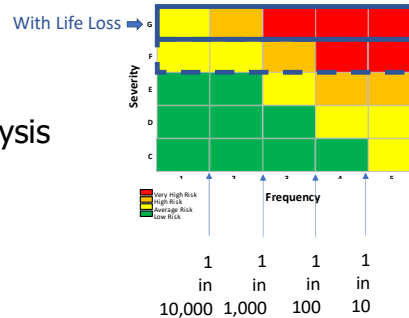


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Improved methods

- Improved governance models – EoR, Review Board
- Risk-informed design and decision-making
 - ▶ Potential failure mode analysis
 - ▶ Design basis memoranda
 - ▶ Construction record
 - ▶ Quality assurance
 - ▶ Deviation accountability report



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- **Final remarks**
 - ▶ **Should upstream TSFs be outlawed everywhere?**
 - ▶ **Could the failure at Feijao have been avoided?**
 - ▶ **At what cost?**



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Thank you for your attention!

Questions?

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