The Brumadinho tailings dam failure and the future of waste dam construction

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Chicago Geotechnical Lecture Series
Case studies and lessons in Geotechnical Engineering
Geo-Institute Chapter of the ASCE Illinois Section
May 10, 2019

Why talk about Brumadinho?

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

https://www.youtube.com/watch?v=3myeSbQSW4
Why talk about Brumadinho?

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

Why talk about Brumadinho?

• Many more dams like Dam I in Brazil
• No official count, but estimated 3,500 tailings dams worldwide
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Several industries produce solid wastes after use of valuable fraction of materials

- Metal 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
• Downstream (D/S)

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

© Jon Engels

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

Martin and McRoberts (1999)
TSF construction

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

• Placement

Mendes (2007)

TSF construction

• Downstream
• Centerline (C/L)
• Upstream (U/S)

• Placement
  ▶ Cyclone

Courtesy of W. Pirete
TSF construction

- Downstream (D/S)
- Centerline (C/L)
- Upstream (U/S)
- Placement
  - Spray bar
  - Spigot

Courtesy of W. Pirete
• Downstream (D/S)
• Centerline (C/L)
• Upstream (U/S)
• Placement

TSF construction

- Grain size distribution

https://www.911metallurgist.com

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
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

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

http://damsafetyca.blogspot.com/2008/05/424-calaveras-dam.html
• Rapid placement of hydraulic fill triggered failure of Calaveras dam during construction in 1918
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• Best known example: Fort Peck Dam
• Failure along Bearpaw shale foundation layer triggered liquefaction in sluiced fill materials

[Diagram of Pre-failure and Post-failure geometries]

www.fortpeckdam.com
Failure of foundation materials

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

usace (1976)
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
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

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

Weber (2015)

Hryciw et al. (1990)
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

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

Hryciw et al. (1990)

Olson et al. (2000)
• Dumped fill used to create North Dike of Wachusett Dam in 1907 failed during first reservoir filling

Olson et al. (2000)

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

taxiings.info
Failure resulting from crest overtopping

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

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
Days before the failure

3 days after the failure
Dam I at Feijao mine, near Brumadinho

3 days after the failure

Dam B1

Vale (2017)

- Maximum height: 87 m
- Crest length: 700 m
- Stored volume: 12.7 Mm³
- Status: No operation to tailings disposal
Dam I at Feijao mine, near Brumadinho
• Clearly, something triggered liquefaction
• International panel investigating the failure

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• What does the future hold for TSFs?
• Final remarks
Is the failure at Feijao mine unique?

- No, not in Brazil...

Is the failure at Feijao mine unique?

- No, not in Brazil... even recently (November 2015)
Is the failure at Feijao mine unique?

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

Is the failure at Feijao mine unique?

- No, not elsewhere in the world either - http://www.wise-uranium.org/mdaf.html
Is the failure at Feijao mine unique?

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

Is the failure at Feijao mine unique?

- Mount Polley, Canada (August 4, 2014)
Is the failure at Feijao mine unique?

• Bingham Canyon, USA (April 2013)
Is the failure at Feijao mine unique?

- Las Palmas, Chile (February 27, 2010)

Is the failure at Feijao mine unique?

- Kingston fossil plant, USA (December 22, 2008)
Is the failure at Feijao mine unique?

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

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 ~ 1:700 to 1:1750 (compared to water-retaining dams at ~ 1:10,000) (Davies 2001)

![Graph showing number of TSF failures/accidents by decade]

Bowkers and Chambers (2015)

Overview

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- **What does the future hold for TSFs?**
- Final remarks
What does the future hold?

- Despite the failures, TSFs keep getting bigger

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
What are the alternatives?

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

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
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

Dry stack/filtered tailings

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

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- Is the failure at Feijao a unique occurrence?
- What does the future hold for TSFs?
- **Final remarks**
  - Should upstream TSFs be outlawed everywhere?
  - Could the failure at Feijao have been avoided?
  - At what cost?
Thank you for your attention!

Questions?

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