Advances in Mine Waste Management in South America

Tailings and Mine Waste 2017
Advance

What does the global record show?
The Failure Record for 2016 and 2017

- June 30, 2017
  - Mishor Rotem, Israel. Phosphate.

- March 12, 2017
  - Tonglvshan Mine, China. Copper, Gold, Silver, Iron. 2 Fatalities

- August 27, 2016
  - Mulberry Florida, USA. Phosphate.

- August 8, 2016
  - Dahegou Village, Luoyang, China. Bauxite.

From: The Landslide Blog
WWW.Wise-Uranium.com
In what areas of mine waste management are we advancing?
Areas of Advance

- Stewardship of mine waste management facilities
- Social responsibility
- Health and safety on large mining company sites
- Dewatering technology
  - Thickeners, Filters, Flocculation
- Alternative disposal concepts to reduce stored water
  - Co-disposal, Co-mingled, PasteRock, Geowaste, Dry Stack
- Ultra-high dams
- Analysis
  - Deformation based design approach
  - Instrumentation linked to deformation analyses
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- **Ultra-high dams**
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Health and Safety Advance

The Safety Share
2017

- A worker died on July 27, 2017 when the vehicle he was in was run over by a haul truck, officials said. "It appears he was sitting in his work truck, a Ford F550, when he was run over by a large mining haul truck that had just finished dropping its load".

- A contract worker drove a pickup truck into the wrong lane of a haul road into the path of a haul truck. Another worker immediately radioed the driver who pulled over to the side of the road. The loaded haul truck passed within a few meters of the pickup truck without the driver seeing the pickup.
2017

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1974

- A repairman died on July 11, 1974 as a result of injuries received when the 1-ton flatbed truck he was operating was crushed by a 120-ton truck. He parked on the blind side of the truck waiting to proceed to the shovel. As soon as the truck being loaded started to leave, the haul truck drove his truck up over the other vehicle.
Ultra-High Dams
Height > 200 m

Constructing/operating dams with design heights to 300 m
Detail designs for dams > 300 m
Conceptual designs for dams ~ 400 m
Ultra-High Dam Examples

- Peru: Rockfill Tailings Dam H~280 m
  - Starter Dam 135 m
  - 1 billion tonnes > 140,000 tpd

- Chile: Tailings Sand Dam H~240 m
  - Starter Dam 82 m
  - 1.7 billion tonnes > 175,000 tpd

- Peru: Tailings Sand Dam H~260 m
  - Starter Dam 85 m
  - 1 billion tonnes > 120,000 tpd
Why consider ultra-high dams?
The Site Selects the Dam

Ultra-High Dam Site

High Dam Site
Site Examples

1 billion tonne capacity
280 m high dam - 720 hectares

4 billion tonne capacity
105 m high dam – 6000 hectares

November 6, 2017
Rationale for Ultra-High Dams

- Large mineral resource
- Deep, narrow valley site
- Storage capacity requires thick tailings deposit
  - Thickness similar for all disposal methods
- No room to manage process water separately from tailings solids
  - Limestone – karstic areas or other reasons cannot manage water separately from solids.
Rationale for Ultra-High Dams

High production rate → High availability/reliability

- Deposition cycle
  - Discharge, sedimentation, consolidation, drying sequence
- Tailings conveyance, distribution system
  - Pumps, pipelines, launders, valves, spigots
- Thickeners or filters
- Dam construction materials
  - Mine waste rock, tailings coarse fraction
  - Borrow
Rationale for Ultra-High Dams

- Seismically active regions
  - M8 to M9 design event → PGA 0.4 to 0.8 g
  - Liquefaction is a certainty for loose, saturated tailings
- High rainfall – wet season/dry season
  - Infiltration → saturation
  - Surface erosion → sediment generation
    - Sediment management
Rationale for Ultra-High Dams

- Extensive precedent for dam design, dam construction and dam management
  - Extending rather than creating the precedent
  - Precedent for tailings stacks/piles for these conditions does not exist

- Downstream construction decouples construction from tailings deposition/operation
Thickening for Ultra-High Dams

- Thickened tailings may give an increment to the final density

  ▶ Increased storage capacity not a lower dam
    ▪ Steeper beach slope for thickened tailings may reduce capacity for perimeter discharge into large TSF
      ▪ Change operation in final years – reduce thickening
Chilean Alternative to Ultra-High Dam

- Tailings site remote from mine
  - Long distance slurry transport
  - Gravity systems

- Chilean examples:
  - Andina Mine: Ovejeria TSF – 86 km concrete launder
  - Los Bronces: Las Tortolas Concentrator – 56 km ore slurry pipeline
  - El Teniente: Caren TSF – 87 km pipeline, launder, stream channel
Remote Tailings Sites - Chile

Tailings - 45 km - Mines

Google Earth
Rockfill Dams

Upstream Face Construction

Dam Performance Related to Staged Construction

Material Testing

Asphaltic Concrete Cores
Rockfill Dam Upstream Face

Lean Concrete Curb on 1.3H:1V to 1.4H:1V Slope
Developed for Ita Dam in Brazil
Upstream Face Construction

- Lean concrete curb (3 MPa)
  - Zero Slump
  - Low strength = low modulus
- Sequence:
  - Place 0.5 m high curb
  - ~ 8 hours for strength gain
  - Place/compact 2 filter layers
  - Place/compact transition layer
- Eliminates compaction on face
- Eliminates trimming to design line
- Eliminates filter erosion
- Simplifies geomembrane installation

November 6, 2017
Curb Machine – Towed or Self-Propelled
Staged Downstream Construction

Impact on Dam Deformation
Staged Downstream Construction
Staged Construction Related Deformation
Staged Construction Related Deformation

- Dam surveillance program must anticipate the consequences of the construction method
  - Increased deformation rate as downstream (stabilizing) fill placed
  - Potential cracking of crest
  - Instrumentation needed on crest and dam face

- Starter dam may control final height dam deformation

- Definition of potential maximum height of dam necessary when designing the starter dam

- Increasing compaction specification for the later downstream fills less effective than heavier compaction of starter dam fill
Seismic Design Issue

Volumetric Strain due to Cyclic Loading
Rockfill Testing

University of Chile
1 metre diameter triaxial test
1 metre diameter oedometer
Field Tests
Rockfill Testing

- 150 to 180 mm minus rockfill
- Nonlinear strength function
  - Leps (1970)
- Moduli for one way loading
- Moduli for load-unload-reload
- Particle crushing
  - Single load path
  - Load-reload path
- Allows calibration of constitutive relations for models
  - Shear induced volume change during cyclic loading
Triaxial Test
Volumetric Response for Seismic Design

- Shear stress-strain response

b) Volumetric-shear strain response
Particle Crushing
Field Tests – Stiffness and Strength
Crosshole Shear Wave Velocity Measurement
Confirmatory Data from Instruments

Pressure Cells

Extensometers

Horizontal stress reduction → Extension
Ultra-High Sand Dams

Precedent Advances from Chile and Peru
Sand Dam Design - References

- Obermeyer et al “Design, Construction and Operation of A Large Centerline Tailings Storage Facility with High Rate of Rise” Tailings and Mine Waste 2011
- Eldridge “Design for a 240 m High Sand Dam “ 2o Seminario Vale de Geotecnia e Hidrogeologia Aplicadas à Mineração, Belo Horizonte, Novembro de 2009
Sand Dams

- Upstream constructed dams are prohibited in Chile
  - Regulation requires downstream or centreline construction
- Design components:
  - Prepared foundation
  - Drains on foundation
    - Unsaturated sand – drained behavior – liquefaction control
    - Drain sized for at least 10 times estimated flow
  - Compacted sand – more compaction in areas that could saturate if drains are compromised
  - Downstream face at 3H:1V to 4H:1V
    - Hydraulic placement
    - Reduce seismic deformation
    - Low foundation shear stress
Sand Dams

- Sand hydraulically deposited from crest
  - Sand placed at 68 to 70% pulp density
  - Sand will flow 400 to 600 m down slope
  - Crest raised continuously
- Paddocks typically not used except at start-up when developing downstream slope
- Construction sequence
  - Deposit 30 to 50 cm thick layer of sand
  - Allow to sand to drain
  - Spread and compact
  - Deposit Sand
  - 3 to 7 day cycle
Sand Specification

- Sand is an engineered construction material
  - Strength and deformability
  - Undrained behaviour
  - Hydraulic conductivity
- Total tailings grain size distribution and mineralogy are starting point for material design
  - Maximum particle size is defined by the metallurgical process
  - Fines content is a design parameter
    - Fines < 20% by regulation in Chile – this is not the design value
    - Cyclone separation – consider range that will be produced
    - Consider segregation during placement
    - Consider stress level dependent material behaviour
- *Chile now requires laboratory testing to confirm material characteristics*
Output from Cyclone Station

Grain Size Distribution as Placed

~8% range in fines content
Sand Demand vs Availability

- Sand typically less than 1/3 of the tailings
- Maximum split may be 30% sand / 70% fines
- Cyclone availability considered when selecting maximum sand availability
- Can produce sand earlier than needed and place in downstream toe if cannot meet sand demand later in mine life.
Seismic Performance

- Chilean dams are frequently tested:
  - Feb 27, 2010 Maule Earthquake – M8.8
  - April 1, 2014 Iquique Earthquake – M8.2
  - Sept 16, 2015 Illapel Earthquake – M8.4

- Illapel earthquake generated max. horizontal acceleration of 0.6 g on soil foundation at sand dam site
  - Crest accelerometer not installed at time of earthquake
Monotonic Strength Testing - Sand

Graphs showing the relationship between particle size and percentage passed, and the stress-strain relationship for different effective stress levels at \( \phi = 35^\circ \).
Cyclic Loading – Sand Response

Drained Response

Undrained Response

Compacted

Uncompacted
Asphaltic Concrete Cored Dams

Two asphaltic cored dams to contain tailings are being constructed in South America
Asphaltic Concrete Cores for Embankment Dams

Experience and Practice

KAARE HÖEG

Statkraft
Veidekke
Norwegian Geotechnical Institute
1993
Are there areas that are not advancing?
Ralph B. Peck quotes:

“Designers and regulatory bodies tend to place increasing reliance on analytical procedures of growing complexity and to discount judgment as a nonquantitive, undependable contributor to design.”

“Construction deserves more attention in design. Our permanent structures are too often designed as if they come into existence without the necessity for being constructed.”

“Those who try to force Nature into the pattern by simplifying assumptions of theory will be courting disaster.”
Closing Words for Reflection

From Ken Been, our colleague, regarding the tailings dam failure record:

“The problem is not the mine manager or shareholders. The problem is the standard of engineering.”

From:

*Characterizing Mine Tailings for Geotechnical Design*

Key Note Address

5th International Conference on Geotechnical and Physical Site Characterization, Queensland Australia

Australian Geomechanics, Volume 51: No. 4, December 2016
Thank you.