# The Influence of Tailings Dam Failures on Canadian Practice with an emphasis on Mount Polley and Fundao

- Canadian Geotechnical Society
- Toronto Branch
- March 23, 2022

# Limitations of this Presentation

- This presentation is not a publication and has not been peer-reviewed
- Each slide represents a talking point that the author expanded upon during the meeting. Thus, individual slides may not appear sensible.
- This presentation represents the opinions of the author at the time that the presentation was given. These opinions may change.
- No permission was sought from the original authors of peer-reviewed publications for use of figures and diagrams as this is not a publication.
- Anyone using or quoting information in this slide deck does so at their own risk


Self Regulation
Governments Adopt CDA
BC Government Prescriptive Regulations
2019 ● Brumadinho
2018 ● Cadia
2016 ● BC Mining Code
2015 ★ Samarco
2014 ★ Mount Polley
1999 ● CDA Major Update
1998 ● MAC Guidelines
1998 ★ Los Frailes
1995 ★ Omai
1995 ● CDA

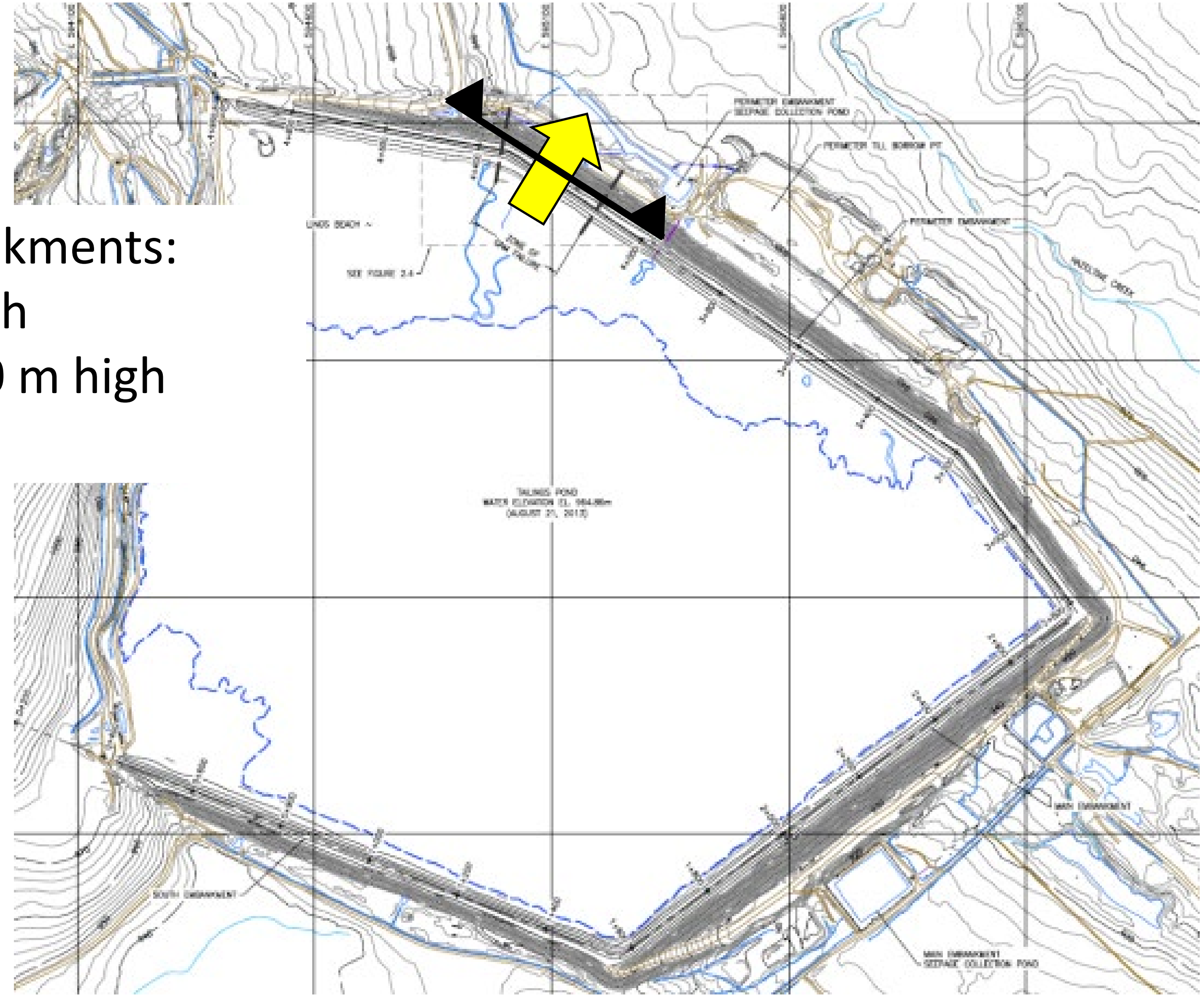
# *Industry reaction after Omai and Los Frailes?*

- *Management Guidelines*
  - MAC Guideline No. 1 (1998, updated 2011)
  - MAC Guideline No. 2 (2003, updated 2011)
  - MAC Guideline  No. 3 (2011)
- *Dam Safety Guidelines*
  - CDA Guidelines – 1995, 1999, 2007, 2013, 2014 - Mining Supplement
  - APEGBC – Legislated Dam Safety Reviews in BC – Appendix B – Mining Dams – July 2013
  - ICOLD Bulletin 139 – Improving Tailings Dam Safety – Critical Aspects of Management, Design, Operation and Closure– 2011
- ***Many other great documents and all preceded the Mount Polley failure!!!***

# Mount Polley, BC – Plan

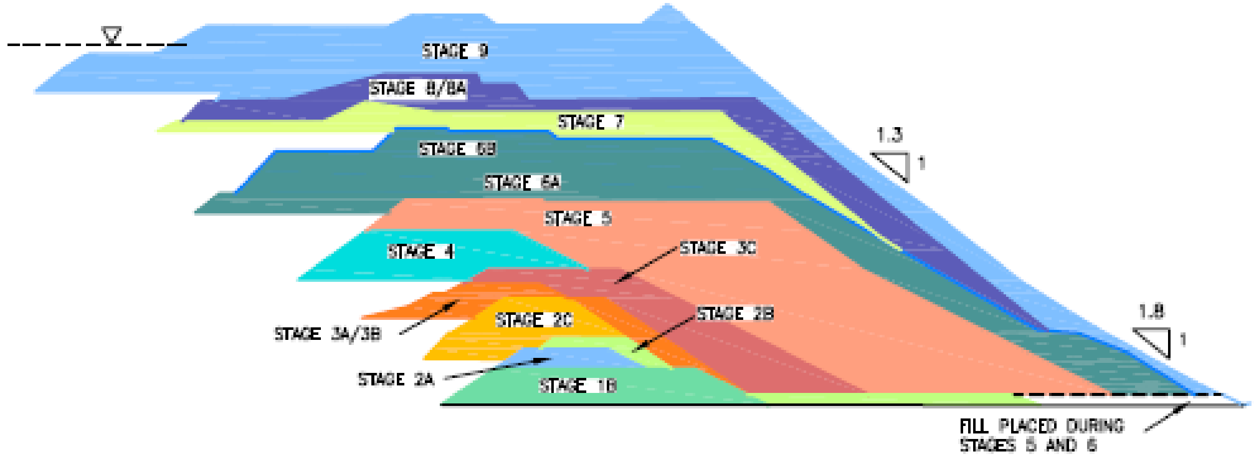
Three embankments:

- 4 km length
- 40 m to 50 m high



# Mount Polley, BC – Section & Construction Sequence

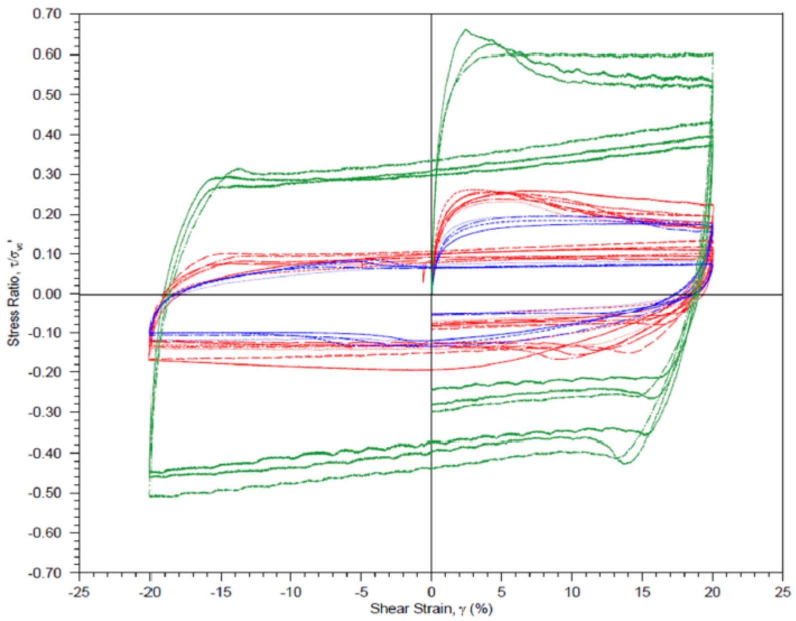
- Perimeter Embankment as-constructed condition:
  - Constructed in 9 stages (raises)
  - Modified centerline dam with low permeability core zone, downstream rockfill with filters



# Mount Polley (2014)

- Failure induced in lightly over-consolidated to normally consolidated clay in the foundation
- Strain-weakening, but not brittle

a) UGLU - MONOTONIC DIRECT SIMPLE SHEAR TESTING

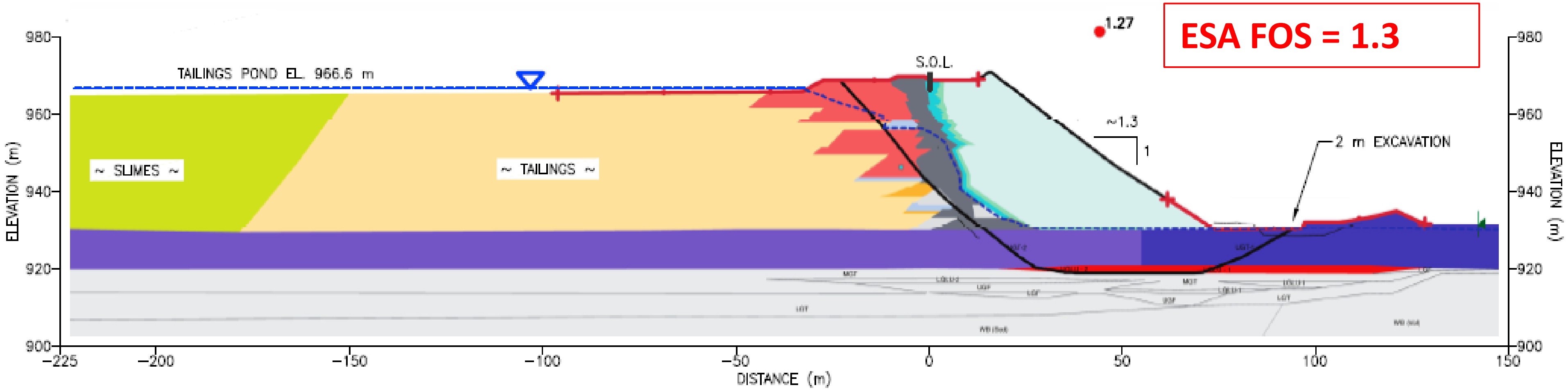



a) UGLU - FREE FIELD DOWNSTREAM OF FAILED EMBANKMENT

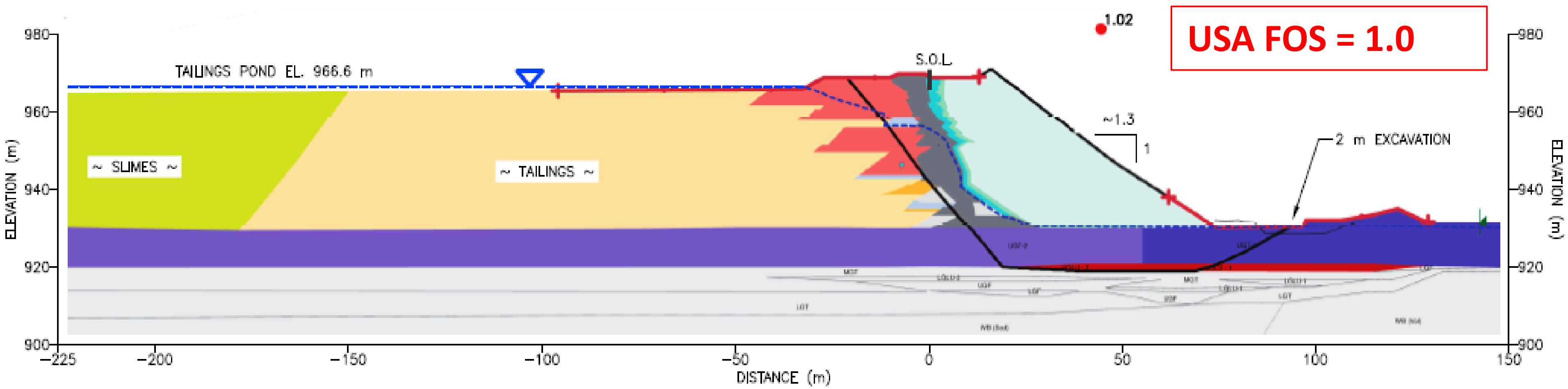
SH14-10 (Middle/Top UGLU Layer) Approximate El. 921.1 m to 919.5 ,m

Sub-horizontal varved bedding. Water content = 35.7%; Liquid limit = 60%; Plastic index = 20%; Clay fraction = 58%

# Mount Polley (2014)



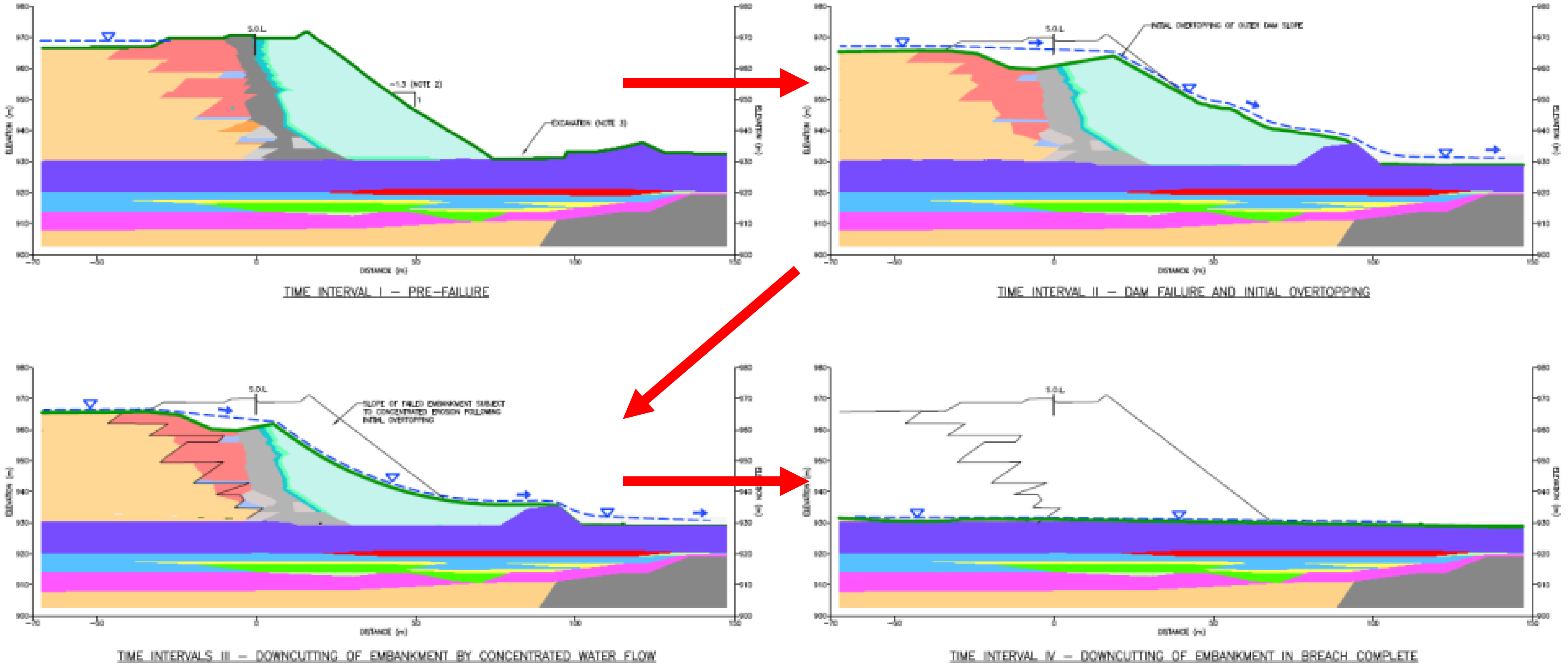

a) STAGE 1 – PEAK DRAINED STRENGTH IN UGLU



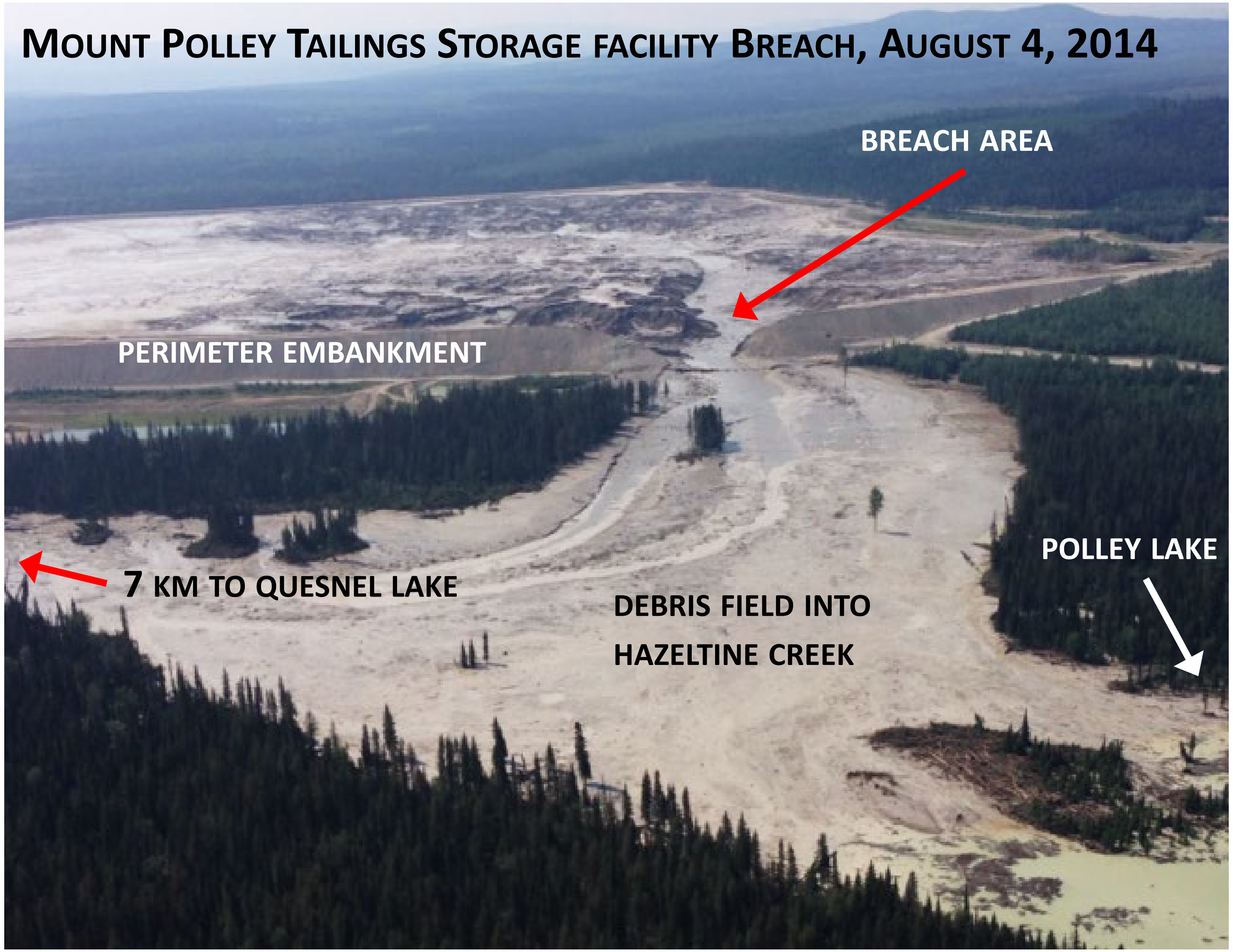

b) STAGE 2 – PEAK UNDRAINED STRENGTH IN UGLU

# Mount Polley, BC – Failure Illustration

Erosion followed the failure as the water overtopped the slumped crest of the embankment.



# Mount Polley, BC – Failure Consequence



# Mount Polley (2014)

**Take-Aways from the two forensic investigations**

- Project team were unaware that the UGLU was present in this location under the perimeter dam. Two test holes drilled in 2011 were on either side of this narrow unit (about 100 m wide)
- Downstream slope was unusually steep at 1.3H:1V
- There was a shallow excavation at the toe of the Perimeter embankment which was not backfilled at the time of the failure
- Undrained failure caused by loss of undrained strength in transition from overconsolidated (OCR about 4 to 5) to normally consolidated response in the UGLU due to embankment loading
- Absence of any monitoring data to provide early warning

A PhD has been done at the UofA to look at the failure from a 3D perspective using FLAC3D by E. Zabolotnii

# Zabolotnii, Morgenstern, and Wilson (2022) Canadian Geotechnical Journal

- “Failure caused by a confluence of conditions:
  - a reduction of shear resistance in a small portion of the Upper GLU to post-peak values,
  - the development of local failures in the UGT above the strain-weakening zone and an associated reduction in the levels of mobilized shear resistance;
  - and the incomplete mobilization of shear strength in the rockfill until the late stages of collapse.
- The localization of strains in a shear band with a thickness ≤12-13cm was requisite for the initiation of this failure, and the incomplete mobilization of shear strengths in the shell zone explains why the nominally considerable three-dimensional stability effects present in this slope did not act to stabilize it. “

So, shear band formation in the UGLU was necessary to explain the failure in a 3D analysis

The more a failure is studied, the more is learned.

# Mechanism of Failure of the Mount Polley Tailings Storage Facility

Elena Zabolotnii[1], Norbert R. Morgenstern[2], G. Ward Wilson[3]

[1]Department of Civil and Environmental Engineering, University of Alberta, 9211 116 St., Edmonton, AB, Canada T6G 1H9, ezabolot@ualberta.ca

[2]Distinguished University Professor Emeritus, Department of Civil and Environmental Engineering, University of Alberta, 9211 116 St., Edmonton, AB, Canada T6G 1H9, norbertm@ualberta.ca

[3]Professor, Department of Civil and Environmental Engineering, University of Alberta, 9211 116 St., Edmonton, AB, Canada T6G 1H9, wwilson2@ualberta.ca

Corresponding author: Elena Zabolotnii

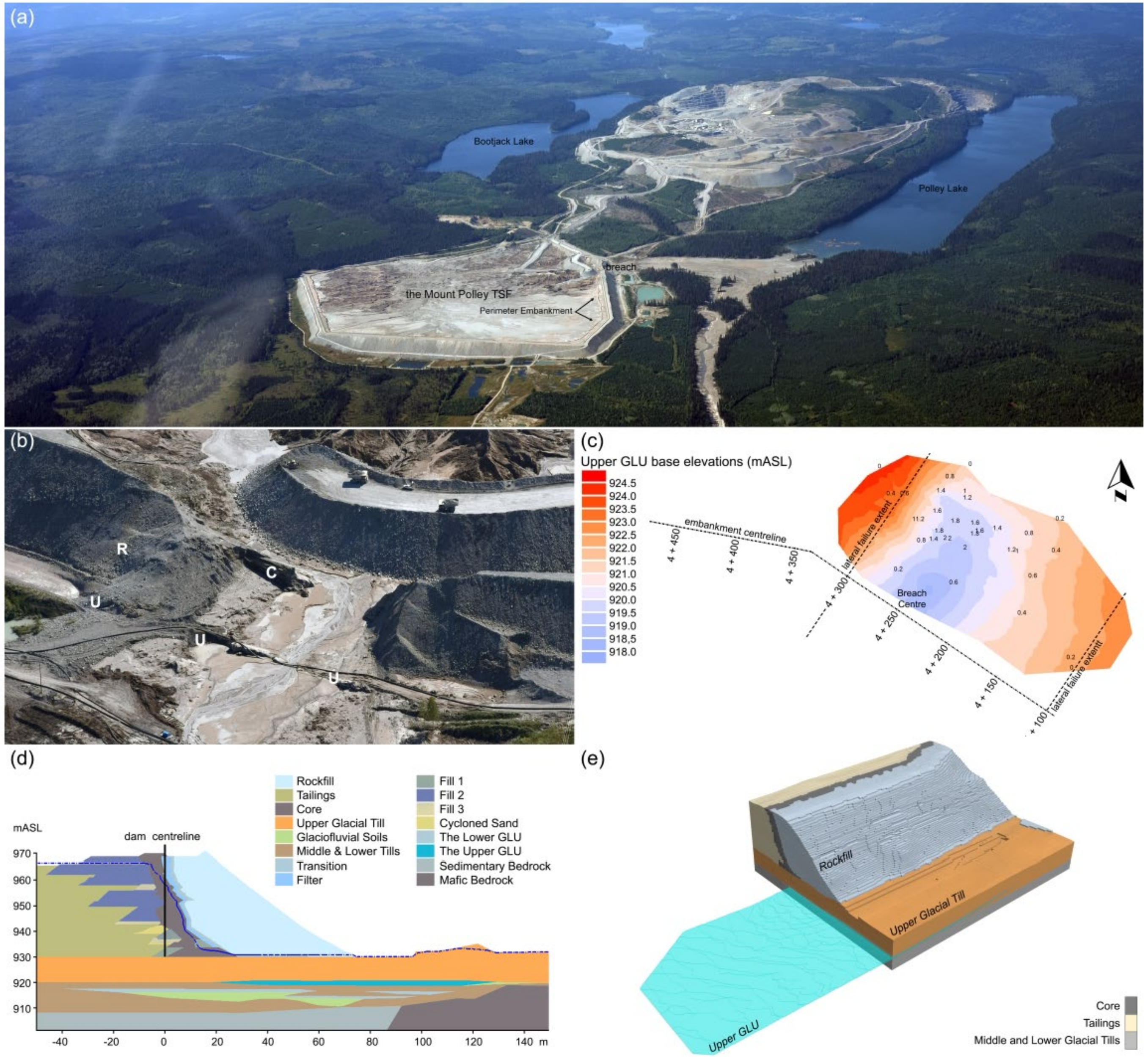
Address: 9305 – 84 AVE NW, Edmonton, AB, T6C 1E6

Cellular: +1 780 885 5933

Email: ezabolot@ualberta.ca







# Lessons Learned from Mount Polley Failure

1. Transition from drained to undrained behaviour of cohesive soils/ undrained stability analyses needs to be considered – significant change in Canadian practice. And, FOS of 1.5 for tailings slopes became mandatory
2. Independent Review Panel – use Best Available Technology – has led to filtered tailings options being considered for most projects – significant progress made in Brazil scaling to larger throughput
3. BC Government changed mining legislation guidance so that there is a better definition of relative site roles: Mine Manager, EOR, RP, and ITRB.  Basic underlying theme is that responsibility and authority go together
4. Severe repercussions for the geotechnical designers – 3 engineers disciplined in BC with careers devastated!

# 1. Effective Stress Analyses used primarily in practice up to Mount Polley Failure

- As example downstream slope failure to the right occurred in 2008 in an embankment on the prairies on a weak clay foundation
- Forensic investigation used effective stress analyses exclusively. No consideration of the undrained failure mode
- Now, undrained static stability analyses are considered on every project in Canada using a basic Shansep approach if the foundation soils are cohesive

# Shewbridge (2019) – ASCE Journal - read this paper!

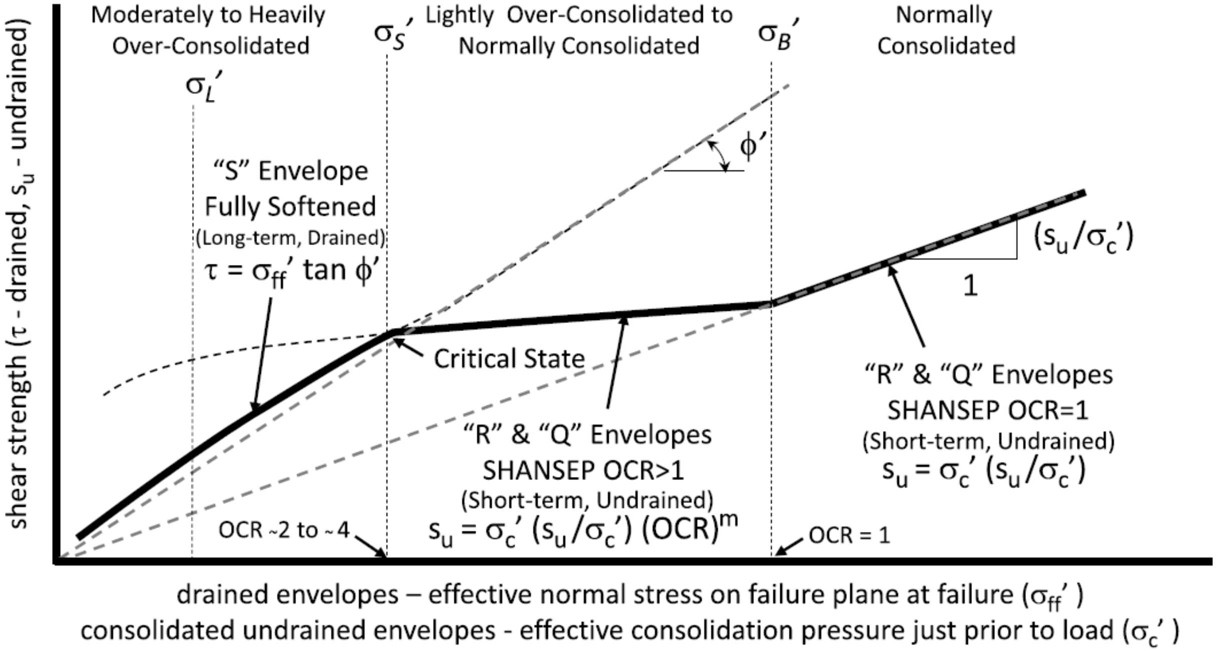
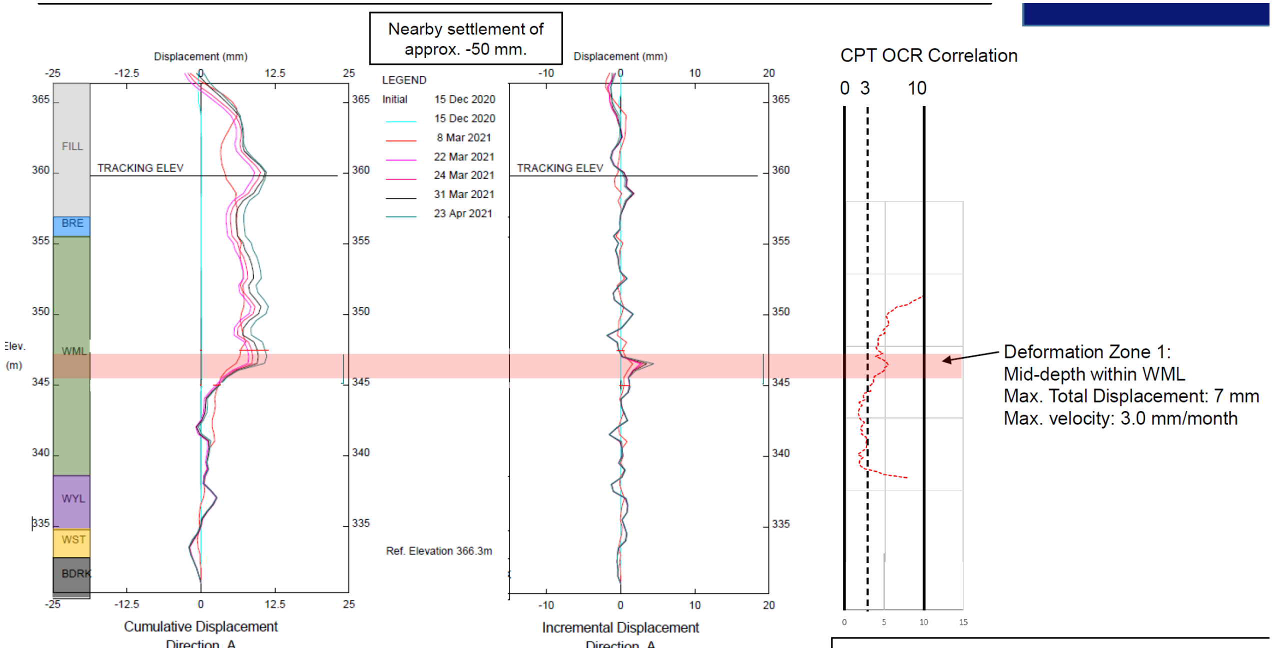



**Fig. 7.** Overlay of SHANSEP, fully softened, and critical state concepts and USACE design envelopes (Q, R, and S) on Taylor (1948) relationship of Mohr envelopes for the drained and consolidated-undrained cases. For OCR greater than about 2–4, drained strength is controlling. For OCR less than about 2–4, undrained strength is controlling.

# Standard Undrained Stability Analysis Practice in Canada

- Perform CPTu test with FVT to obtain Nkt, soil classification, pore pressure dissipation
- Use sleeve friction to estimate minimum undrained strength profile (See Robertson 2021 –CGJ)
- Obtain undisturbed samples in drill holes for testing
- Perform index tests. Water content is supremely important because it yields density if soil is saturated
- Perform direct simple shear tests to obtain Su/p’ ratio independently of CPT
- Can estimate Shansep parameters directly as backup from critical state, see multiple publications by Paul Mayne – Su/p’ about ½ sinσ’ and , m=0.8
- Practice is still evolving and highly variable globally. See clever correlation of OCR to inclinometer readings to the right



# 4. EGBC Discipline of Three Design Engineers

- Discipline initiated by BC Peng. Association through press conference in 2018 – not initiated by an external complaint
- First senior engineer did not contest charges and retired.  Unaware of current circumstances for second young engineer. Career severely hampered.
- Third engineer vigorously defended his position.  EGBC used several experts to prepare their case. Seemingly unlimited budget, took years.
- Third engineer agreed to lesser charges to end proceedings.  Consent order recently published by EGBC
- Financial penalties to engineers in these types of circumstances are onerous. Must pay for all EGBC costs if unsuccessful even on a minority of charges.
- Even if the engineer is successful defending all charges, EGBC does not pay defendants costs.
- Third engineer is now retired and not practicing.
- Third engineer had an outstanding career.  Our profession is less without him.
- Lesson – if this can happen to the third engineer, then it can happen to any one

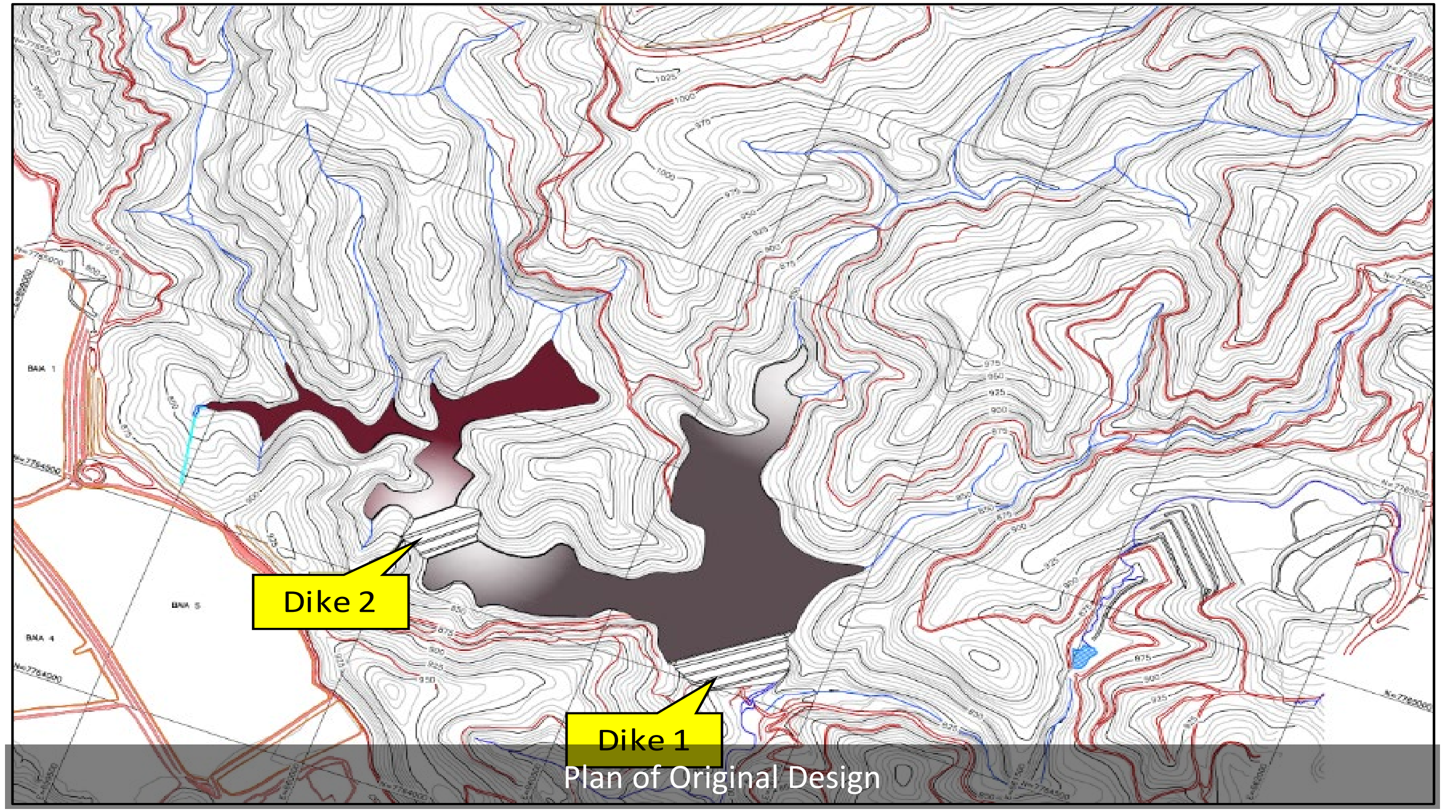

# The Fundao Failure

# Before and After

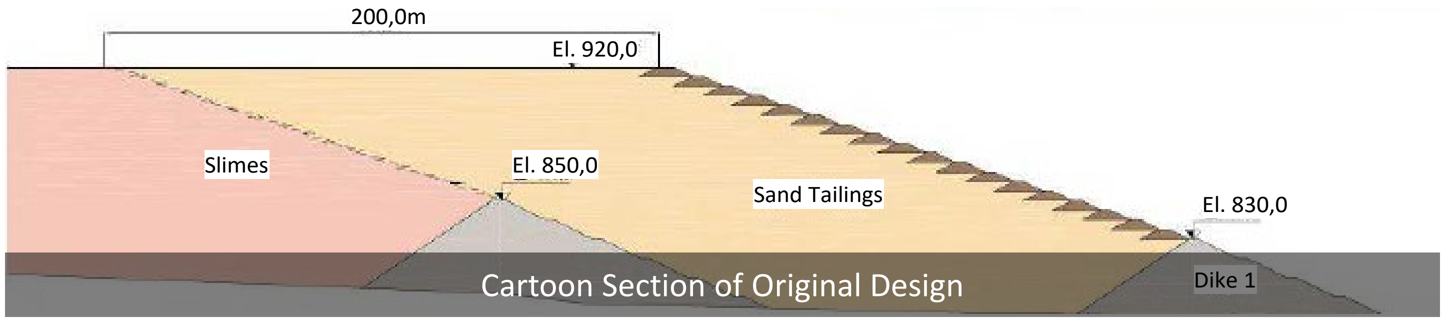
# Some basic facts on the Fundao Dam Failure

- Dam failed by static liquefaction on Nov. 5, 2015
- Dam was just one of several in the immediate vicinity to store tailings from open pit iron ore mining using the same design
- Crest at  El. 900 m, toe at 795 m, so 105 m high
- Failure during raise to El. 920 m
- Planned to raise to El. 940 m
- Released 32Mm$^3$ of tailings to the environment

# Original Design Concept – completely drained sand tailings

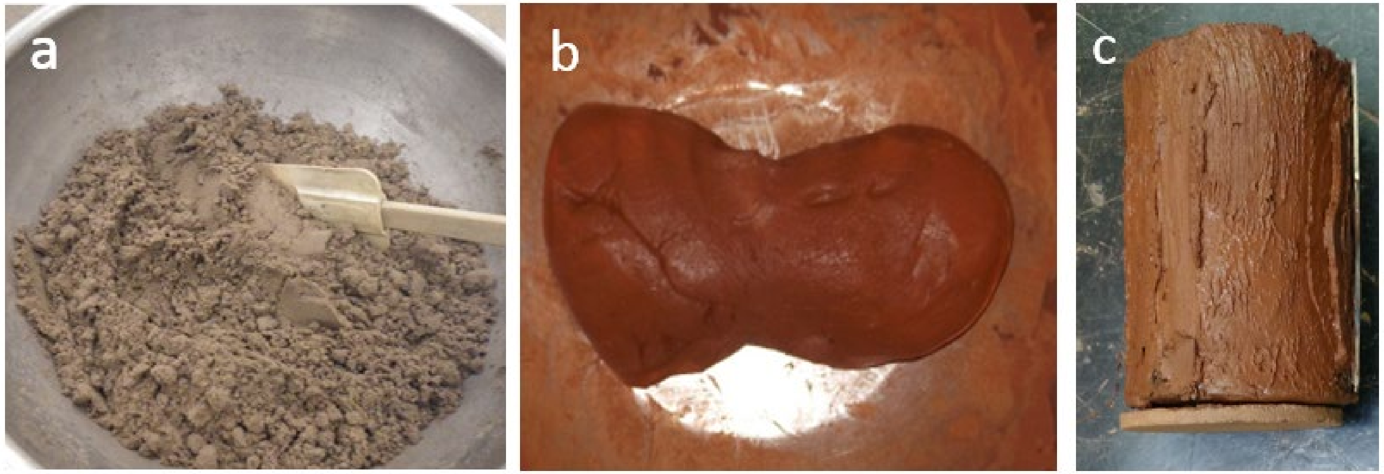


Plan of Original Design



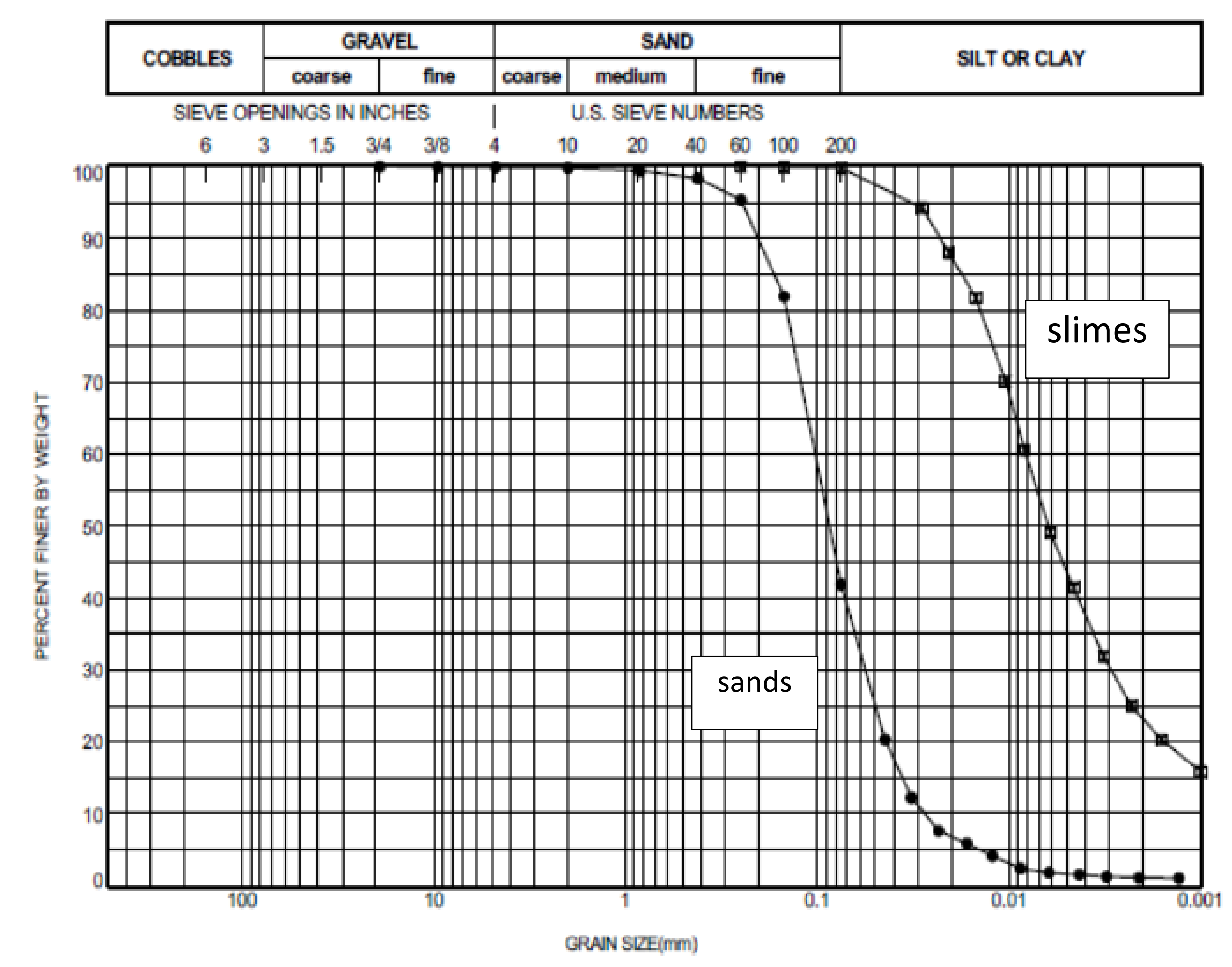
Cartoon Section of Original Design

# Iron Ore Tailings in Brazil – Sand and Slimes separated at plant and pumped in different pipelines to the impoundment



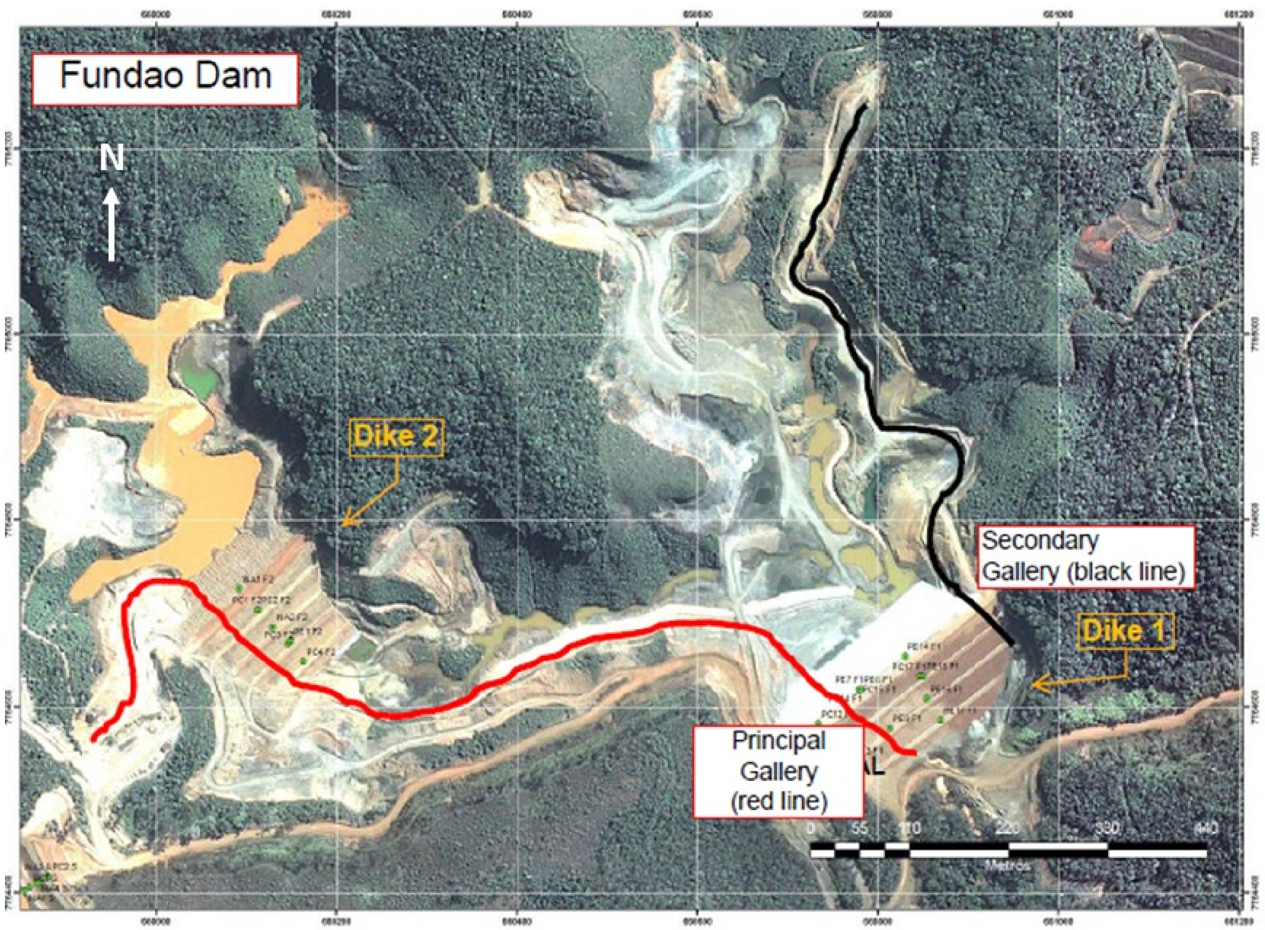

| Property | Sands | Slimes |
|---|---|---|
| **percent minus 0.074 mm** | 40-45 | 98-100 |
| **percent minus 0.002 mm** | <2 | 20-25 |
| **specific gravity** | 2.8-2.9 | 3.9-4.0 |
| **plasticity index** | non plastic | 7-11 |
| **permeability** | $3 \times 10^{-4}$ cm/s | $< 10^{-6}$ cm/s |

# Iron Ore Tailings – Gradation Curves



# Decant Conduits and Foundation Drainage

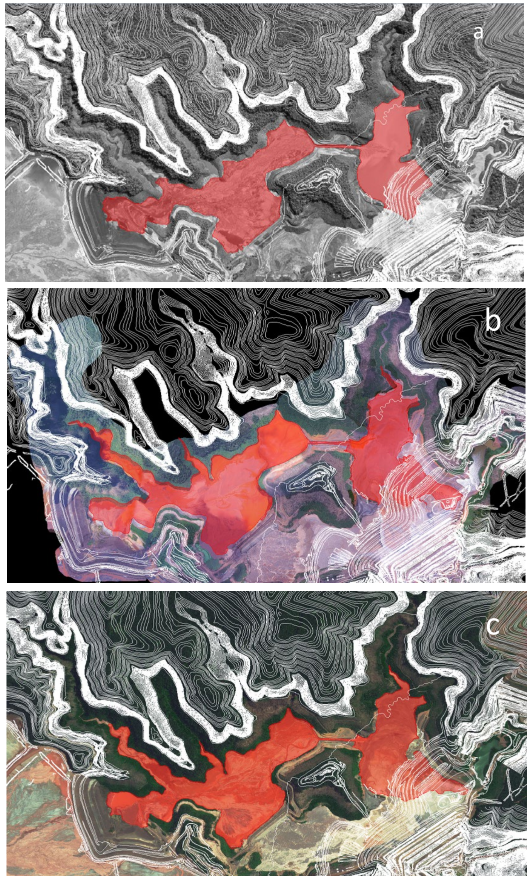
- Sand section was to be completely drained with valley finger drains discharging through Dike 1.
- Galleries were installed on the foundation soils to drain ponds to downstream dam.
- Both finger drains and galleries eventually failed.



# The Slimes

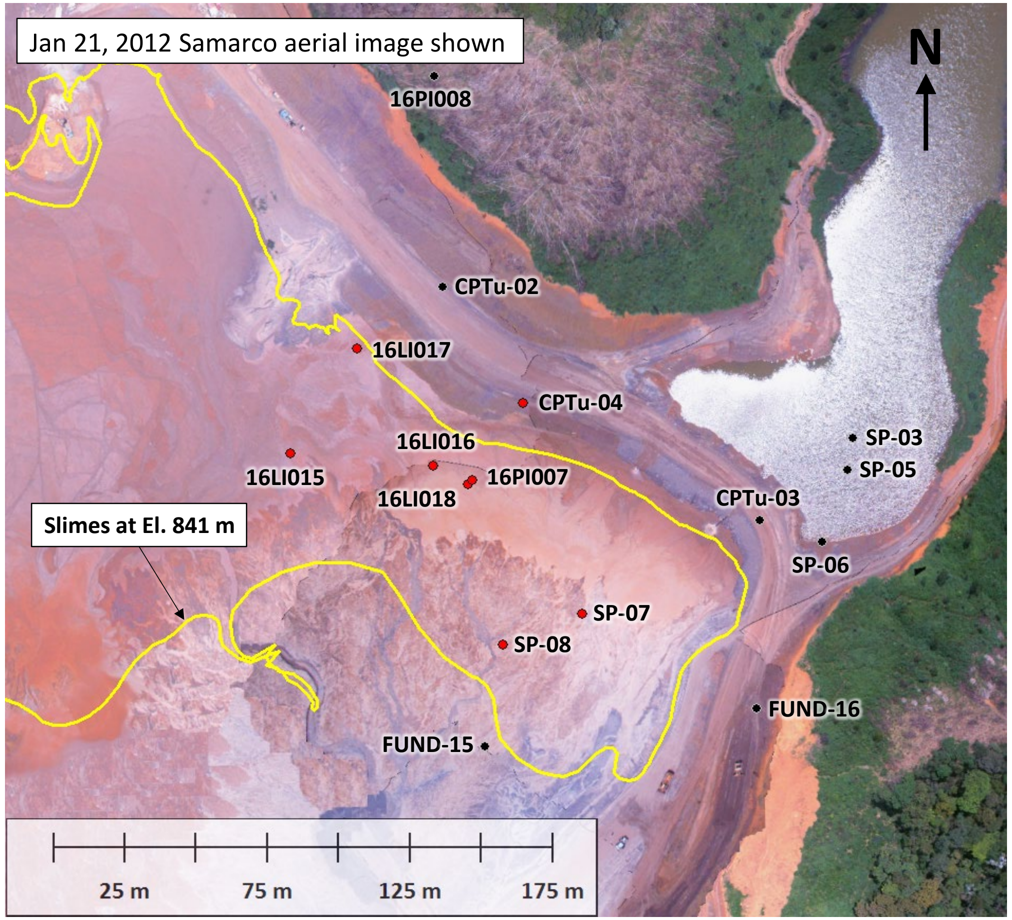
# Fundao Dam Failure – Slimes Encroachment

Slimes diverted to Dike 1 when principal gallery was being repaired

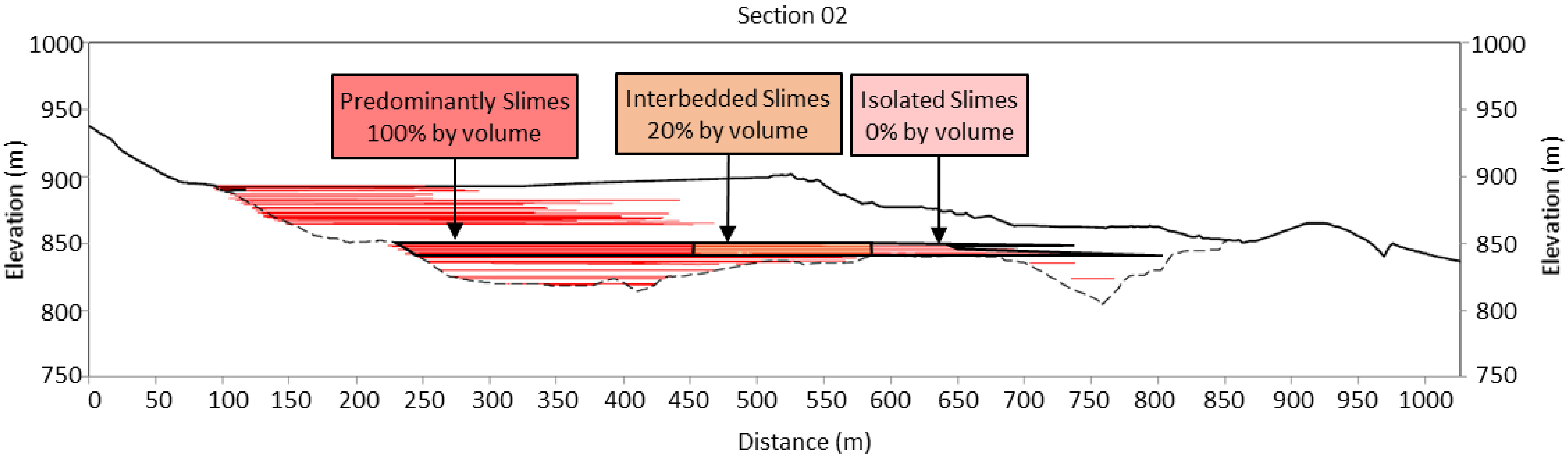



(a) September 20, 2011;
(b) January 21, 2012;
(c) March 3, 2012

# Test Hole Verification of Slimes Encroachment



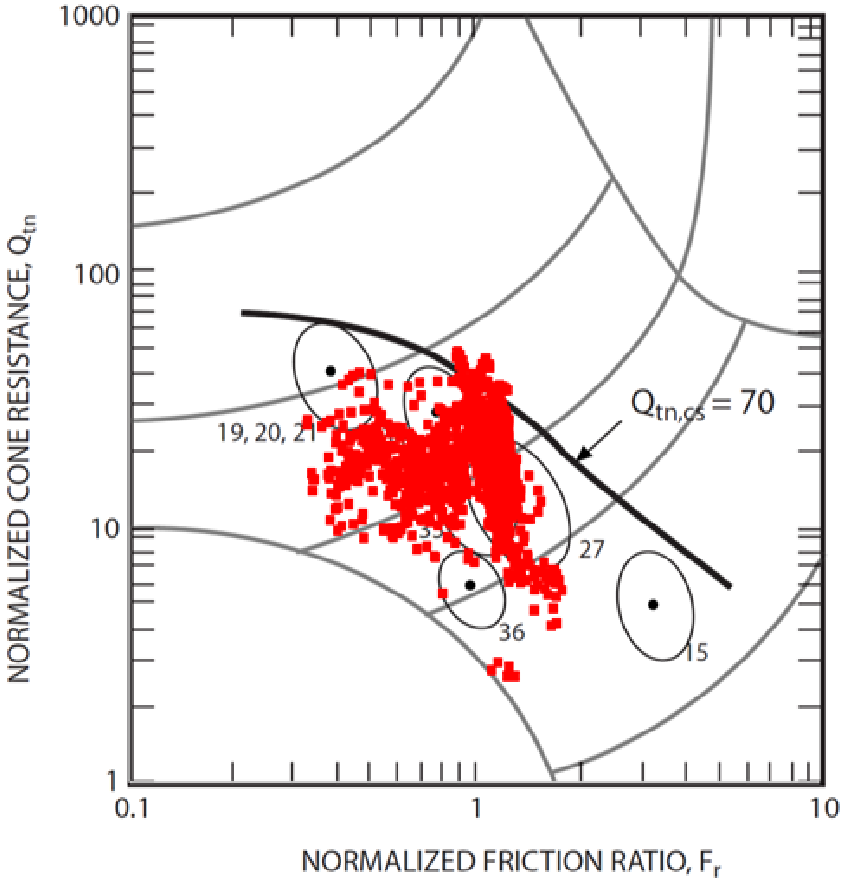
# Section 02 on Left Abutment Setback



# Fundao Dam Failure

All tailings were liquefiable

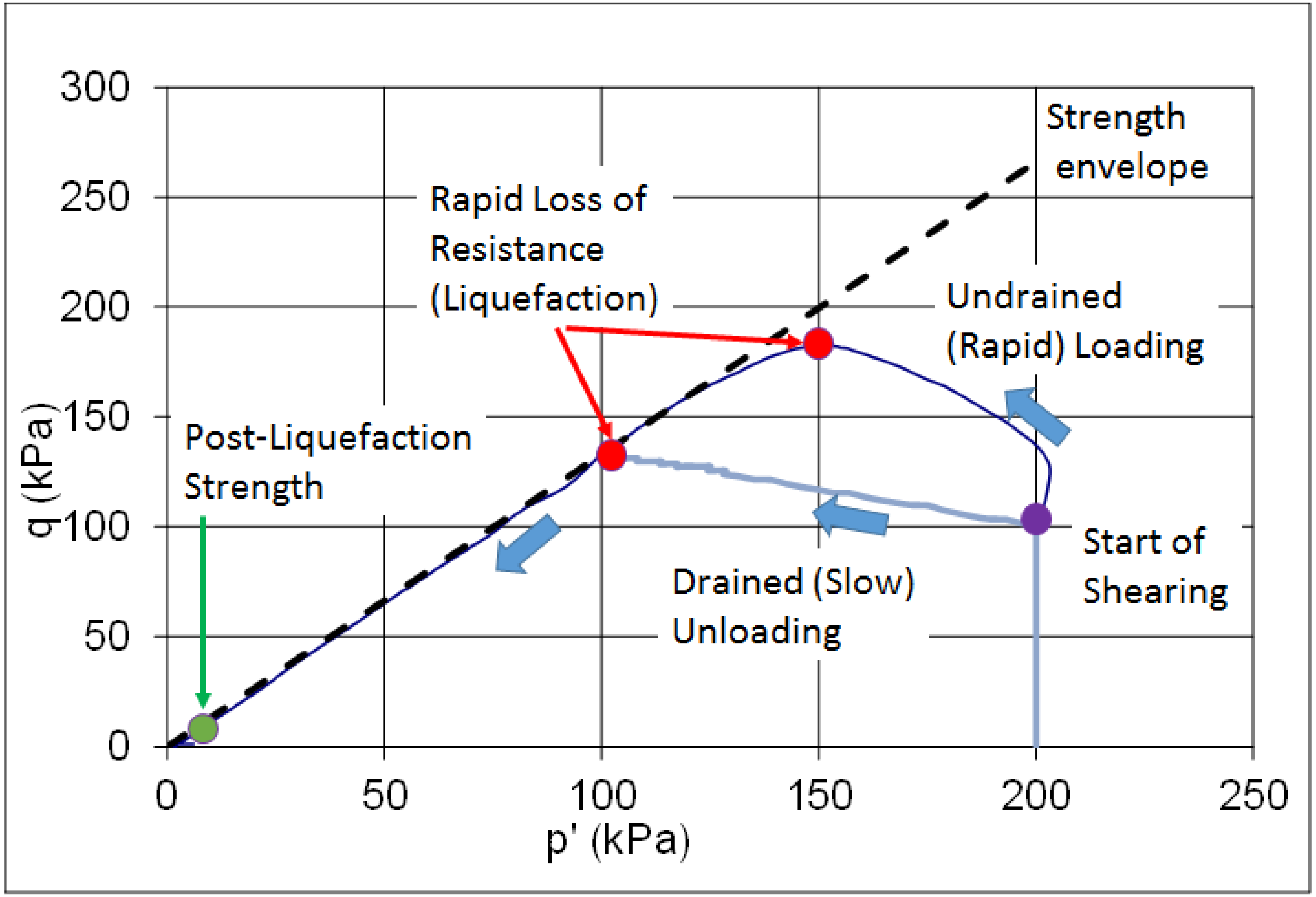
# Compilation of CPT Results on Robertson Chart



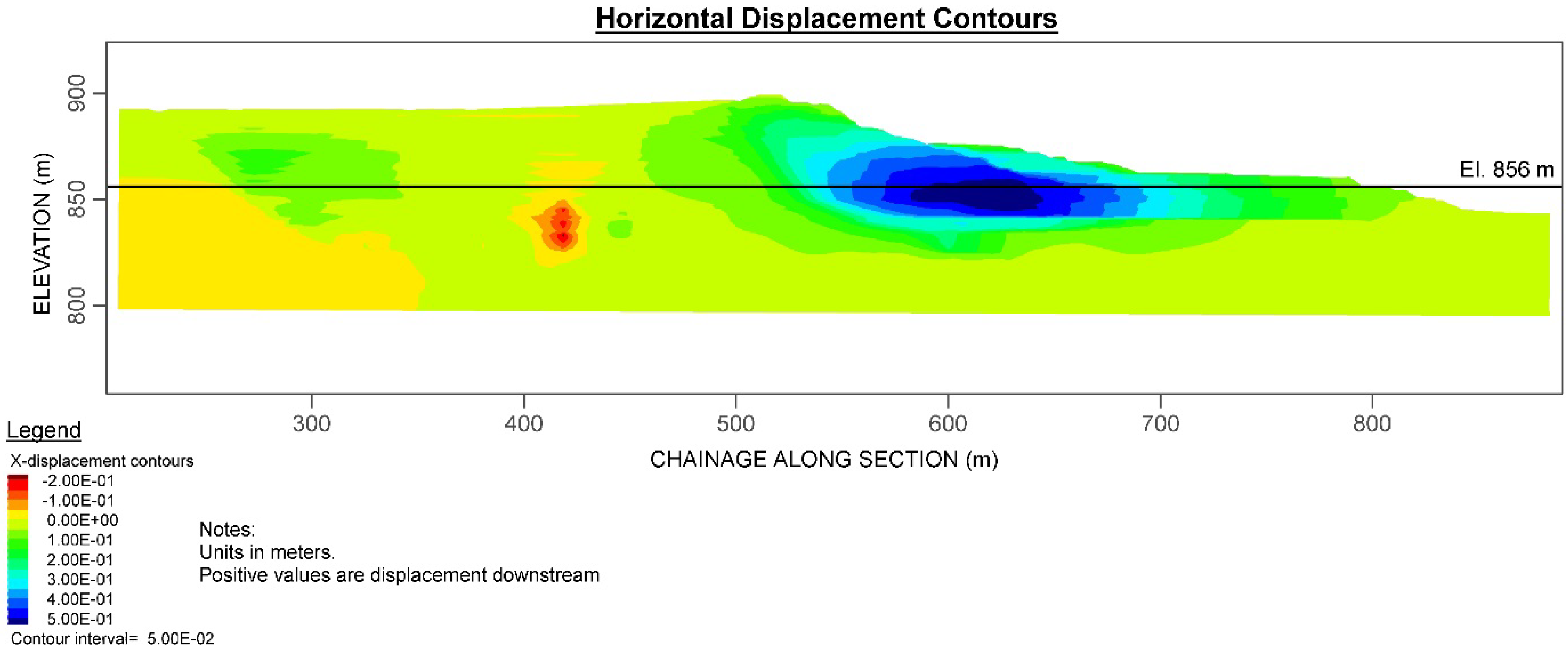
# Fundao Dam Failure

The winning hypotheses – extrusion collapse

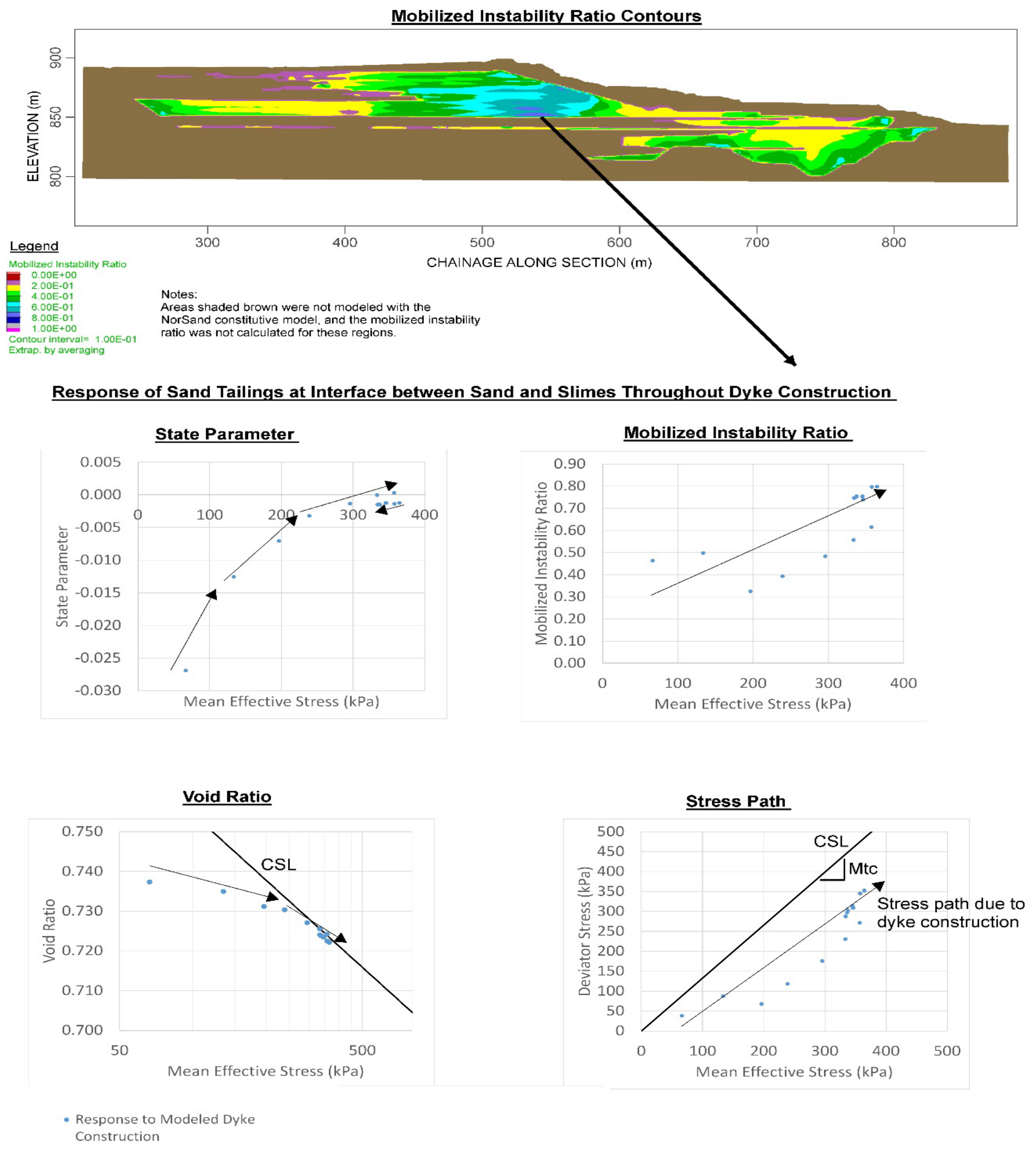
# Drained Path to Failure



# Predicted Horizontal Displacements from Norsand



# Some Norsand Results

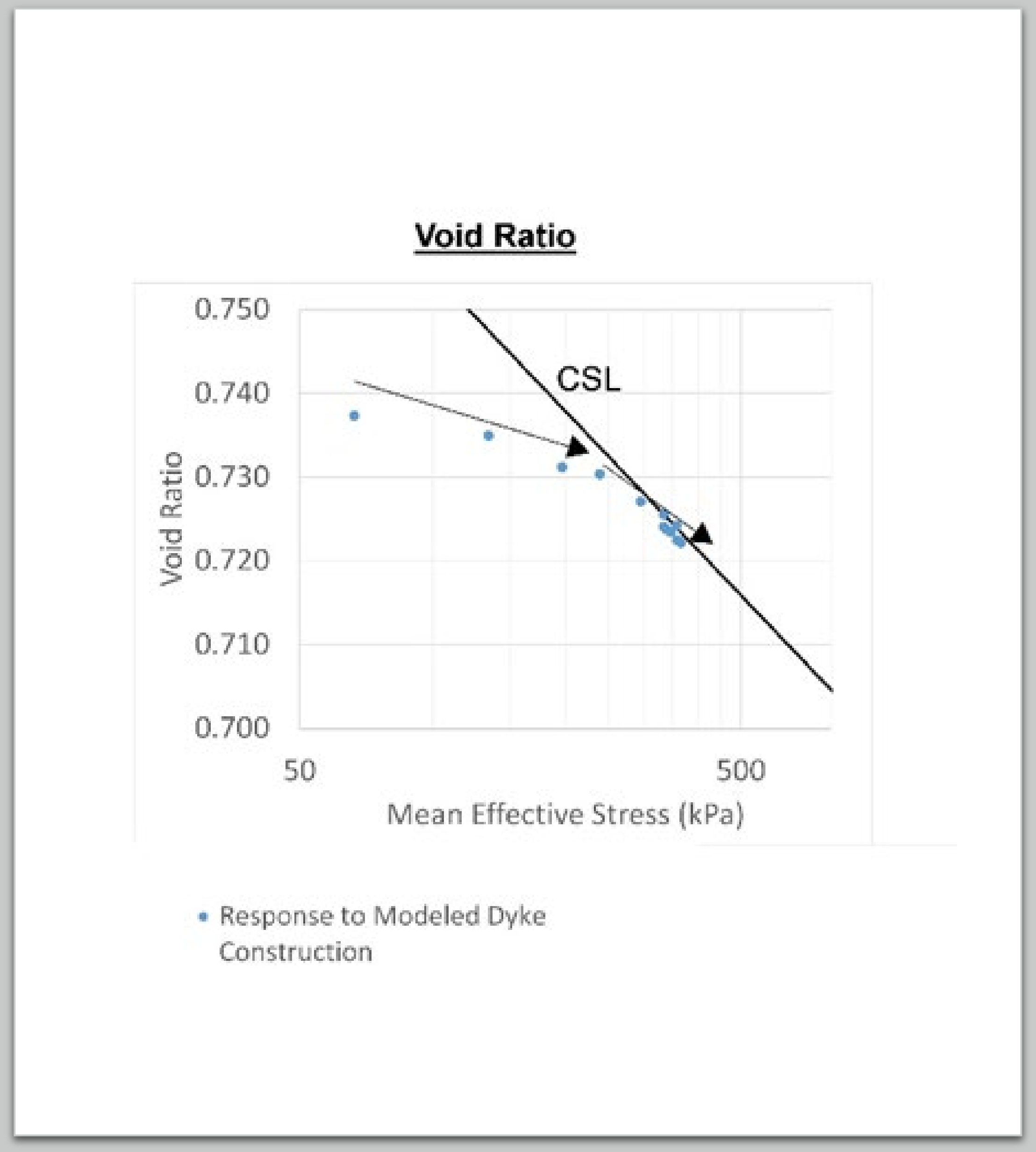


# Lessons from Fundao

So, what did the profession learn from Fundao?

# State is key, not density

- General feeling on design project team was that tailings density was increasing so dam was getting more resistant as it was raised. NOT TRUE
- If the state parameter starts out on the dilatant side of the CSL, raising the dam increases the state parameter; can go from dilative to contractive
- Much more awareness of the importance of calculating the state parameter from the CPT.
- This originated with Been and Jefferies in the mid-1980s and was streamlined with Plewes et al in the early 1990s.
- Estimates of state parameter still being improved
- Normally plot both state parameter and Qtn,cs



# Can’t predict static triggers – must assume will happen

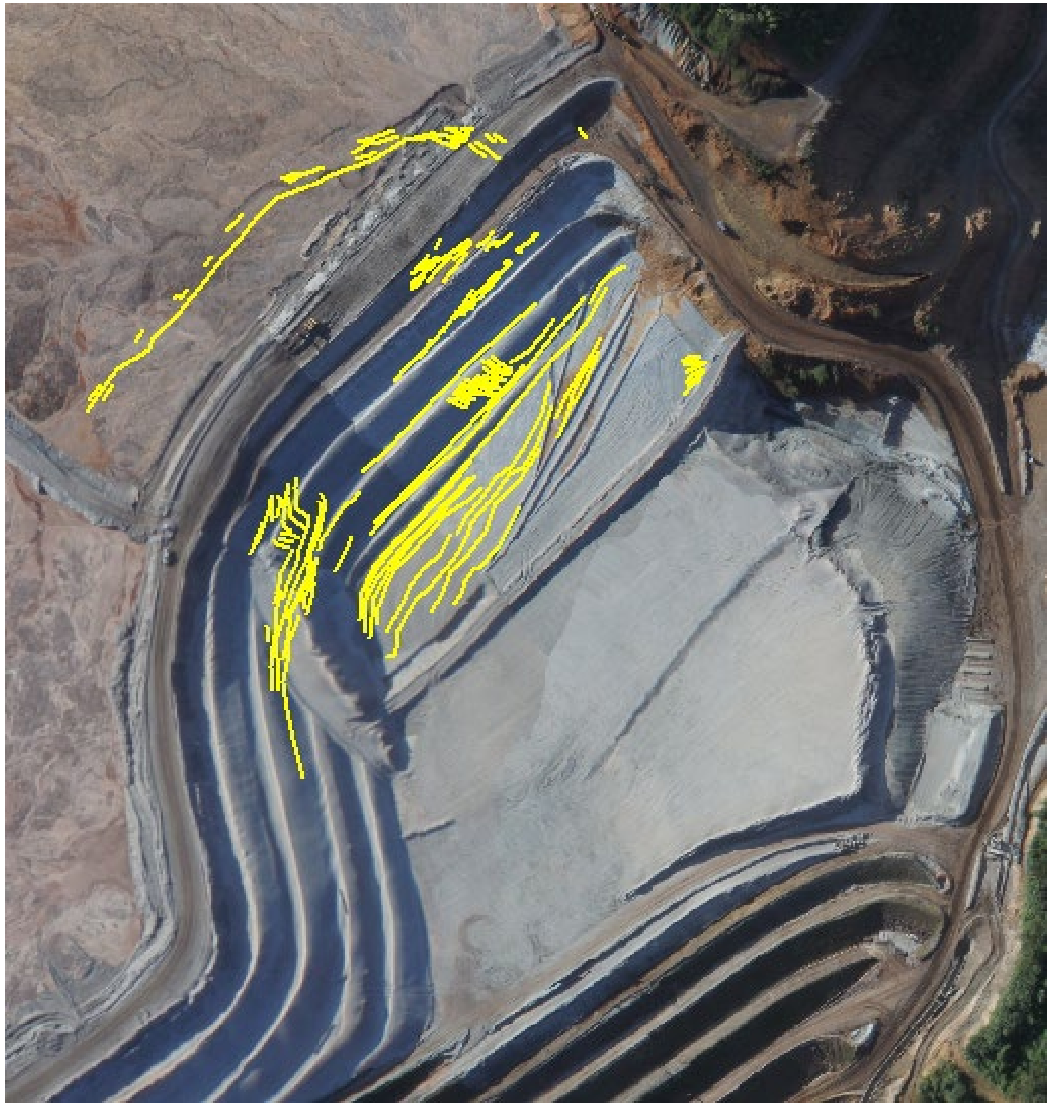
- Static liquefaction triggers are not currently predictable - Assume post liquefaction strengths in contractive saturated zones in tailings if state parameter is greater than -0.05.
- Extrusion collapse – very few understood this static liquefaction trigger mechanism before the failure of Fundao.
- Jefferies and Been(2015) have this concept in their textbook
- Drained loading leading to an undrained response was vaguely understood for sands – U of A did a lot of work on this in the early 1990s but was largely ignored.
- Most? of the profession migrated to use of post-liquefaction strengths for flow liquefaction assessments after this failure, if not already there
- However, there were still some engineers who did not accept this approach after Fundao but Brumadinho brought many more converts.

# *Increased the use of Norsand*

- Fundao Investigation team had to write Fish functions to use Norsand in FLAC
- Fundao Investigation team had been using FLAC/Norsand for about 7 years on oilsands projects so were very familiar – not easy
- Had problems with convergence in FLAC.  Issues were largely solved during and after Fundao
- Now, most popular constitutive software programs include Norsand as a built-in function
- Norsand can be very useful but is not a panacea

# Static Liquefaction Failure Mode Progression

- Must understand how failure modes can develop but drained static liquefaction stress path is difficult to impossible to monitor
- However, the dam essentially issued a warning in August 2014 that something was up
- This warning sign was not appreciated at the time.
- This warning was really only evident in hindsight.



# And, then Cadia and Brumadinho!

- Brumadinho led to GISTM and new global standards for tailings management and design
- Profession is fully aware of design issues with a concerted effort by most mining companies to impose them globally
- This is a difficult, arduous process and is not anywhere near completion. Huge lack of skilled personnel at a time when young bright people are choosing other career paths
- A warning – note that Fundao was the largest of the recent failures with a release of 32Mm$^{3}$. There are tailings dam with over 20 times this volume!