Static Liquefaction:

An Exploration of Advancements and Mitigation Strategies in Dam Safety for Cross-Industry Collaboration

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Association of State Dam Safety Officials | Dam Safety 2024 Conference
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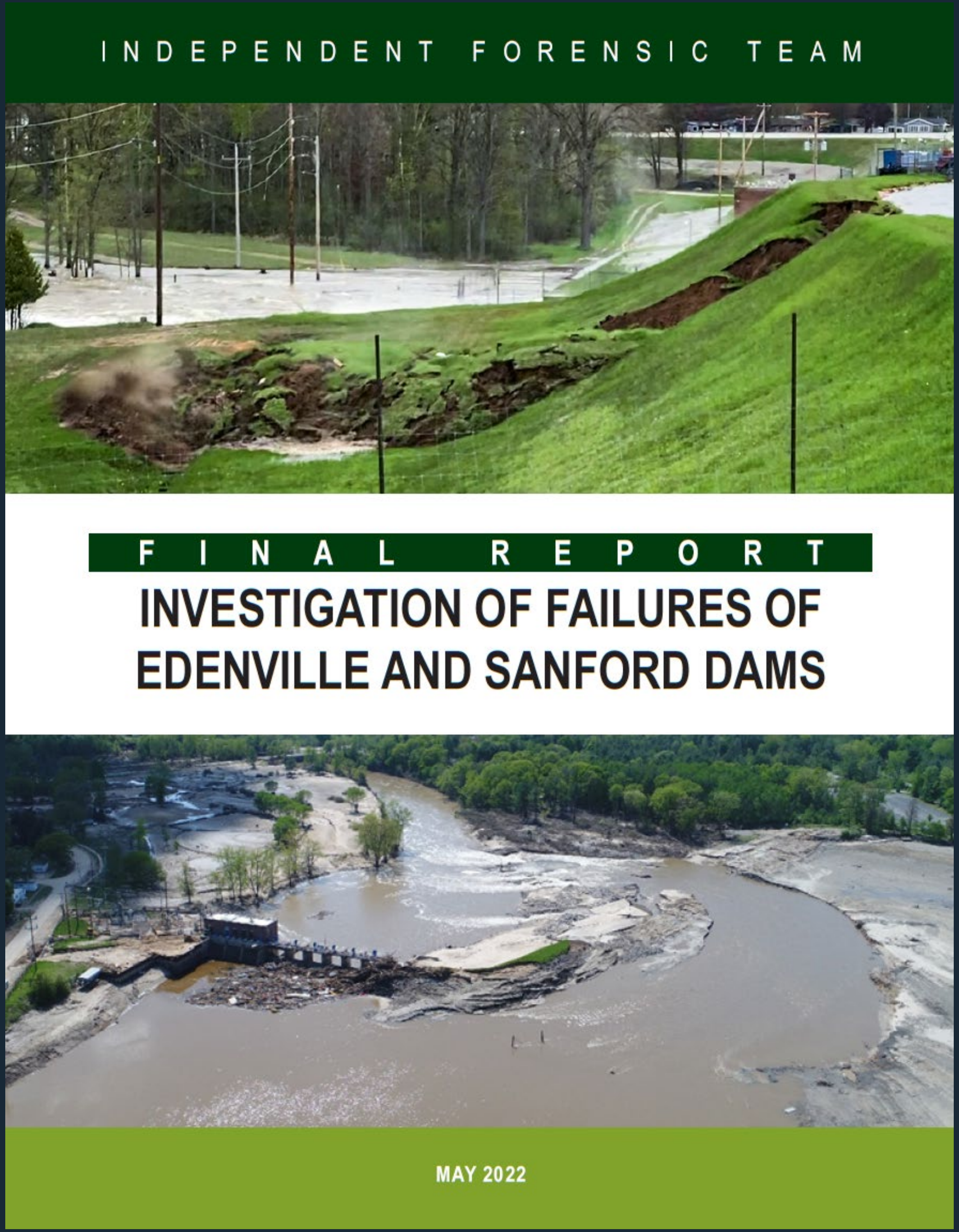
BARR

What do these dam failures have in common?

Lessons to be Learned from the Failure of Edenville and Sanford Dams

Static Liquefaction instability failure should be considered as a potential failure mode (PFM) for water storage or flood management dams when saturated or potentially saturated, loose or very loose sands, silty sands or nonplastic silts are present in the embankment or foundation of the dam. The challenge for water dam engineers now is to develop procedures and protocols to screen and evaluate static liquefaction potential and determine when risk reduction actions to address this PFM are appropriate. Developing these procedures and protocols should leverage the work that has been done by tailings dam practitioners.

from Independent Forensic Team Final Report, Investigation of Edenville and Sanford Dams (France, et al., 2022)



Timeline of Tailings Dam Failures over Past Decade

from CBC News (2014)

from Mining Journal (Fitzgerald, 2018)

from The Landslide Blog (Petley, 2022)

NOTABLE FAILURES

2014
Mount Polley
(Canada)

2015
Samarco
(Brazil)

2018
Cadia
(Australia)

2019
Brumadinho
(Brazil)

2022
Edenville Dam
(USA)

2022
Jagersfontein
(South Africa)

2022
Williamson
(Tanzania)

2024
Lone Khin
(Myanmar)

2024
Siana
(Philippines)

Timeline of Tailings Dam Failures and Advancement of Industry Documents

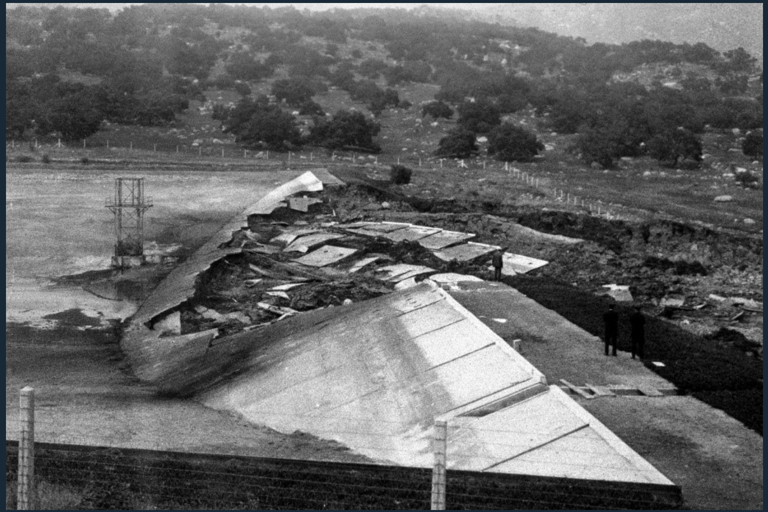
Flow Liquefaction Described in Earth and Earth-Rock Dams (Sherard et al., 1968)

Calaveras Dam Failure (1918)

from UC Davis Civil and Environmental Engineering

<u>Mechanism</u>: Construction flow slide of hydraulically-placed fill

Sheffield Dam Failure (1925)

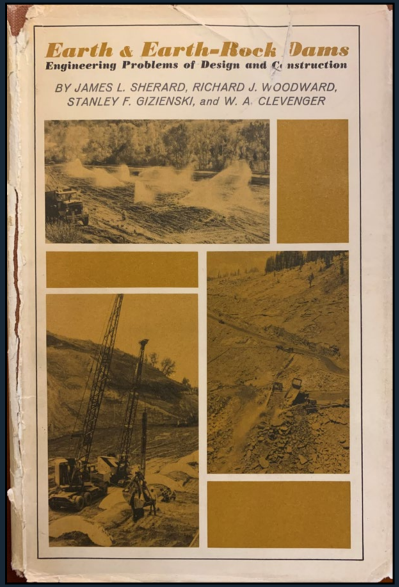


from ASDSO (after California DSOD Archives)

<u>Mechanism</u>: Liquefaction of poorly compacted, saturated, granular embankment fill during earthquake

Red Mountain Dam Failure (1949)

<u>Mechanism</u>: Localized liquefaction of uncompacted horizontal sand drain after discharge blocked with waste material



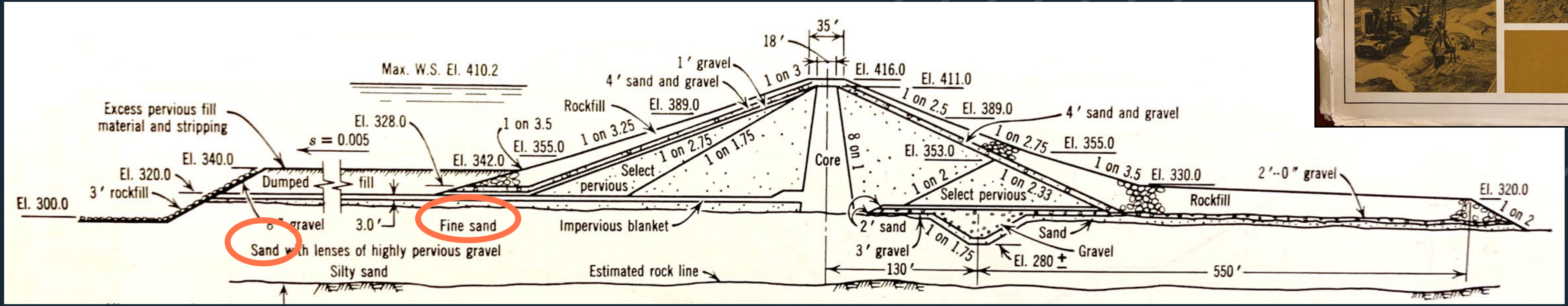
"The failures described above leave no doubt that flow slides can occur in the lower portions of embankments consisting of loosely compacted granular materials."

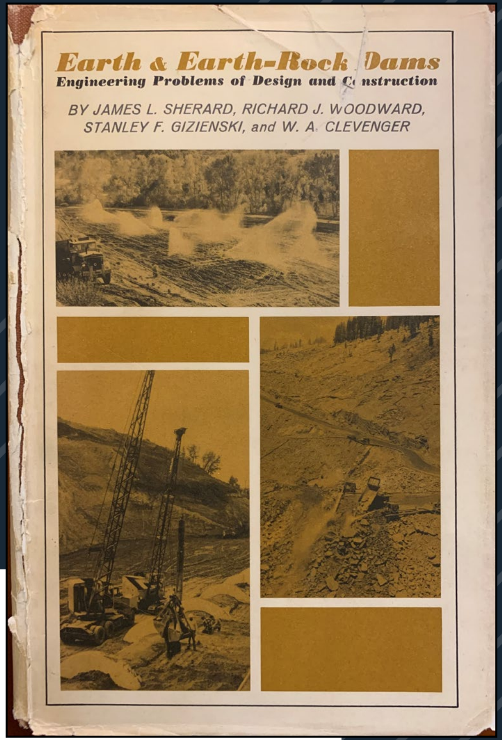
Flow Liquefaction Described in Earth and Earth-Rock Dams (Sherard et al., 1968)

"It is well known that 'flow' or 'liquefaction' slides have occurred in slopes of natural soil consisting of deposits of fine sand and silt, and in some types of clays."

"Flow slides in natural soil deposits have been triggered by earthquake shocks and by undercutting of the toe of the slope; in a few cases they have apparently been caused by increases in the ground water pressure."

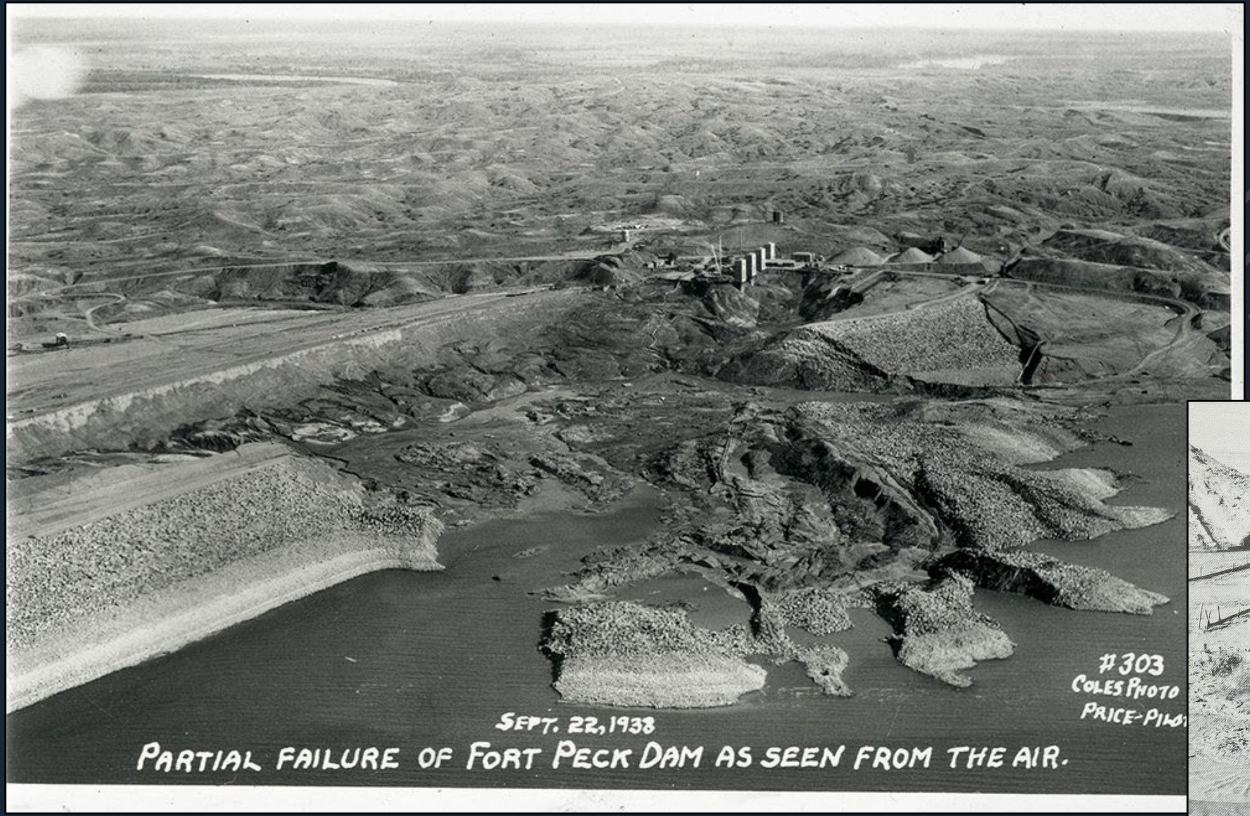
"We are tempted to assume that sand foundations are safe from liquefaction regardless of the density… We must assume that, under extreme conditions, liquefaction failures may occur.





Triggering Mechanisms of the Fort Peck Dam Failure

- Hydraulic Fill Construction Methods
- Liquefiable Native Foundation Soils
- Basal Movement of Shale Foundation

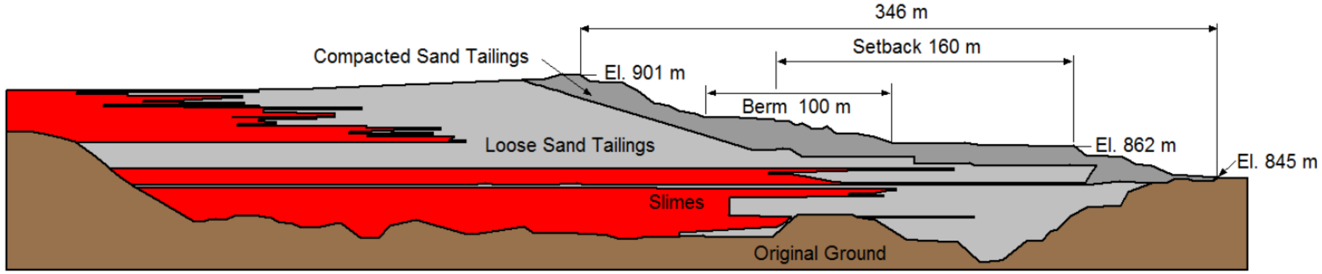


from ASDSO Case Study: Fort Peck Dam (Montana, 1983)

from Historical Vignette: Fort Peck Dam (USACE, 2015)

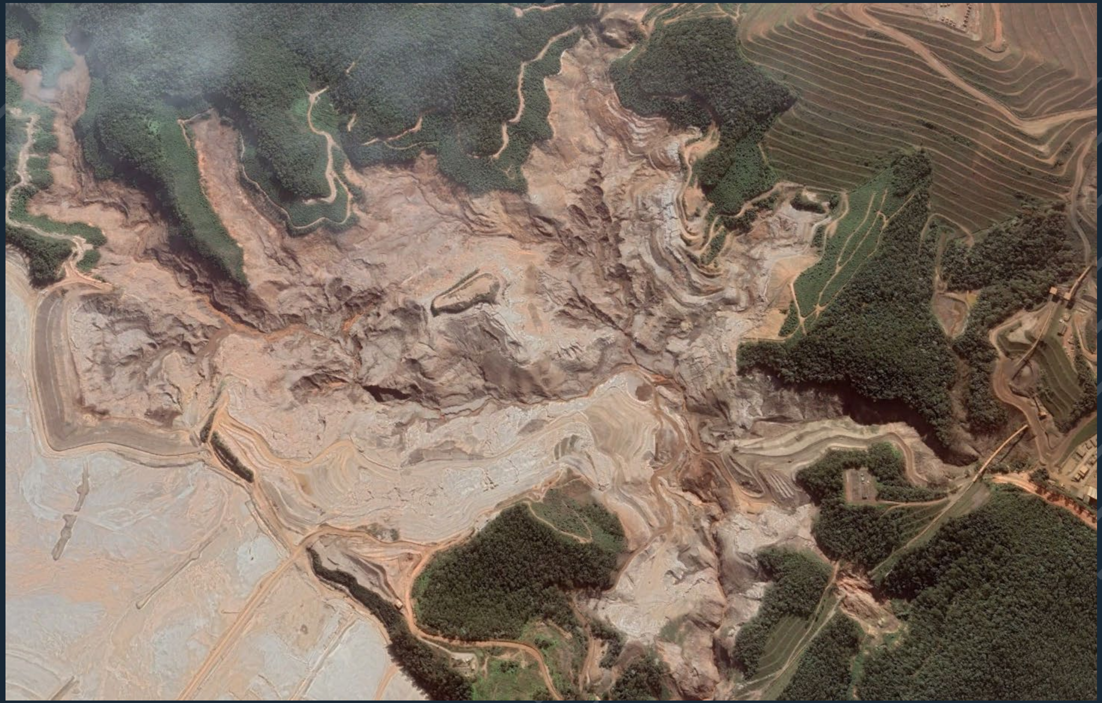
Triggering Mechanism of the Samarco (Fundão) Tailings Dam Failure

- Hydraulic Fill Construction Methods
- Liquefiable Sand Tailings Foundation
- Basal Movement of Plastic Tailings Foundation



from Report on the Immediate Causes of the Failure of the Fundão Dam (Morgenstern et al., 2016)

from Google Earth

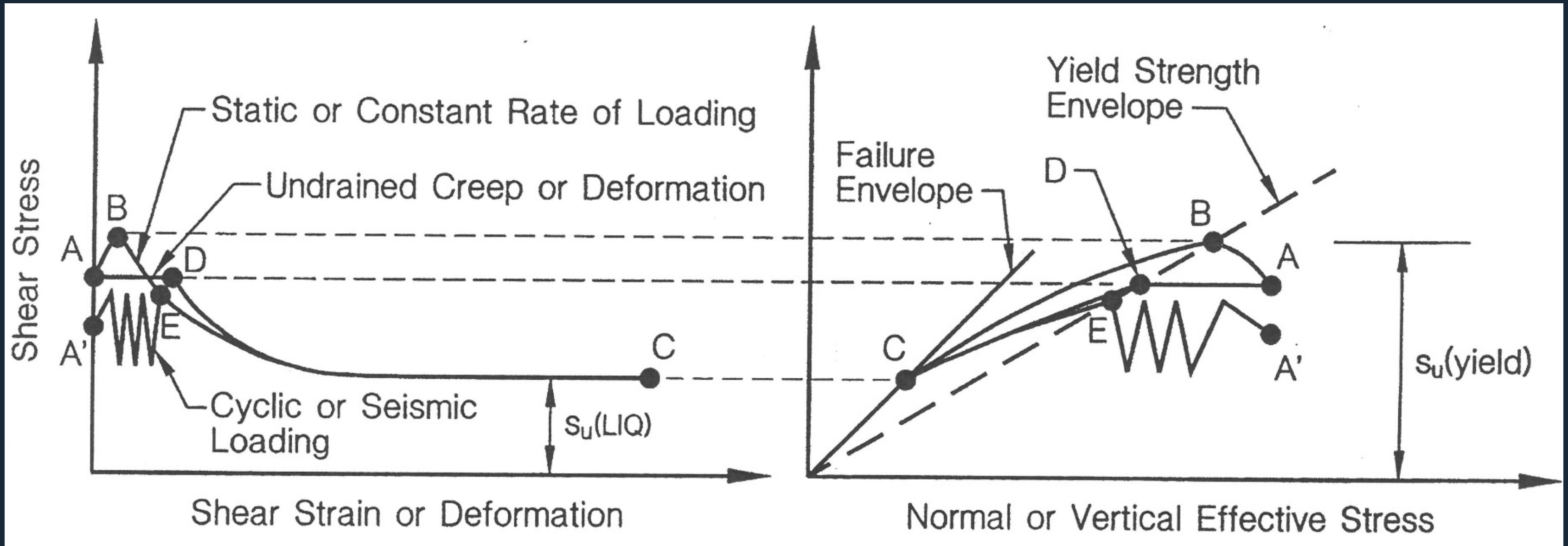


from Google Earth

Triggering Mechanisms for Undrained Failures

Liquefaction is the sudden loss of shear strength in response to a trigger, which occurs in loose, nearly saturated, and non-plastic to low plasticity soils.

- Accelerations/Vibrations
  - Earthquakes
  - Construction
  - Blasting
- Oversteepening
  - Surface Water Erosion
  - Drained (Initially) Sloughing
  - Excavation
- Overloading
  - Rapid Impoundment Raising
  - Fill Placement at Crest
- Changes in Pore Pressures
  - Deteriorated Underdrainage Performance
  - Increased Pond Levels
  - Accelerated Rate of Construction
- Reduction in Mean Effective Stress
  - Saturation
  - Basal Movement
- Overtopping
  - Blockage of Outlet Structures
  - Severe Storm Runoff
  - Seismic Deformation and Loss of Freeboard



from Yield Strength Ratio and Liquefaction Analysis of Slopes and Embankments (Olson and Stark, 2003)

from Some Considerations in the Stability Analysis of Upstream Tailings Dams (Martin and McRoberts, 2002)

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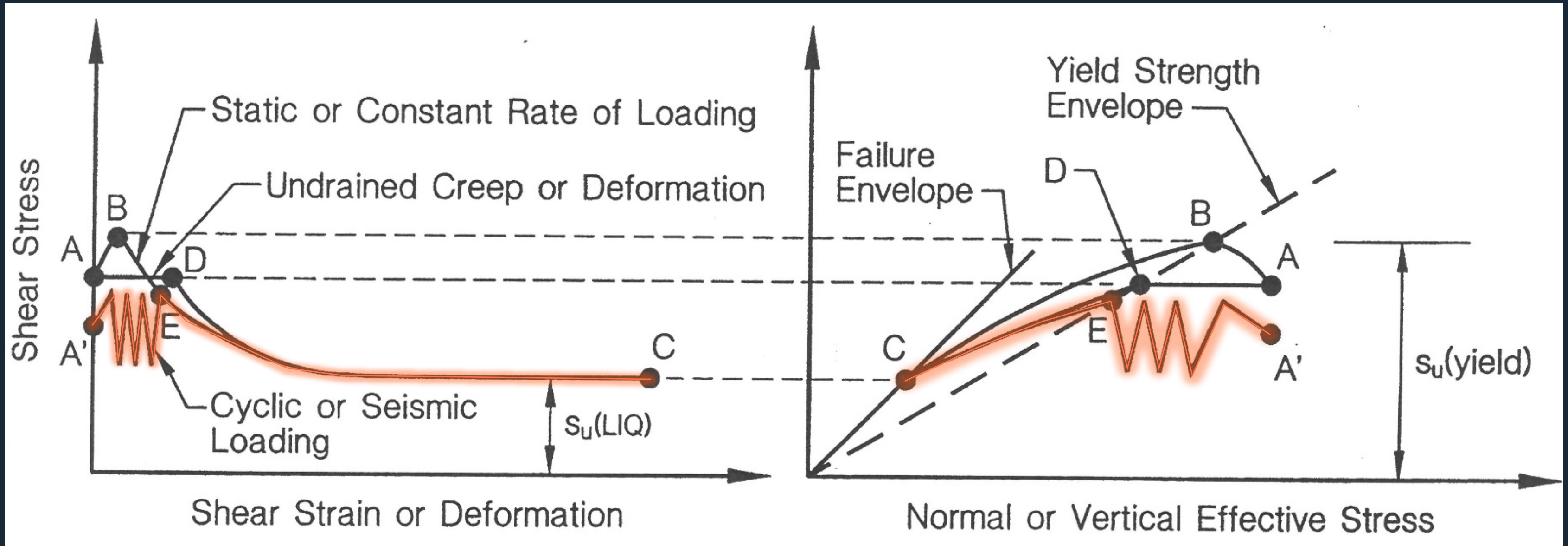

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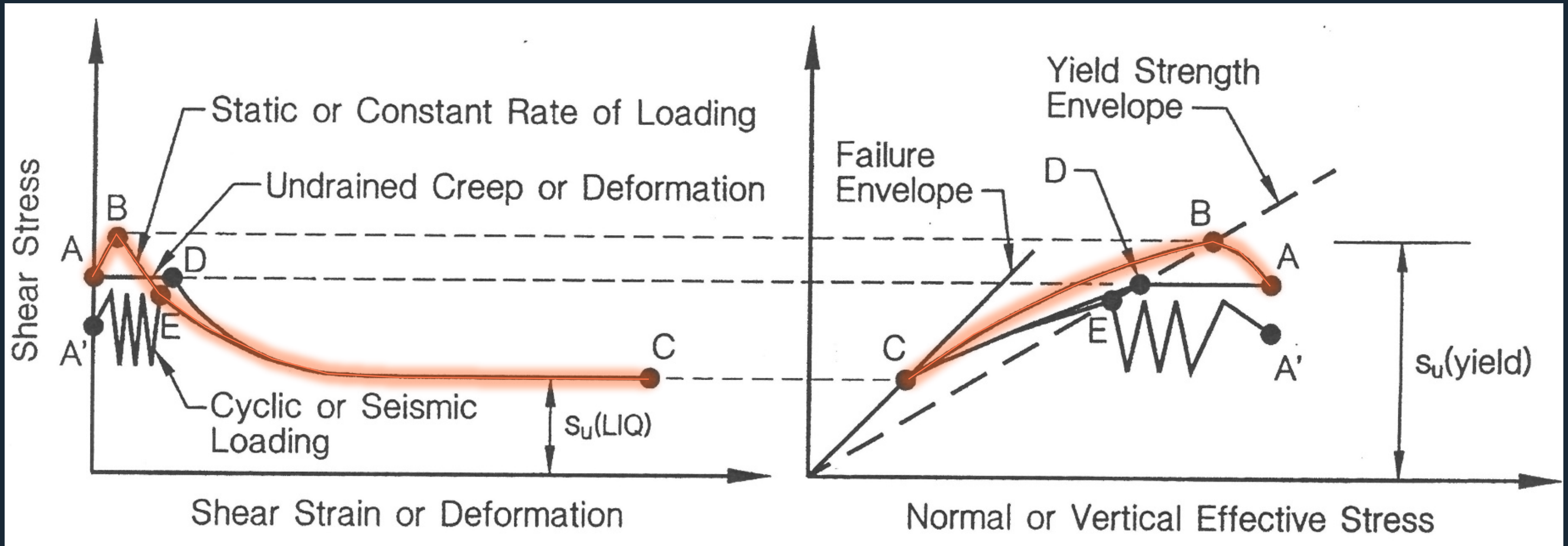

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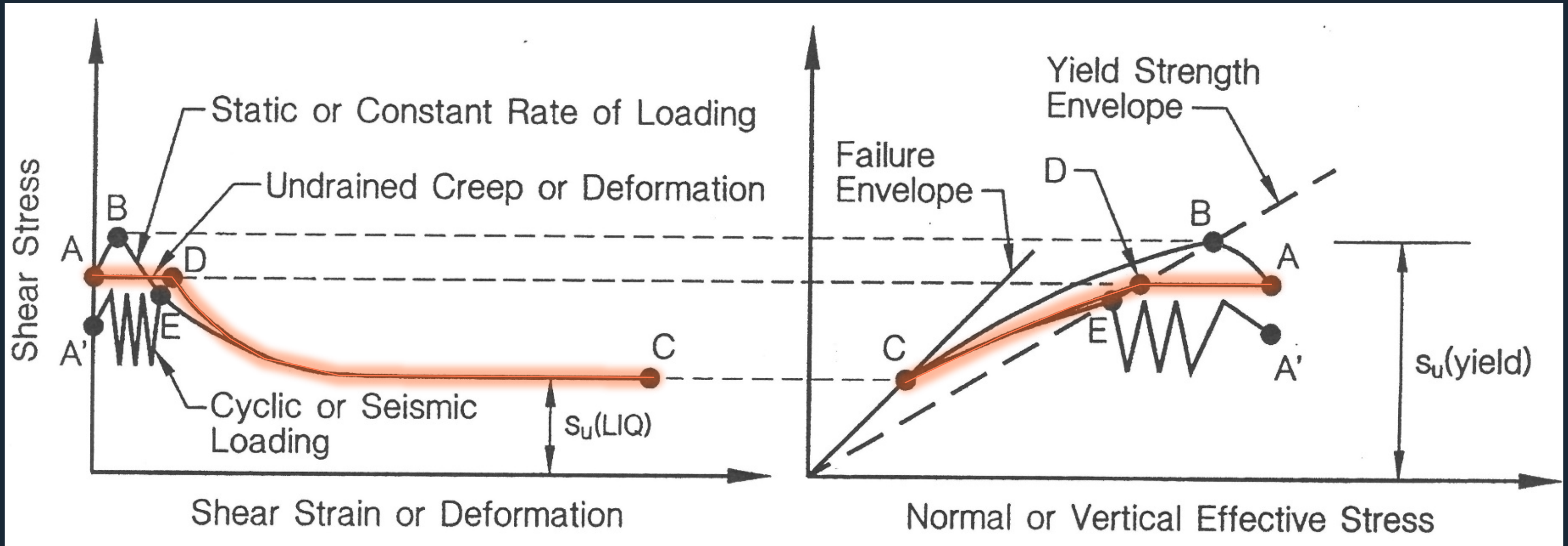

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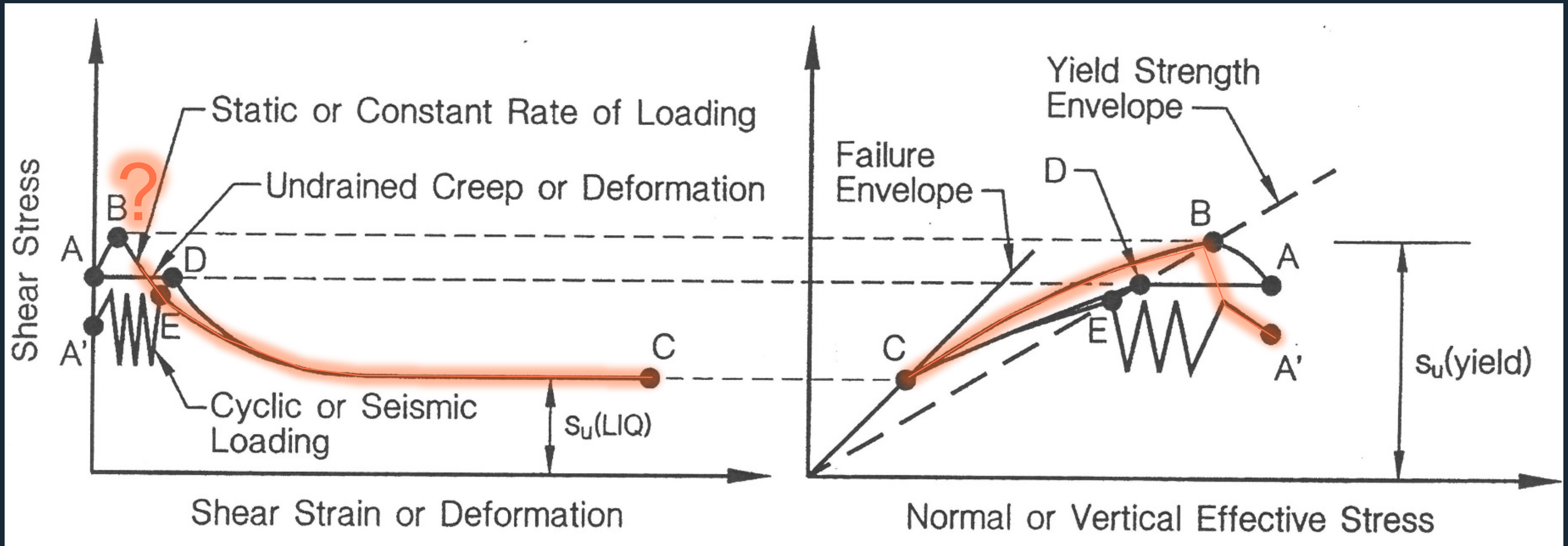

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Geotechnical Analysis Approach and Considerations

Recommended Analysis & Design Approach for Static Liquefaction from Martin and McRoberts (2002)

"Assume that if a soil can liquefy it will."

Liquefaction Susceptibility Assessment

Determine whether or not the dam slope is comprised of materials that are contractant or dilatant under shear.

Stability Analysis with Peak Undrained Shear Strengths

If the dam slope is fully or partially composed of contractant materials, both ESA and USA should be carried out.

Triggering Assessment

Review the operational and design factors necessary to assess the probability of undrained shear being triggered… Unless one is very sure that undrained triggers absolutely do not exist, it is considered prudent to assume the worst.

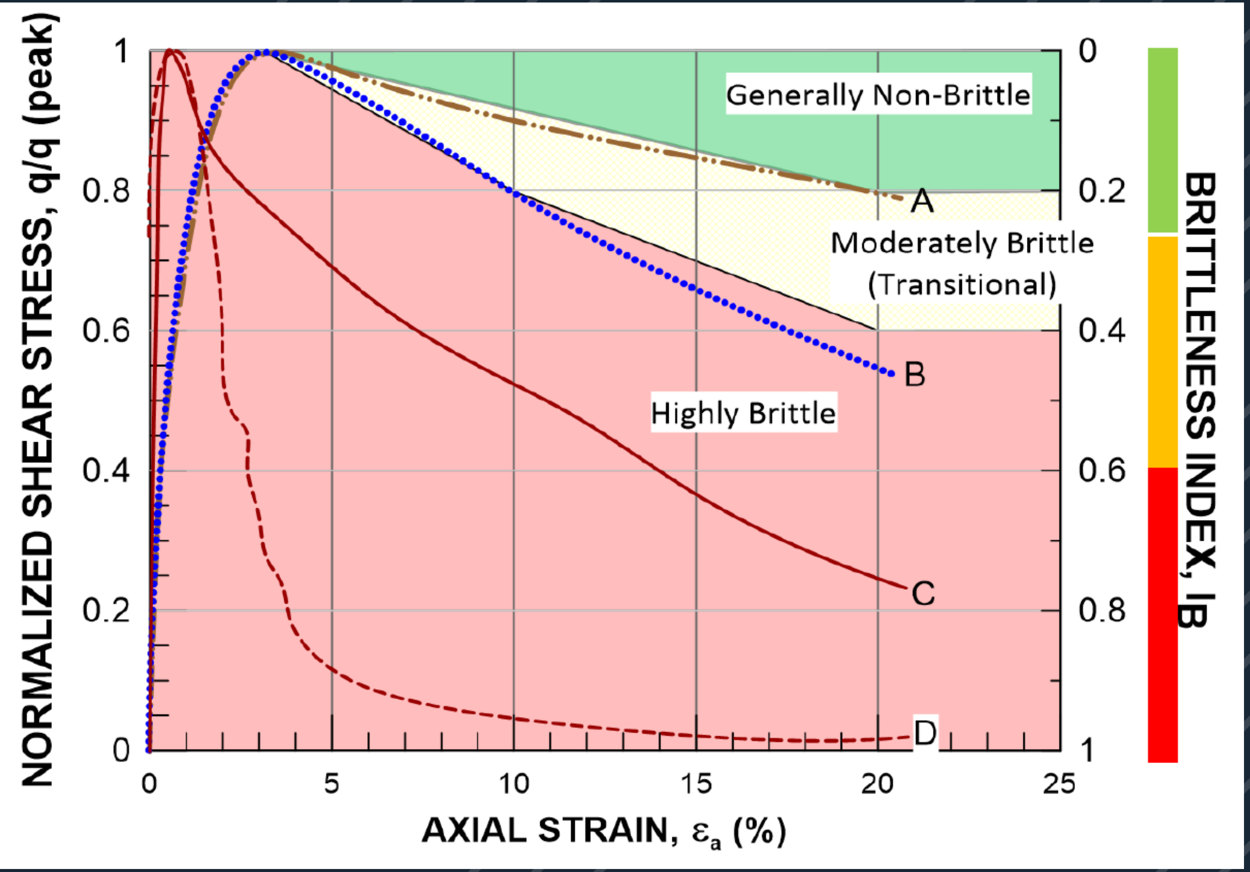
Stability Analysis with Post-Liquefaction Undrained Shear Strengths

If the [materials] are both contractant and brittle, then a… steady state strength… analysis should be carried out.

ICOLD Tailings Dam Safety (Bulletin 194)
Target Factors of Safety for Limit Equilibrium Slope Stability Analyses

Stability Condition	Target Minimum Factor of Safety
Static	1.5
Post-Liquefaction	1.1

Assuming that leading international practice has been adopted with respect to the site characterization, selection of parameters, and design approaches, and that a [Geotechnical Design Model] has been developed.



Framework provided for selection of stability analysis techniques and target FOS accounting for brittleness of contractive materials susceptible to static liquefaction.

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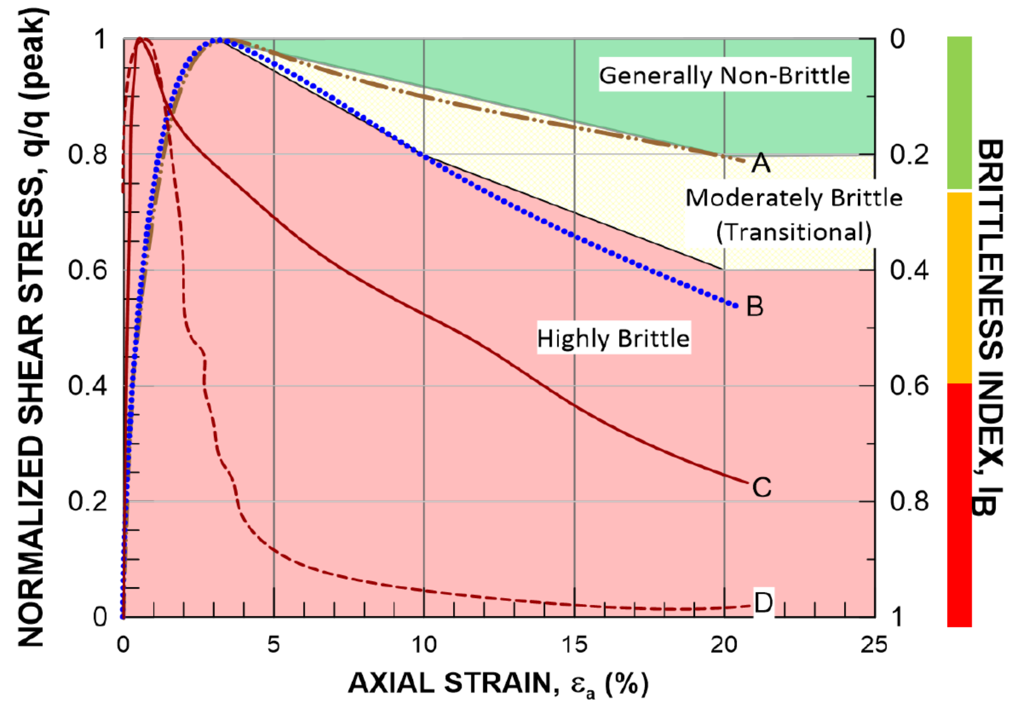


- Prioritizes Safeguarding Against Residual Shear Strength, More Advanced Analyses as Brittleness (I_B) Increases
- Limited to No Strain Softening ($I_B < 0.2$)
  - Limit Equilibrium Methods
  - Lower FOS_{PEAK} (≈1.3) may be appropriate
- Moderately Strain Softening ($0.2 < I_B < 0.4$)
  - Limit Equilibrium Methods
  - Numerical Deformation Analyses if $FOS_{LIQ} < 1.1$
- Case 4: Highly Brittle Behavior
  - Limit Equilibrium Methods
  - Numerical Deformation Analyses if $FOS_{LIQ} > 1.1$ due to secondary deformation effects (e.g., overtopping)
  - Risk Assessment if $FOS_{LIQ} < 1.1$ (for Low to Significant Consequence Class)
  - Prioritize Mitigation Measures if $FOS_{LIQ} < 1.1$ (for High to Extreme Consequence Class)

Performance-Based Design and Numerical Deformation Analyses

Post-Liquefaction Deformation for Design (FOS_{LIQ} > 1.1)

- Using Mohr-Coulomb (or similar) material model, and assumes all contractive materials liquefy

Post-Liquefaction Runout for Dam Breach (FOS_{LIQ} < 1.1)

- Using Mohr-Coulomb (or similar) material model, and assumes all contractive materials liquefy
- Using Material Point Method (MPM)

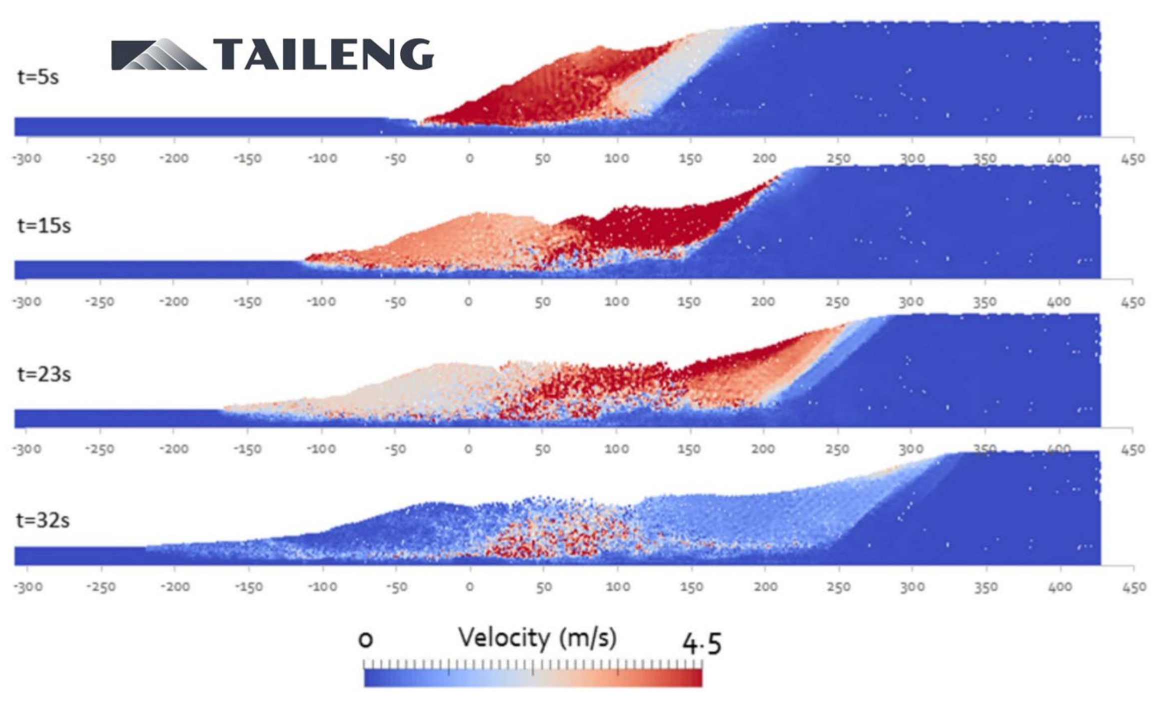
Back-Analysis of Flow Failure Case Histories

- Using NORSAND (or similar advanced constitutive model) to simulate triggering explicitly with known response

Evaluation of Potential Triggers (as part of Risk Assessment)

- Using NORSAND (or similar advanced constitutive model) to simulate triggering explicitly for forward prediction

from Cadia TSF Failure Assessment Considering Triggering and Posttriggering Mechanisms (Macedo et al., 2024)



Evolution of Post-Liquefaction (Static) Runout of Cadia TSF Failure Using Material Point Method (MPM)

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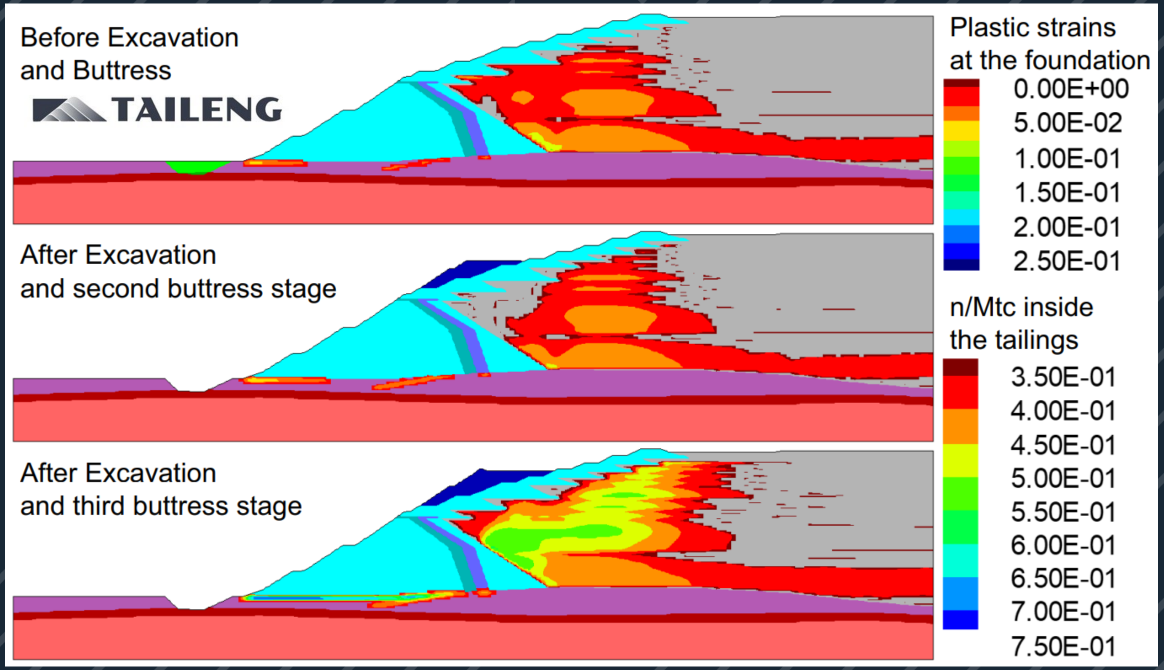


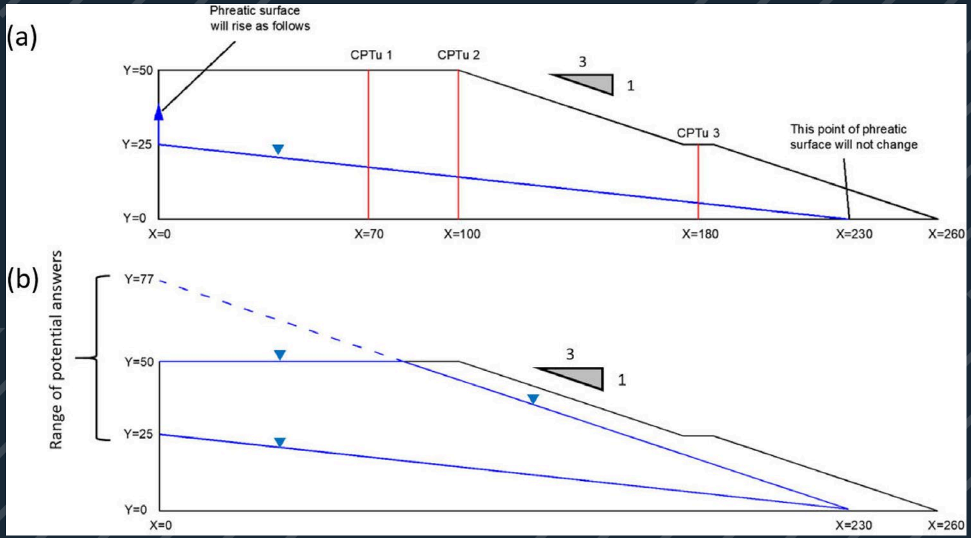
Evolution of Plastic Strains in Foundation and Instability Ratio in Tailings During Static Liquefaction of Cadia TSF Failure Using NORSAND Model

Performance-Based Design and Numerical Deformation Analyses

Development and Outcomes of a Tailings Slope Stability Comparative Design Exercise (Reid and Fourie, 2024)

Problem Statement: Predict the level at which a rising phreatic surface triggers static liquefaction in a hypothetical tailings dam given initial conditions and in-situ/laboratory testing data.

- Majority of participants used limit equilibrium methods, few used stress path (analytical) or finite element / difference methods
- Wide range, no consensus of predicted phreatic surface level
- Varied initial stress states (K_o and η_{IL}) and stress-strain behaviors
- Some assumed drained conditions because CPT was drained



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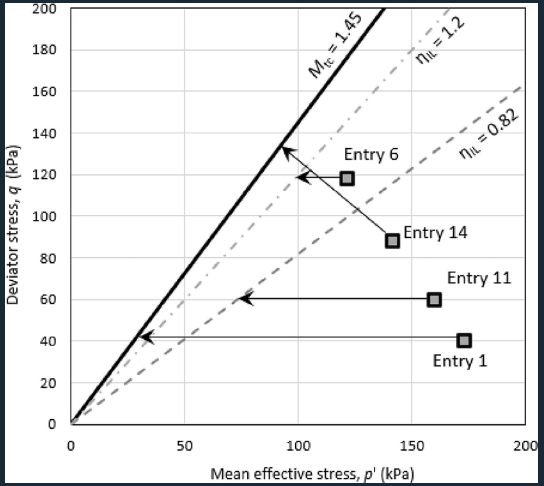
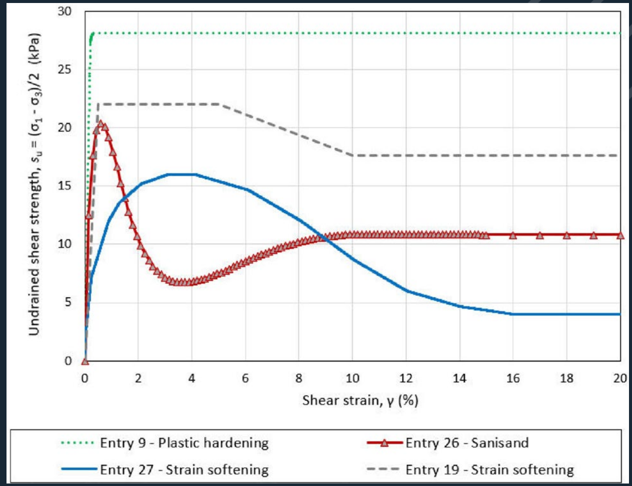
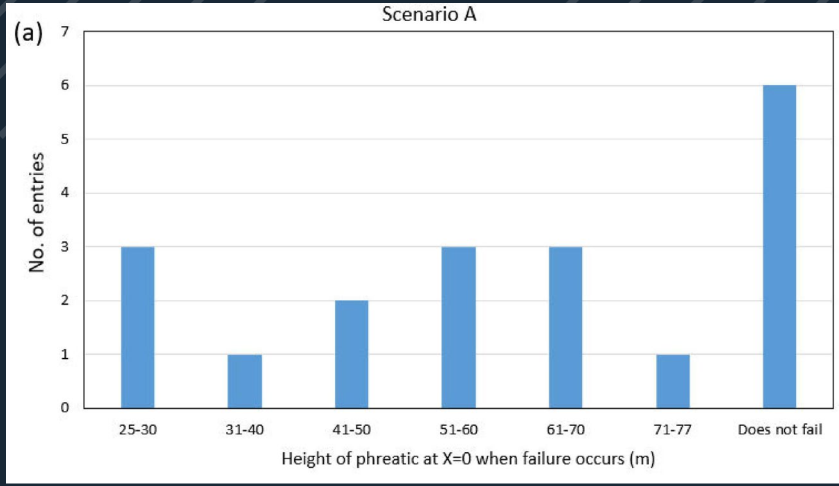






Geotechnical Investigation Methods

Standard Penetration Test (SPT)

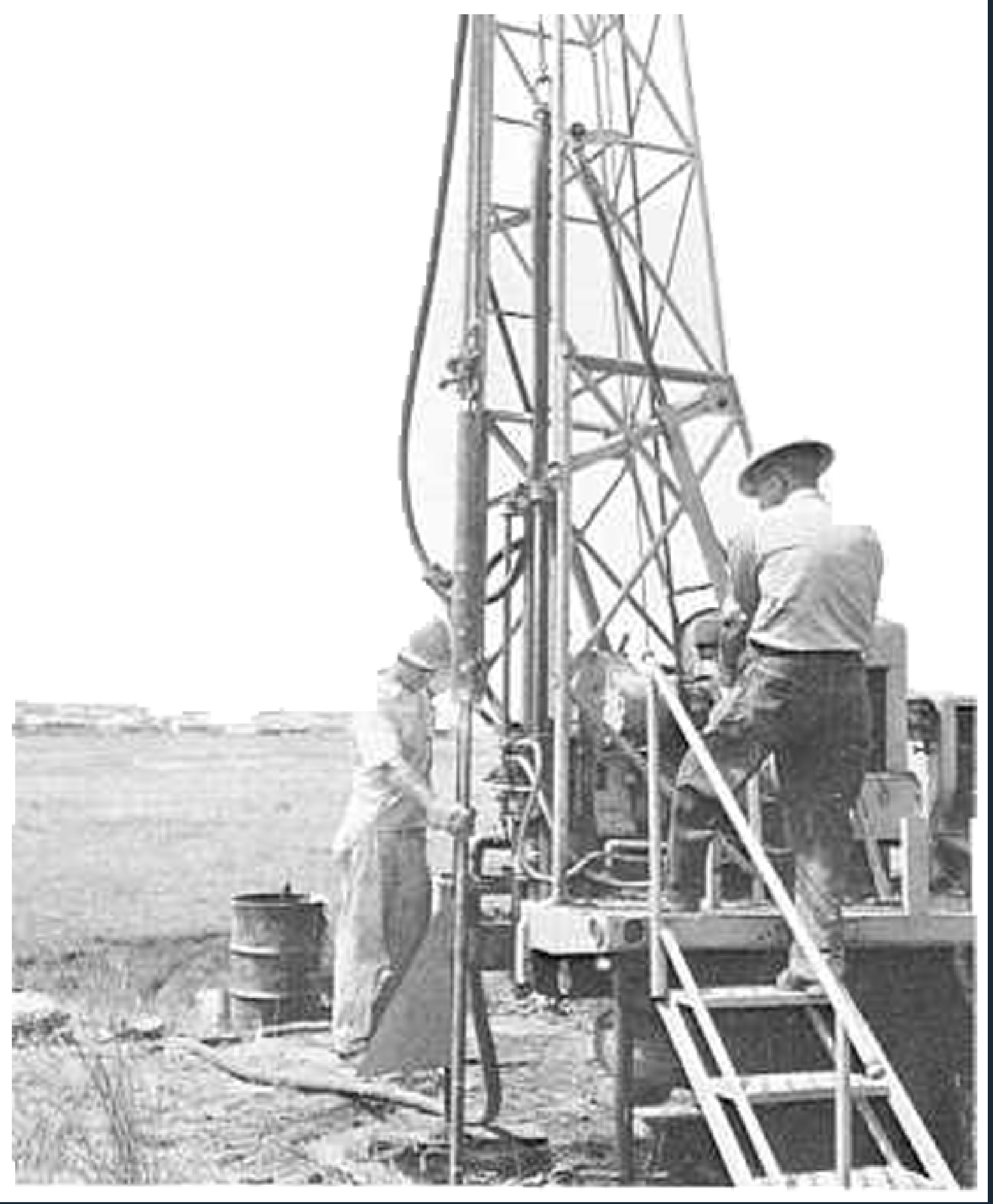
STOP USING THIS DATA

- Not relied upon in tailings dam engineering
- Sample collection tool but nothing more
- Has its place but not in dam safety

USE OF HISTORICAL DATA

- “But it’s the only available data…”
- “Loose or quick conditions in the borehole…”
- “Too risky to put another hole in the dam…”

SUBSURFACE TEST DATA IS ALL WE HAVE, BETTER HAVE CONFIDENCE



from Design of Small Dams, Third Edition (USBR, 1987)

In-Situ Testing Tools and Procedures

FOCUS ON IN-SITU TESTING DUE TO UNDISTURBED SAMPLING CHALLENGES

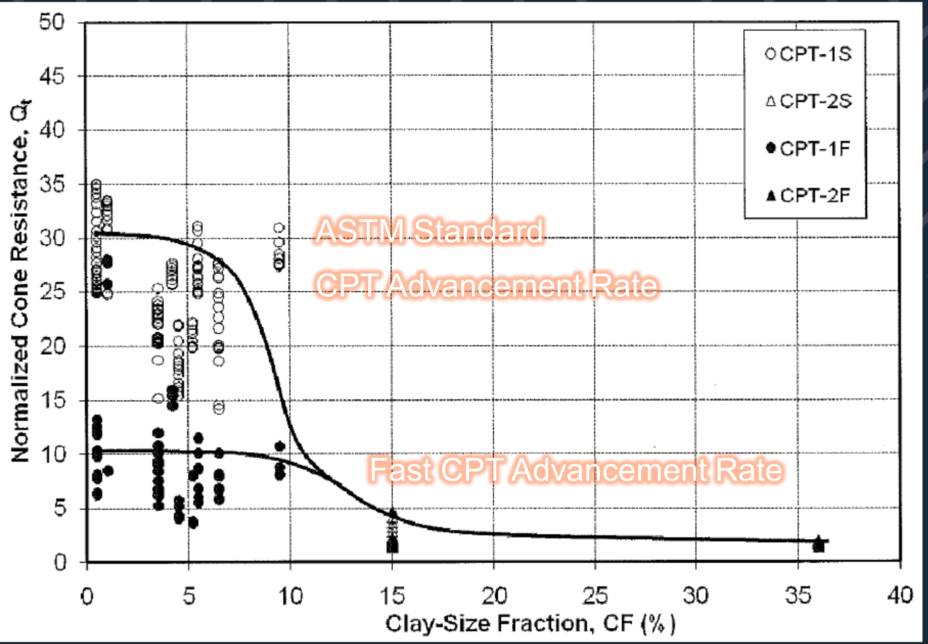
ASTM STANDARD EQUIPMENT AND PRECEDURES MAY BE MODIFIED

PARTIAL DRAINAGE EFFECTS OF INTERMEDIATE SOILS

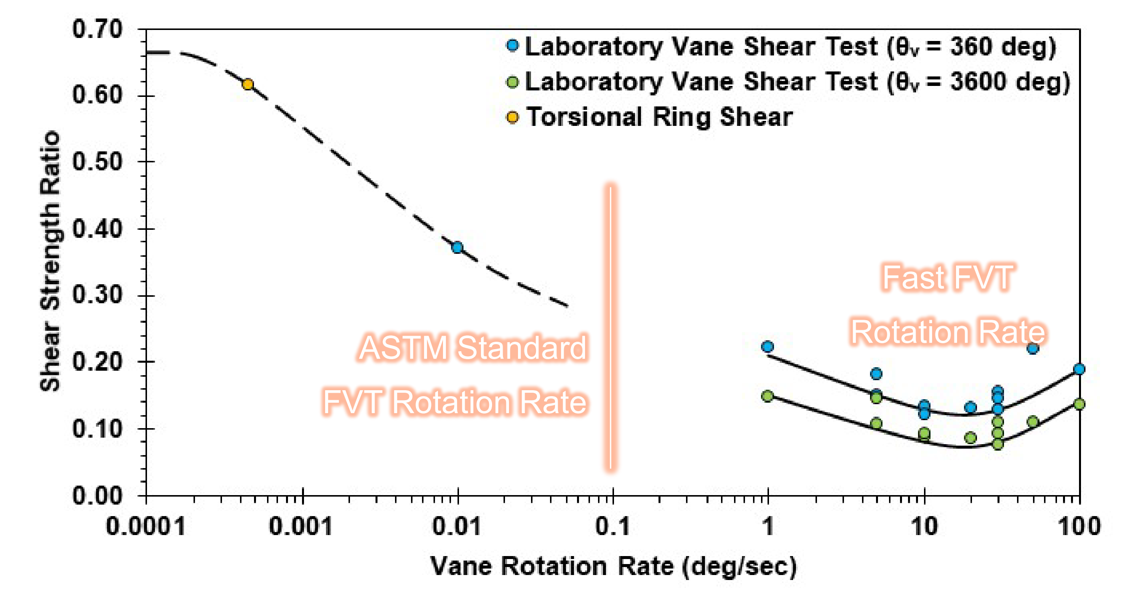
- CPT Advancement Rate
- FVT Rotation Rate
- DMT Membrane Expansion Rate

"A CPTu sounding being drained does not mean the soil cannot fail in an undrained manner."

- David Reid and Andy Fourie



from Evaluation of CPT Response under Fast Penetration Rate in Silty Soils (Contreras and Grosser, 2009)



from Laboratory Vane Shear Testing Apparatus for Evaluating Critical State Parameters and Undrained Shear Strength of Mine Tailings (Harvey and Contreras, 2022)

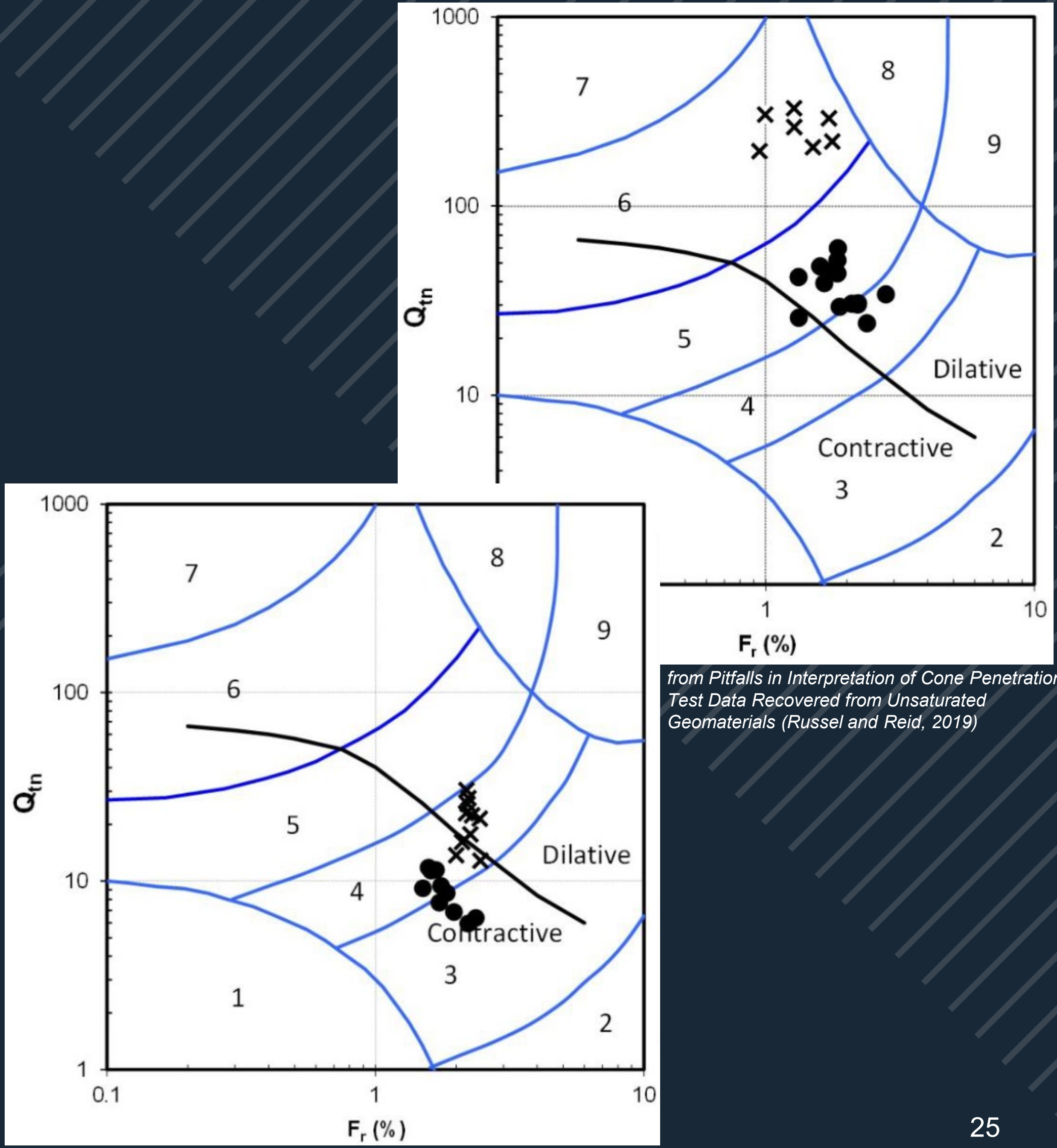
In-Situ Testing of Unsaturated Zone

LIQUEFACTION OF UNSATURATED ZONE

- Susceptible if Sr > 85% (approx.)
- Measured with Vp concurrent with sCPT or field moisture content profiles

UNCERTAINTY OF CPT IN UNSATURATED ZONE

- Most correlations require saturation assumption
- Challenges predicting state (contractive/dilative) of soils subject to future rising phreatic surface
- Potential for suction hardening to show apparent dilative response of loose soils (Russel & Reid, 2019)
- Future research advancements in tailings

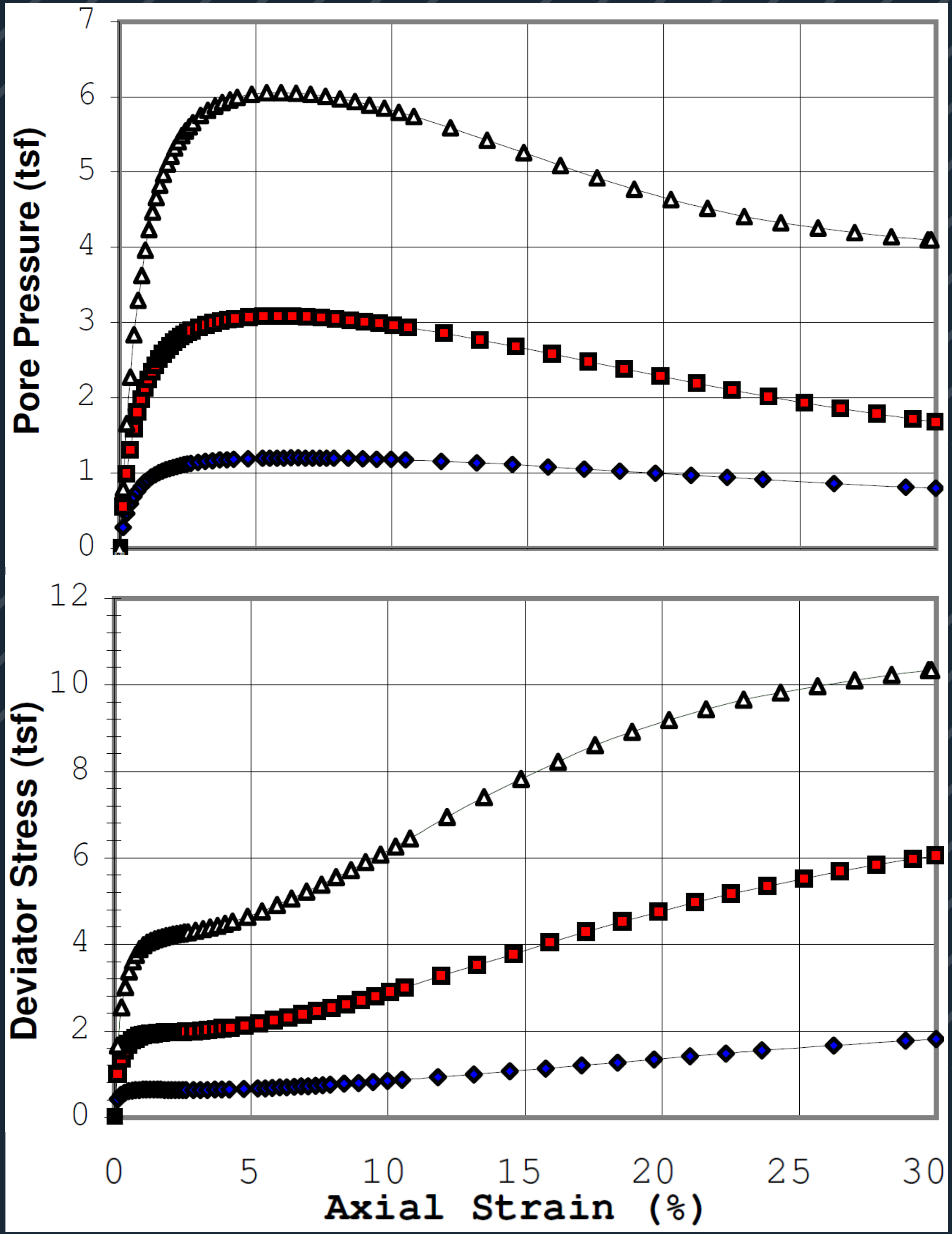


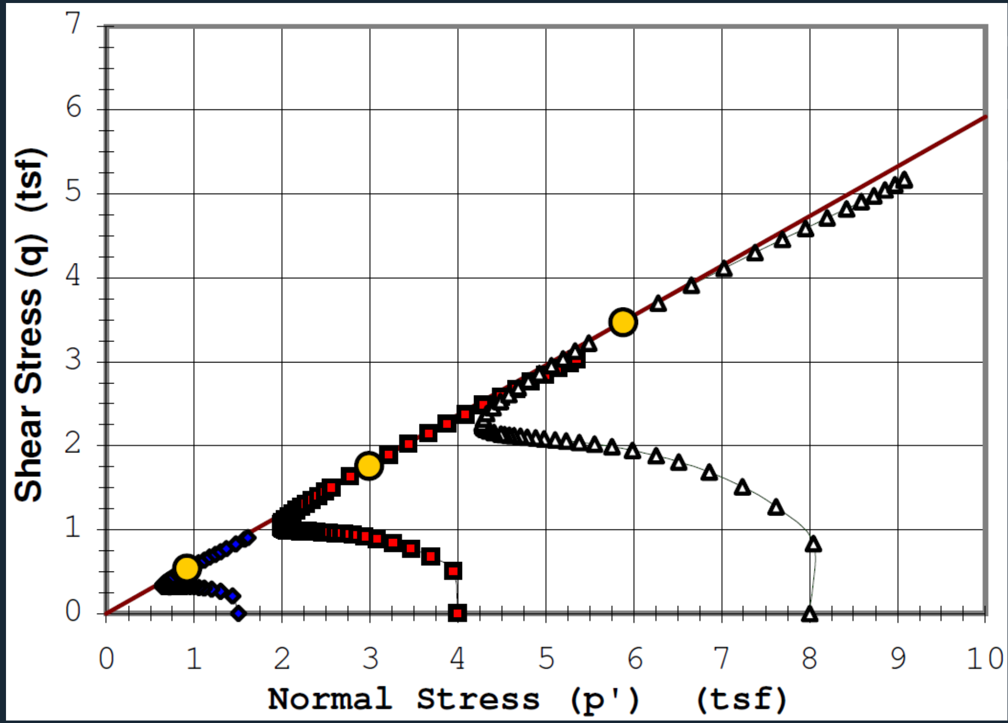
from Pitfalls in Interpretation of Cone Penetration Test Data Recovered from Unsaturated Geomaterials (Russel and Reid, 2019)

Laboratory Testing of Intact Specimens

DON'T BE FOOLED BY DILTIVE RESPONSE OF INTACT SPECIMENS IN LABORATORY TESTS

- Significant sample disturbance of loose specimens (sampling, transport, preparation, etc.)
- Contradictory to susceptibility based on in-situ testing





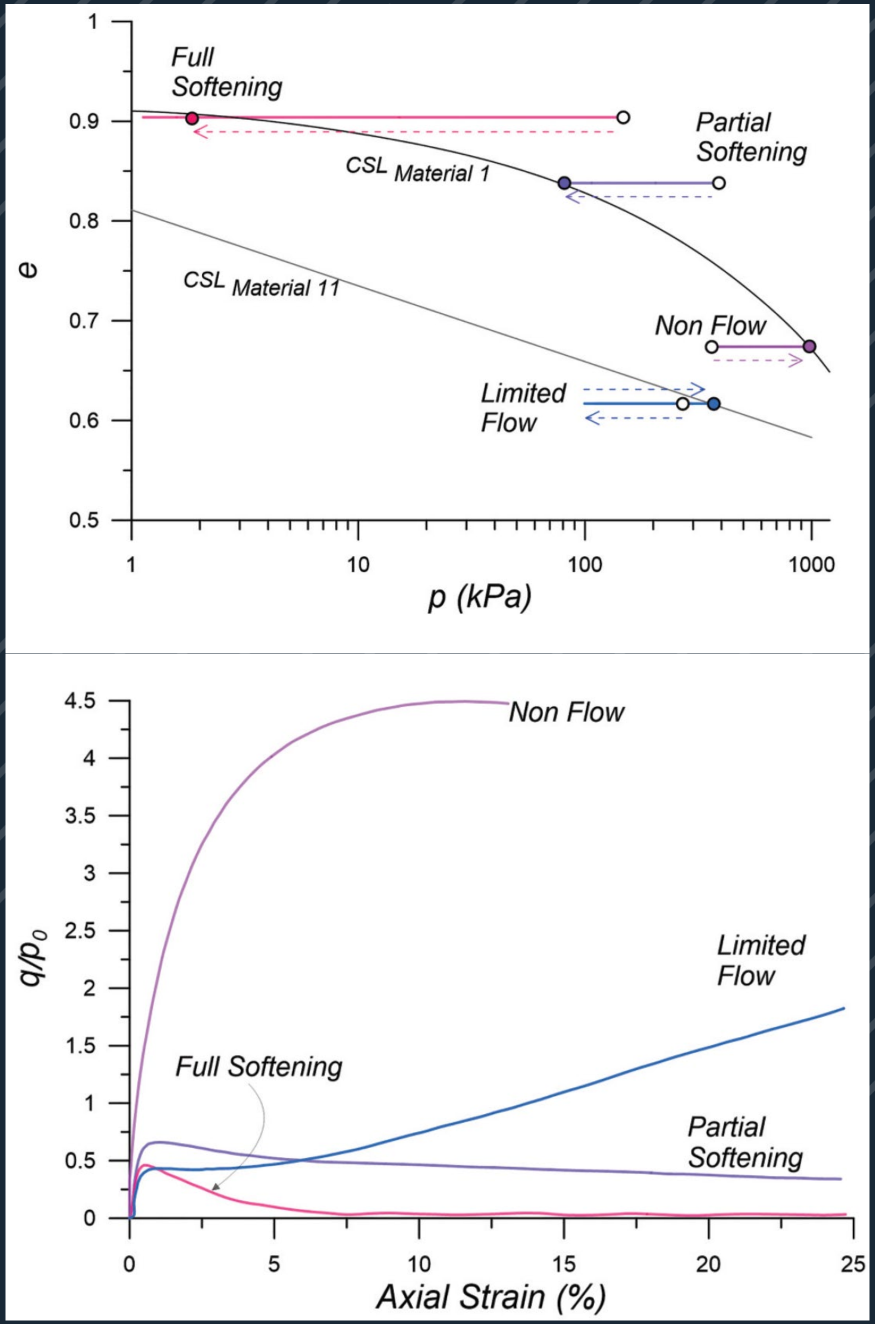
Critical State Soil Mechanics Laboratory Testing

INTEGRAL COMPONENT IN ANY MODERN TAILINGS CHARACTERIZATION STUDY

- Advanced constitutive models
- Soil compressibility (λ)
- Susceptibility to liquefaction (ψ)
- Brittleness upon triggering (p'_o/p'_{cs})

PRACTICAL IMPLEMENTATION CHALLENGES

- Multiple CSLs within heterogenous deposits
- Uncertainty of in-situ void ratio / state parameter
- Reliability/reproducibility of laboratory methods
- Reconstitute specimens not entirely representative of in-situ fabric or void ratio
- Reconstitute specimens in loose state may not exhibit contractive response, esp. with plasticity



from Properties of Mine Tailings for Static Liquefaction Assessment (Macedo and Vergaray, 2022)

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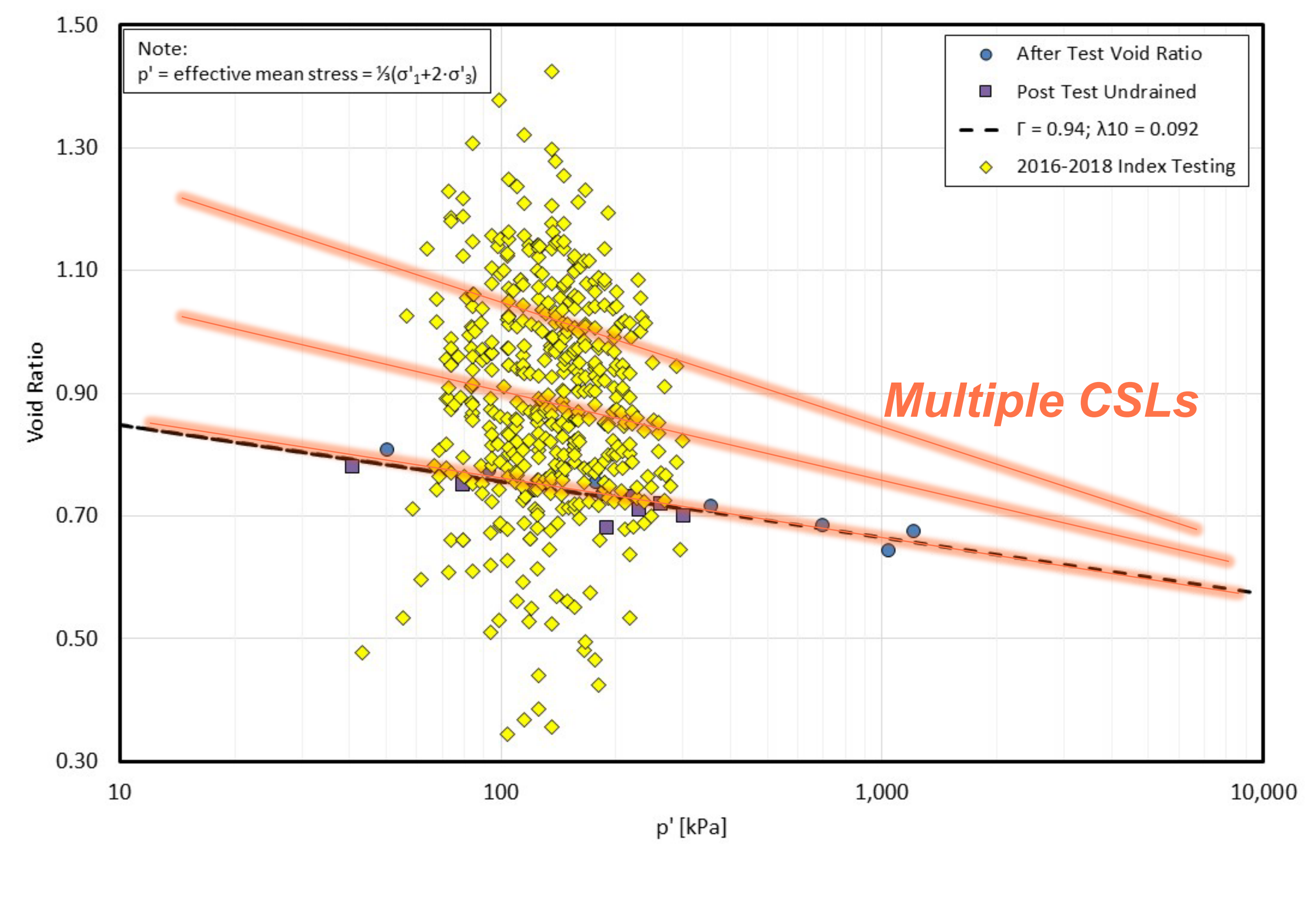

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Risk Mitigation Measures

Risk Mitigation Measures: Dam Safety Management Structure

Risk Mitigation Measures: Surveillance and Monitoring

BRITTLE FAILURE MECHANISMS CANNOT RELY ON INSPECTION OR INSTRUMENTATION MONITORING

Monitor for indicators of potential static liquefaction triggers using Trigger Action Response Plan (TARP)

- Rising phreatic surface or ponds (open pipe piezometer)
- Excess pore-water pressures (vibrating wire piezometer)
- Basal movement or lateral extrusion (inclinometer/SAA)
- Creep deformation (InSAR)

Automation + Dedicated Monitoring Staff

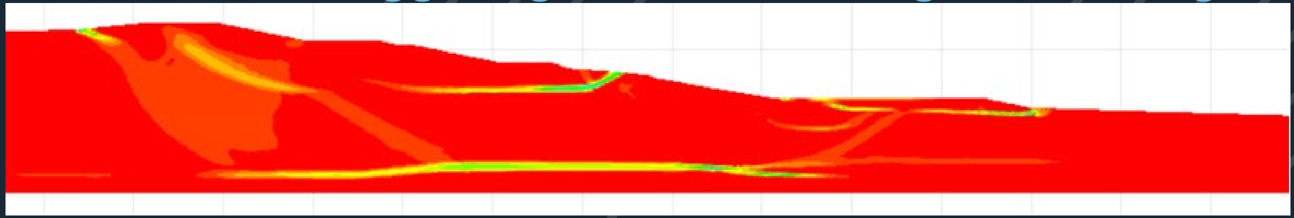
Dam Breach Early Warning Systems

Risk Mitigation Measures: Physical Remediation for Static Liquefaction

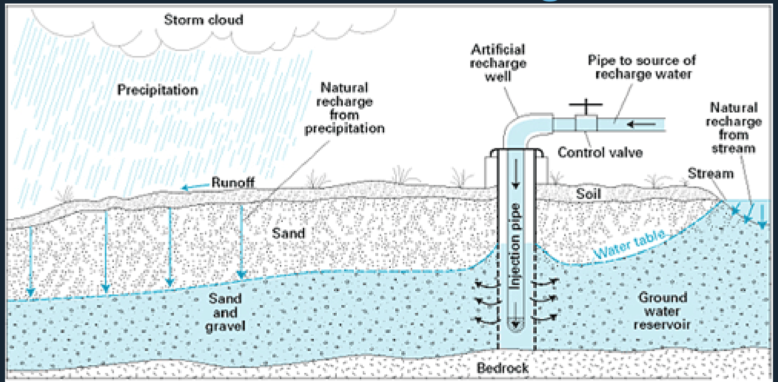
- ❑ Operational Changes ← Temporary
- ❑ Seepage Control/Barriers
- ❑ Ground Improvement
- ❑ Buttressing
- ❑ Downstream Containment
- ❑ Decommissioning
- ❑ Tailings Reduction / Mine Backfill

(Seepage Control/Barriers, Ground Improvement, Buttressing:) Requires Evaluation of Triggering Due to Construction

Evaluation of Triggering Potential During Buttressing



Alternative Water Storage



from Artificial Groundwater Recharge (USGS, 2019)

Vale's Tailings Dam Elimination

From Engineering and Mining Journal (2021)

Vale's Containment Dam

From Engineering and Mining Journal (2021)

Conclusions and Where to Find More Information

Lesson-learned among tailings dam industry is that:

- No one approach or method to determine liquefaction susceptibility or liquefied strength
- No one combination of field and laboratory test or procedure applicable for every material
- No one correlation or analysis technique works for all materials and situations

Must implement a wholistic approach that comes at the problem from multiple approaches.

"Assume that if a soil can liquefy it will."

TAILENG Short Courses

- Georgia Tech
- Colorado State University
- University of California – Berkeley
- University of Illinois at Urbana Champaign

TAILLIQ Publications

- University of Western Australia, et al.

USSD – Static Liquefaction Working Group