Tailings Dams and Geophysics

BCGS – Fall Symposium

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Tailings Dams and Geophysics -- Talk Outline

- History of soil mechanics and engineering of dams
- History of tailings dams
- Types of tailings dams
- Tailing dam technologies
- Tailings properties
- How do tailings dam fail?
- Monitoring technologies for tailings dam safety
- How do geophysics help and Case Examples
- Summary

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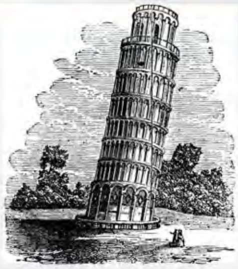
History of Soil Mechanics and Engineering



Bearing capacity failure on weak clay layer at 10 m depth (1173)

Sliding on weak clay layer at 10 m depth - Mt. Polley (2014)

• Pre-1900

- 1493 – Leonardo da Vinci theory on friction - Charles Coulomb (1780) friction and cohesion/retaining walls
- 1882 – Christian Mohr: 2-D stress state and mohr circles, shear stress
- 1880's Henry Darcy Q=kiA
- 1872 William Rankine – lateral earth pressure theory (retaining walls); British Geotechnical Society: Rankine Lecture

- Empirical and experience (if it falls down build it stronger)
- The "first" drill rig? – New York Subway tunnels (1891)
- William Parsons (Parsons Brinkerhoff) Drilling with 2" steel pipe, with a 1" pipe driven inside to sample soil at 5 ft intervals!

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History of Soil Mechanics and Engineering

3

- Swedish contributions: Albert Atterberg (1913) Atterberg limits and clay classification
- 1930's Karl von Terzaghi (Austrian) formulating the Theory of Soil Mechanics (Father of Soil Mechanics)
- Following WW II, along with Ralph Peck published "Introduction to Soil Mechanics" 1948, 1967, 1996
- Imperial College, London – Sir Alec Skempton, Allan Bishop, Nordie Morgenstern (Alberta)
- UofC Berkley: Dr. Harry Seed (Father of Geotechnical Earthquake Engineering)
- Charles Ladd of MIT – undrained shear strength of clay
- University of Alberta – Dr. Nordie Morgenstern
- Earle Klohn (KCB)
- R.M. Hardy

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Development of Engineering and Site Investigations 4

ENGINEERING

- Post WWII: Water dam engineering advanced
- Centerline tailings dams
- 1980's: acid rock drainage & environment
- Empirical basis for upstream dams (rate of rise)
- 2000-Present: seismic hazard assessment, stress/strain models (FLAC); hydrogeological models
- 1980's to present: thickening and filtering

SITE CHARACTERIZATION

- 1950 -1970's: Drilling, undisturbed sampling, SPT, laboratory testing
- 1980's: Geophysical surveys,
- 1990's: CPT, satellite imagery
- 2000 – Present: advanced lab testing, increasing range of geophysics, satellite, INSAR, drones, etc.

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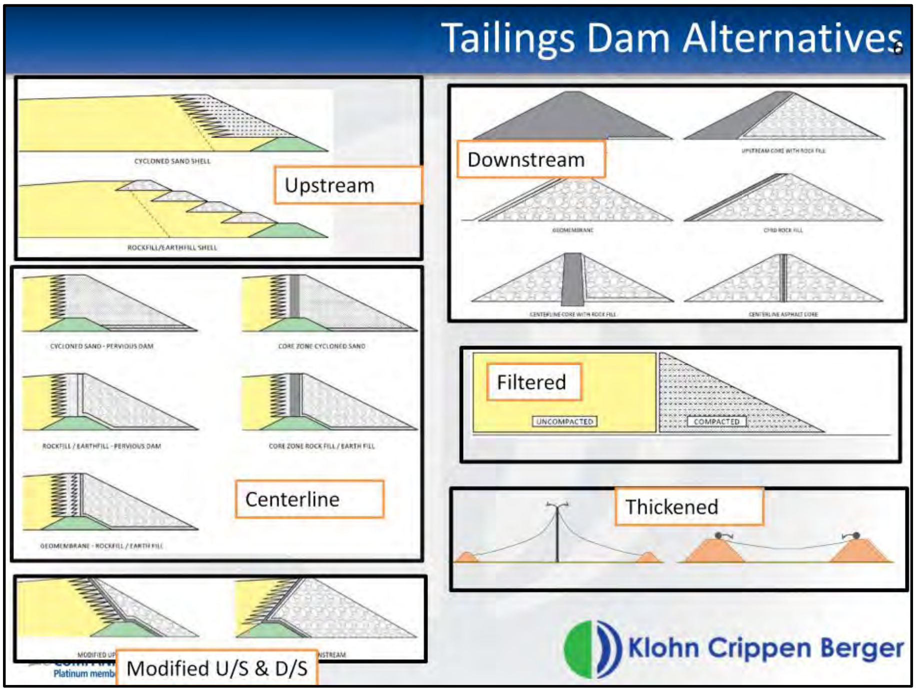
History of Tailings Dam Designs

- Up to 1960's mainly upstream construction – uncertainties (homogeneity, undrained shear strength and seismic response).
- Possibly the first compacted downstream dam in Pennsylvania (1956) - coarse coal refuse dam.
- 1960's Earle Klohn centerline cyclone sand dams for the large porphyry copper deposits.
- Knight Piesold (Africa) cyclone sand shells for upstream dams
- Cyclone sand dams are robust and resistant to piping – dams from the 1960's still meet todays seismic criteria.
- Design sections continue to evolve – incorporating seepage control (environment basis), local materials, site conditions and closure design.
- The benefits of thickened and paste tailings have not materialized
- Filtered tailings, introduced in the 1970's, continues to evolve


Tailings Dam Alternatives
CYCLONED SAND SHELL
Upstream
ROCKFILL/EARTHFILL SHELL
Downstream
UPSTREAM CORE WITH ROCK FILL
GEOMEMBRANE
CENTERLINE CORE WITH ROCK FILL
CENTERLINE ASPHALT CORE
CYCLONED SAND - PERVIOUS DAM
CORE ZONE CYCLONED SAND
ROCKFILL / EARTHFILL - PERVIOUS DAM
CORE ZONE ROCK FILL / EARTH FILL
GEOMEMBRANE - ROCKFILL / EARTH FILL
Centerline
Filtered
UNCOMPACTED
COMPACTED
Thickened
Modified U/S & D/S
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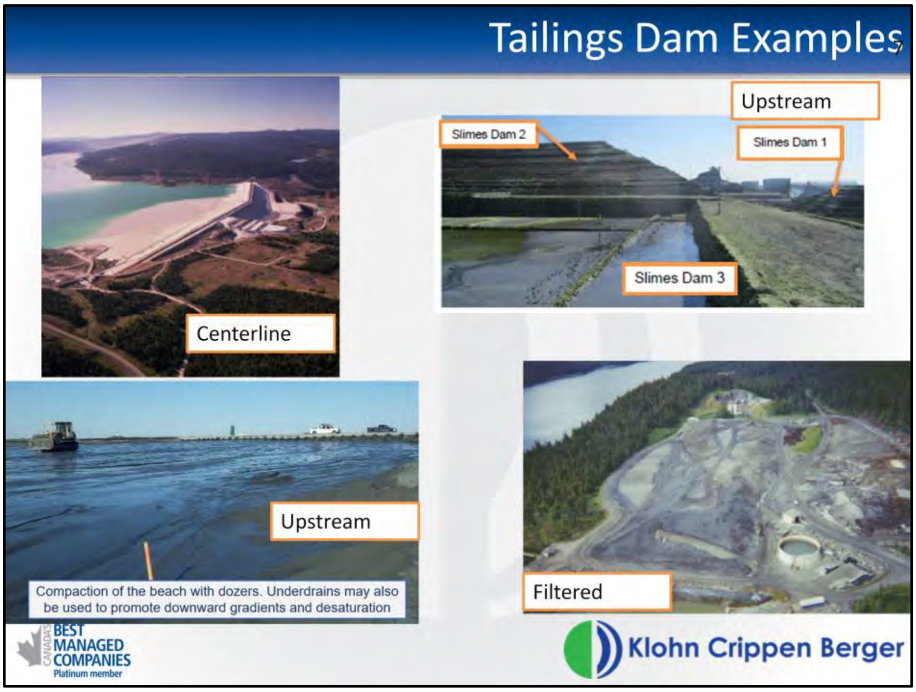
Tailings Dam Examples
Upstream
Slimes Dam 2
Slimes Dam 1
Slimes Dam 3
Centerline
Upstream
Compaction of the beach with dozers. Underdrains may also be used to promote downward gradients and desaturation
Filtered
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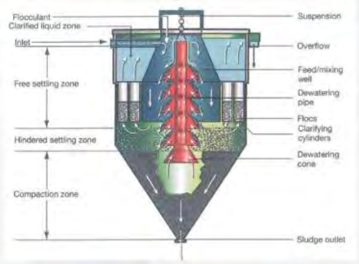
Tailings Dam Technologies



- Tailings can be thickened in situ or in mechanical thickeners
- Filtered tailings can have challenges with high tonnage/low value ore and site conditions.

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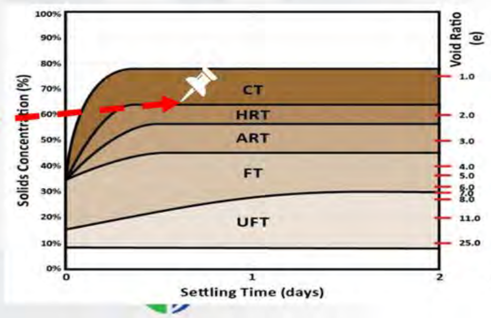
There are Many Different Tailings Types

Tailings Type	Symbol	Description	Example of mineral/ore
Coarse tailings	CT	Silty SAND, non-plastic	Salt, mineral sands, coarse coal rejects, iron ore sands
Hard Rock tailings	HRT	Sandy SILT, non to low plasticity	Copper, massive sulphide, nickel, gold
Altered Rock tailings	ART	Sandy SILT, trace of clay, low plasticity, bentonitic clay content	Porphyry copper with hydrothermal alteration, oxidized rock, bauxite. leaching processes
Fine tailings	FT	SILT, with trace to some clay, low to moderate plasticity	Iron ore fines, bauxite (red mud), fine coal rejects, leaching processes, metamorphosed/weathered polymetallic ores
Ultra Fine tailings	UFT	Silty CLAY, high plasticity, very low density and hydraulic conductivity	Oil sands (fluid fine tailings), phosphate fines; some kimberlite and coal fines



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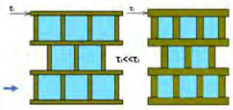
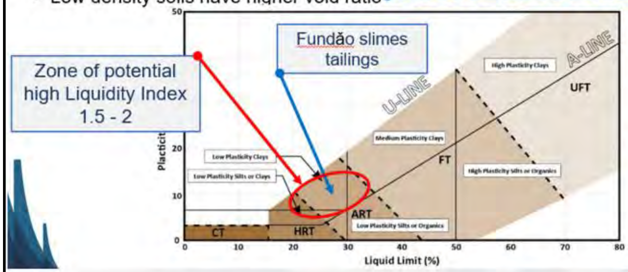
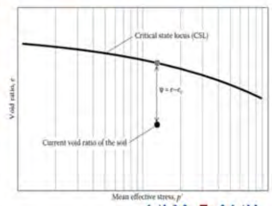
- ICOLD is publishing a new Bulletin called Tailings Dam Technology Update
- Classification of tailings into 5 categories from Coarse to Ultra Fine
- Classification can be done with a simple “jar” settling test – mix tailing to 50% solids by weight – place in a beaker and allow to settle – measure solids concentration after settling (typically 2 hours to 1 day)
- Example of coal fines

Undrained Strength Appreciation –Static Liquefaction

- Linked to the basic properties of the tailings.
  - Plasticity Chart
  - Plastic Limit (rolls like plasticine) and Liquid Limit (soils start to creep/flow)
- Liquidity index (wc-PL)/PI
- Tailings with in situ water content higher than the Liquid Limit
- Low density soils have higher void ratio







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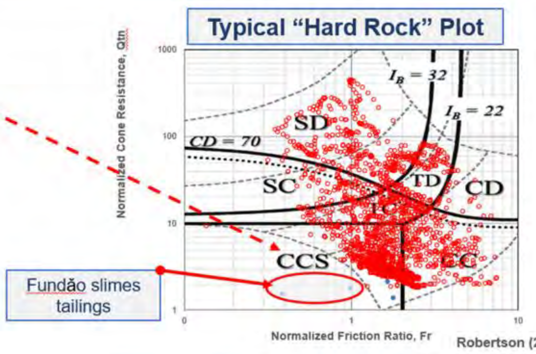
Undrained Strength Appreciation –Static Liquefaction

11

- Indications from Cone Penetration Testing (CPT)
- Robertson (2016) classifies a zone as CCS (Contractant Clay Sensitive)
- Very low residual shear strengths e.g. < s_u/sigma' < 0.05



Robertson (2016)

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How do Tailings Dams Fail?

Material Unwanted Events (Threat/Causes) [Failure Modes]	Preventative Controls	Unwanted Event	Mitigative Controls	Consequences
Foundation	Site investigation Dam design Deformation monitoring Pore pressure monitoring Design – static stability Design – seismic stability	Dam failure and release of tailings	ERP Unload crest of dam Load toe of dam Move pond Minimize pond volume	Catastrophic failure
Dam Slope	Material characterization QA/QC Design – static stability Design – seismic stability Monitoring – pore pressure Monitoring - deformations			
Piping	Design - limiting hydraulic gradients Design - filter compatibility QA/QC of filters		ERP Move pond Minimize pond volume Place inverted filters	
Overtopping	Design criteria Design -flood storage capacity Design - spillway capacity Monitoring water levels Monitoring flows		ERP Build emergency spillway Move pond Minimize pond volume Pump	
Decant	Design decant structure Operations and maintenance procedures Monitoring flows	Release of tailings and water	ERP Plug decant Move pond Minimize pond volume	Environmental and social impacts
Erosion	Design erosion controls Inspection and maintenance	Release of sediment	ERP Repair eroded zones Move pond Minimize pond volume	Operation upsets
Geohazards	Design geohazard controls Monitoring slopes, snowpack, deformations	Dam overtopping Release of sediment and water	ERP Avalanche controls Increase freeboard Stabilize slopes Minimize pond volume	Operation upsets
Water Contamination (groundwater and surface water)	Waste and water characterization Design of seepage controls Design of filters for ARD precipitates Monitoring water quality Monitoring water flows	Contaminated water release	Design of filters and slope stability Interception wells Seepage cutoff walls Attenuation ponds Design change for saturation of tailings	Environmental and social impacts

Monitoring Technologies

Equipment Measuring Device and Methods	Parameters Measured	Application	Research / Experience
Monitoring of Pore Pressures or Moisture Changes			
Electric piezometers with telemetry to process plant or phone	Pore pressure and temperature	Monitor pore pressure changes due to loading and changes in hydrogeological conditions	Standard practice at many mines. Strings at multiple depths are preferred
TDR, Neutron Probes	Saturations levels and temperature		
Self Potential	Passive electrical method which is sensitive to the flow of seepage water	Electrodes are placed on the dam surface both for investigation and monitoring	Research and long term field measurements have been performed especially in US, Canada, France and Sweden.
Distributed Fiber Optic sensing	Temperature and strain are measured in optical fibers using laser light.	Cables are installed in new or old dams for seepage evaluation using temperature and strain analyses to assess movements	Basic research since 1996 in Germany and Sweden. Further research especially in France, Austria, the Netherlands, UK and US. Challenges are calibrating measurements to site conditions.

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Monitoring Technologies

Monitoring of Deformations			
Vibration Measurements	Dynamic response (modes and frequencies)	Long term monitoring of the integrity of concrete structures	Either forced or natural ambient loads are used for excitation. Change in dynamic response under the same loading conditions indicate changes in the integrity of the structure
Borehole Instruments (inclinometers)	Electro-Mechanical devices used to measure deformation	Devices are placed where movements/tilts may occur	Recent developments allow continuous monitoring both in vertical boreholes as well as longitudinally within the dam.
Settlement plates	Change in elevation	Monitoring of dam settlement	Common practice at dams sensitive to settlement and to understand the deformation and stress state of the dam.
Global Navigation Satellite System (GNSS)	Accurate distance measurements between orbits and sensor.	Local monitoring of movements.	Extensive research with improved accuracy for different applications.
Laser scanning and digital imagery	Accurate distance measurements using laser with high spatial resolution over surfaces	Provide a three dimensional geometric model of dam. Deformations can be detected by regular measurements	Technology continuously improving by lasers, sensors and digital image processing. Method is used in several countries as a normal procedure.
Satellite Synthetic Aperture Radar (Satellite SAR)	Photogrammetry method using Satellite images	Surveying of dams and impoundment and monitoring of movements at regular intervals	High resolution surface surveying method producing a digital3-D representation of the surfaces
Ground survey Aperture Radar (GBInSAR)	Photogrammetry method using ground station images	Surveying of dams and impoundments and monitoring of short term movements	High resolution surface surveying method producing a digital 3-D representation of the surfaces

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Monitoring Technologies

Monitoring of Stresses			
Load cells	Stress	Monitor stresses at different locations in the dam	Applicable for high dams sensitive to stress and strain changes.
Other Monitoring Technologies			
Multi-beam bathymetry	Echo-sounding	Bathymetric survey of ponded water	High resolution underwater surveying producing a digital 3-D representation of the surfaces. Used on tailings ponds with a miniature submarine.
Drones and cameras	Visual record	Monitoring of spillways, beach lengths	Allows visual reconnaissance on a continual or periodic basis.
Seismographs (accelerometer)	Earthquake acceleration	Monitoring attenuation of earthquakes and the seismic response of the dam.	Common in high seismic setting.
Resistivity	Active electrical method that can detect changed material properties	Electrodes are placed on the crest or at the dam toe.	Research and long term field measurements have been performed especially in US, Canada, France and Sweden.
Ground Penetrating Radar (GPR)	Detect changes in properties of near surface soil layers, localization of defects or voids in concrete structures	Nondestructive and rapid method based on measuring transmission time for radar signals reflected from or transmitted through a media	Localization of seepage zones, sinkholes and deterioration of cores in embankment dams. Monitor remedial grouting of dams. Limited survey depth
Water quality sensors	Electrical conductivity and pH	Monitoring water quality to optimize attenuation/mixing with receiving waters	

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How Does Geophysics Help?

Dam Foundation Characterization

- Spatial distribution of materials
- Density
- Conductivity (saturation and clay content)
- Ice or voids

Dam Structure Characterization

- Seismic Cone Penetration Testing (SCPTu)
  - Peak undrained shear strength
  - Residual undrained shear strength
  - Shear wave velocity
  - Pore pressure generation & dissipation
  - Emerging moisture content indication

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Case Example: Dam Foundation Characterization – SNIP Mine

Site Context

- Remote site – plane/helicopter
- Pre-feasibility stage
- Complex post glacial geology in a constrained valley
- Subsequent drilling program confirmed geophysical interpretation, with more detail

Geophysical Surveys

- Seismic refraction
- Electrical resistivity

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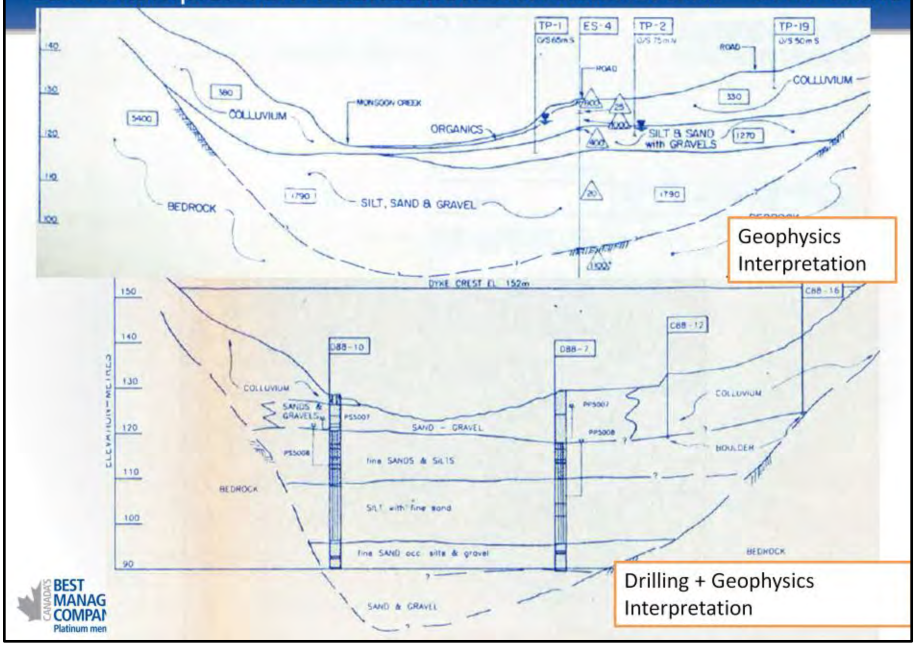
Case Example: Dam Foundation Characterization – SNIP Mine



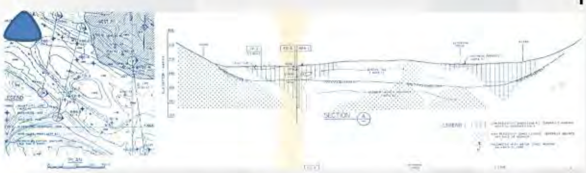
Case Example: Groundwater Flow paths – Ajax

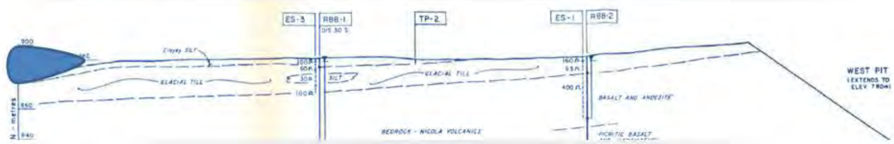
Geophysical Surveys

- Electrical conductivity (ERT) to determine potential flow paths that could drain the lake

Site Context

- Studies carried out in 1988 (not the current proposed mine plan)
- Open pit mine 400 m from Jacko Lake





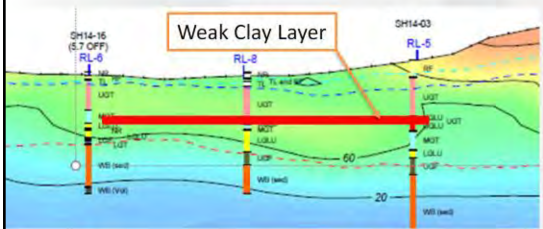
Case Example: Mt. Polley Dam Foundation Characterization

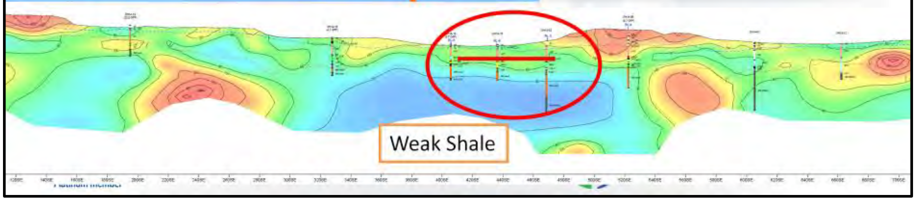
Geophysical Surveys

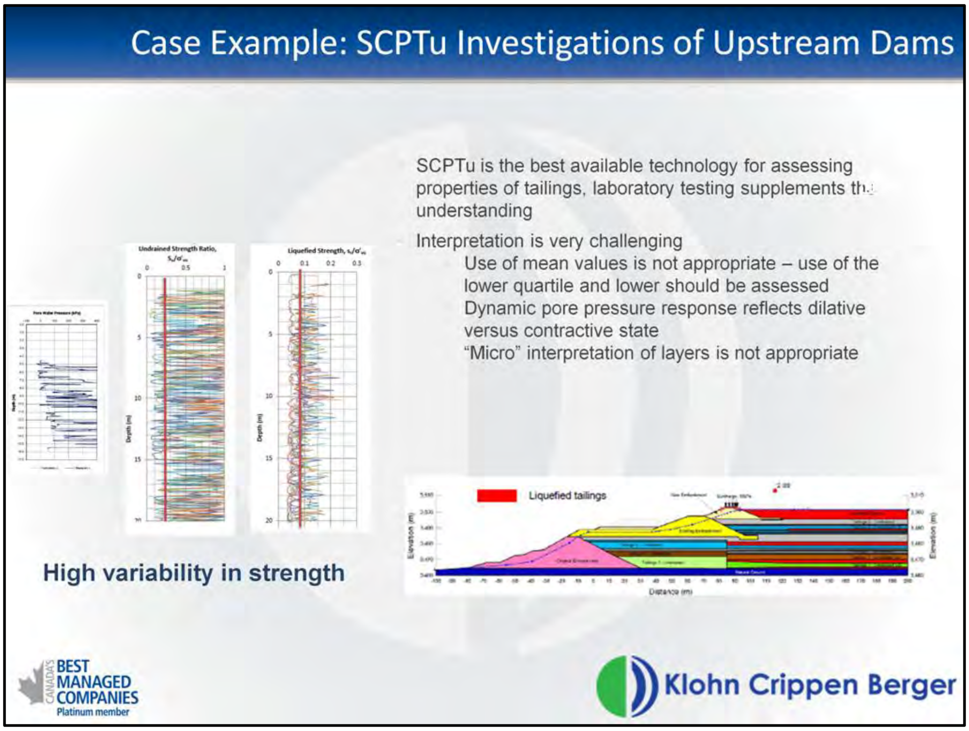
- Electrical conductivity (ERT)
- Seismic refraction
- SCPTu

Site Context

- Geophysical surveys conducted after the failure
- Did not detect the weak clay layer
- But!! Did identify a significant anomaly within the area of the failure
- SCPTu valuable spatial data







- High uncertainty in selecting design values
- SCPTu provides the best way of determining spatial variability and technical application of the results continues to mature – today it represents the best technology available
    - Pore pressure response during driving the CPT indicating contractant response
    - Micro interpretation of layers is not appropriate
    - Selection of minimum values or lower quartile values
    - Selection of liquefied strength uncertain: different methods: Robertson, Bean, case histories
- High uncertainty with collection of representative undisturbed samples for advanced lab testing and interpretation of results – although still a valuable tool for understanding the behavior of tailings under increasing stresses and is valuable for assisting in FLAC modelling

- Need to consider the "body of evidence"

Summary

- The technology to design safe tailings dams has been available since the 1950's; but there has been a disturbing lack of care and attention to the designs
- Recent tailings dam failures are initiating a "step change" with respect to design and governance; but there is still a shortage of qualified practitioners worldwide.
- Geophysical technologies play a very important role in site/dam characterization and continue to evolve
- Technologies for monitoring deformation, pore pressure, saturation, stresses are important for safe construction and operation of tailings dams

THANK YOU

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