The Gamut of Tailings Dam Geophysics

A Review of the Range of Geophysical Techniques Relied Upon in Tailings Dam Design and Assessment

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Engineering, Geoscience & Environmental Services



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Geophysics and the Phases of a Tailings Dam

1. **Seismic Hazard Assessment:** Remote sensing, seismology, fault investigations.
2. **Site Selection and Alternatives Assessment** – Focus on rapid screening: Typically a single seismic line at each site.
3. **Preliminary Economic Assessment** – Support of Conceptual Design, Geophysics to focus drilling in next stages: Grid of geophysics lines, none to several drillholes.
4. **Pre-Feasibility, Feasibility, Detail Design** – Increasing levels of foundation investigation and borrow delineation: Multiple geophysical techniques, seismic, resistivity, Cone Penetration Testing, five to many drillholes per dam.
5. **Operations** – Tailings dams can expand into new foundation areas annually and may suffer from seepage and deformations: Expansion requires more geophysical coverage. Ultimately may have hundreds of drillholes and many problem-solving phases of geophysical investigations.
6. **Closure** – A well designed dam can become a stable landform. But legacy facilities are often not documented: Geophysics used for; original ground surface, depth to bedrock, seepage mapping and tailings consolidation state.

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Site Specific Seismic Hazard Assessment

Geophysical Methods

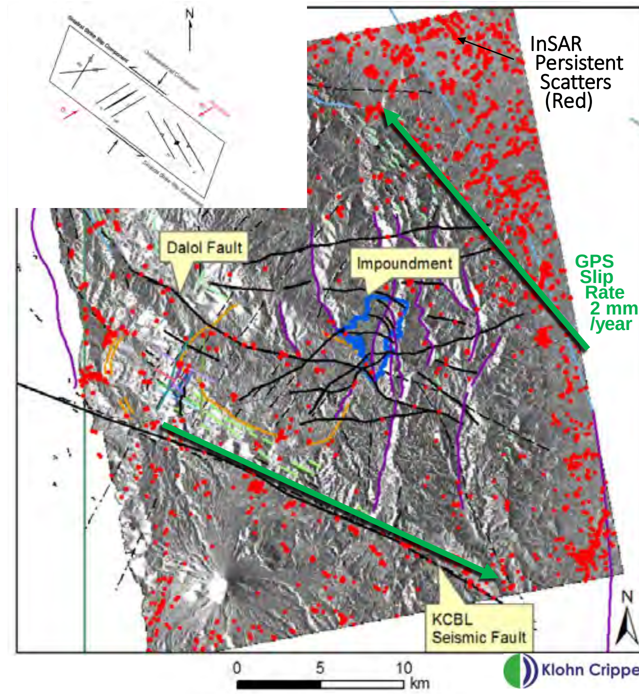
- Magnetics – Identify contacts and faults
- GPS displacement data quantifies movement of active faults and constrains potential earthquake source magnitudes
- Satellite Radar Imagery – length of faults is another input into potential magnitude
- Time lapse interferometric synthetic aperture radar by satellite (INSAR) to determine where deformation is being accommodated and where strain is actively building

Applications

- Seismic Hazard Assessments are required for safe design of tailings facilities

Limitations

- INSAR: viewing angle, requires scattering features



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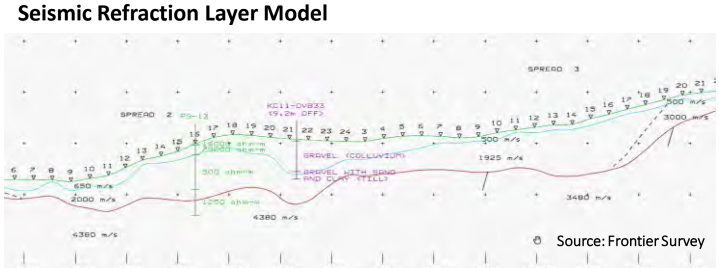
Initial Damsite Foundation Assessment

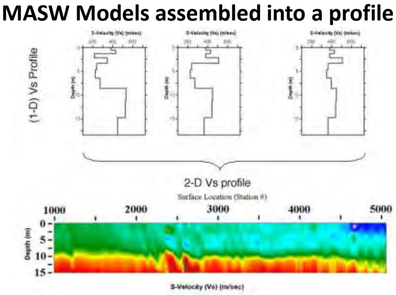
***Standard Geophysical Techniques* – KCB uses at almost every proposed dam site**

- **Seismic Refraction** – overburden layering, material classification by velocity and bedrock depth / fault identification via velocity contrasts. Often both layer model and tomographic velocity model. Identification of till resource for borrow.
- **MASW** – Vs_{30m} A standard measure of average Vs to 30m depth used in foundation assessment for seismic liquefaction. Stacked MASW profiles are useful to confirm refraction bedrock depths.
- **Earth Contacting Resistivity** Tomographic Profiles (ERT). Overburden/bedrock classification and identification of clays (via conductivity and IP response).

Seismic Refraction Layer Model



MASW Models assembled into a profile



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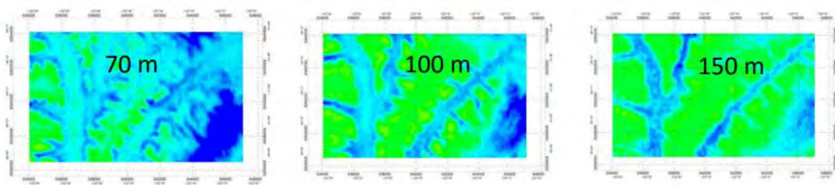
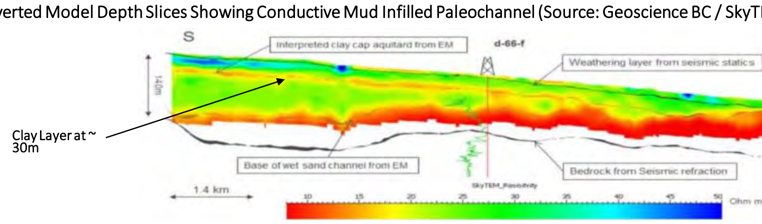
Airborne Mapping of Overburden Characteristics

- Advances in airborne EM and inversion suggest a new paradigm in investigating proposed and existing dam sites.
- Detailed depth slice plans and profiles greatly enhance geological understanding.
- <u>Airborne should be considered as part of normal due diligence for assessing major Tailings Facility sites.</u>



Inverted Model Depth Slices Showing Conductive Mud Infilled Paleochannel (Source: Geoscience BC / SkyTEM Horn River Survey)



Inverted Depth Profile Showing Clay Layer (Source: Geoscience BC / SkyTEM Horn River Survey)

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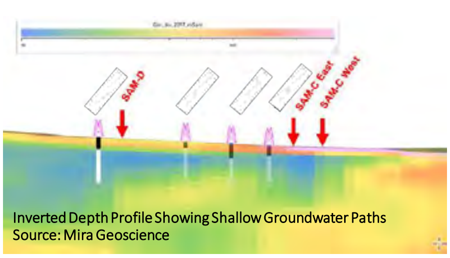
Airborne Mapping of Tailings Dam Sites

Methods

- Time Domain (SkyTEM) – layers, faults
- Frequency Domain EM – overburden features
- Sub-Audio Magnetics – contacts, faults
- Magnetics – contacts and faulting

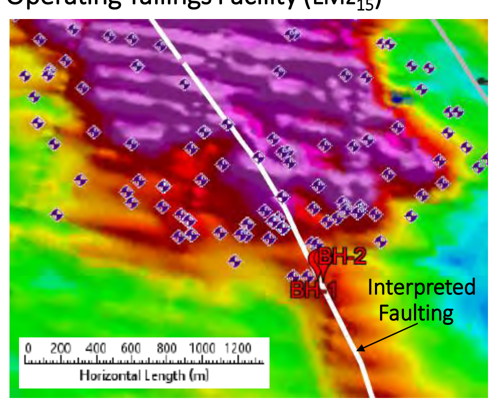
Applications

- Mapping large sites (metal mining complexes and oil sand mines)
- Characterizing seepage pathways and paleochannels
- Locating faults for follow-up drilling



Inverted Depth Profile Showing Shallow Groundwater Paths
Source: Mira Geoscience

SkyTEM Conductivity Mapping of an Operating Tailings Facility (LMz_{15})



Airborne magnetics, ground ERT and SAM also used successfully at this site to characterize seepage pathways.

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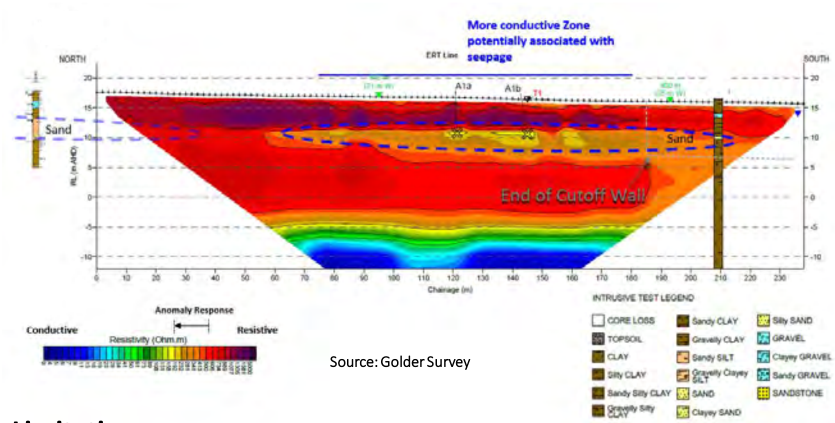
Surface ERT Profiling: Dam Seepage Paths

Method

- Earth Resistivity Tomography (ERT) e.g. Ground Contacting Resistivity
- Typically used to about 50 m depths
- Resolves layers of thickness about 1/5 of depth
- Max. depth is between 1/5 to 1/3 of line length



Applications

- Dam Seepage
- Clay layers
- Bedrock Faults
- Paleochannel and Karst location

Limitations

- Resolution drops off rapidly with depth
- Achieving depth penetration requires long lines
- Conductive surface layers can short circuit current and limit penetration

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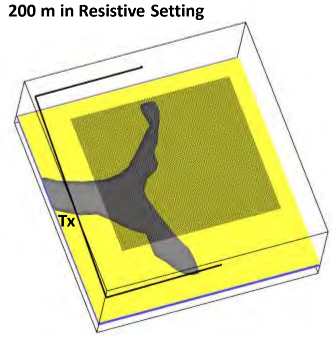
Sub Audio Magnetics (SAM): Buried Channel Detection

Method

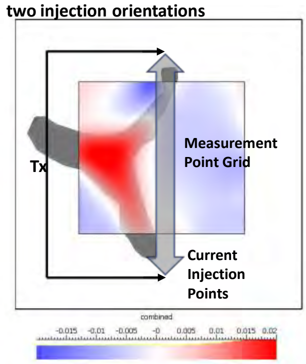
- Current is injected or induced in the ground.
- Current paths detected by sensitive scalar magnetometers, either on ground surface or on aircraft.
- Good at mapping resistive structures or weak conductors even beneath conductive layers. Also provides magnetics data.
- Better depth penetration than ERT or typical EM methods.

Model: Conductive Channel buried 200 m in Resistive Setting



Source: S. Napier et al, 2014

Response from superimposing two injection orientations



Applications

- Dam and impoundment seepage.
- Location of deep paleochannel seepage paths.
- Bedrock faults.

Limitations

- Requires multiple injections to sense all orientations
- May require high injected power but as transmitter can be ground based not a limiting factor for airborne

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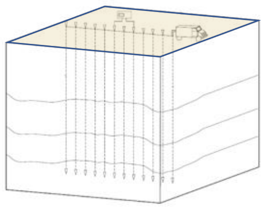
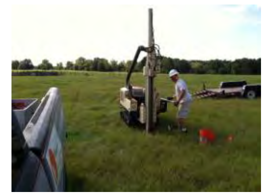
Embedded Electrode ERT: Higher Resolution at Depth

Method

- Push electrode strings in vertically or place horizontally during dam construction

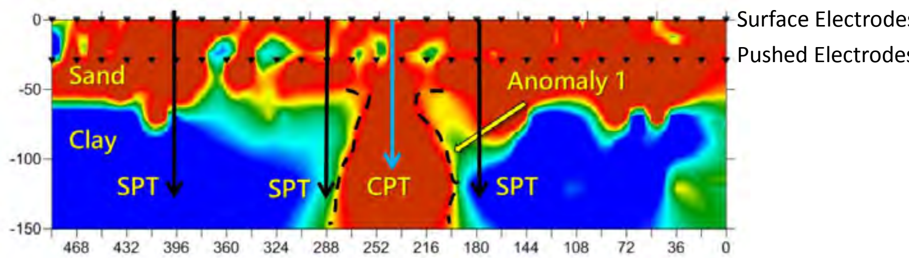


MERIT $_{TM}$ system uses vertically pushed 1.5" diameter electrodes. From Loke et al, Near Surface Geophysics · October 2015.



Applications

- Confined sites
- Dam monitoring and seepage assessment
- Cavity and void assessment
- Tunnel routes
- Can also embed fibre optic strain gauges



Imaged a CPT tested sinkhole to depths of > 50 m

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MASW Profiling by Landstreamer

Method

- Multi Channel Analysis of Shear Waves (MASW)
- Analysis plotted at central point of geophones
- Vertical profile of Vs with depth
- Calibrate against borehole P+S survey, crosshole, seismic cone or SPT

Applications

- Assess seismic liquefaction of embankments
- Around "Turkey's Nest" dams (ring dykes)
- On crests of upstream tailings dams

Plotting of Vs_{30m} Around Dam Perimeter

As a rough rule of thumb, Potential for liquefaction is greatly reduced for Vs > 200 m/s

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Streaming Potential

Method

- Filtration/shear of charge carriers as water streams through porous medium causes charge separation leading to voltages on surface
- Voltage at roving electrode compared with reference electrode
- Uses non polarizable electrodes
- Requires base station to remove telluric (daily) background noise fluctuations
- Useful to have resistivity data to correct for effects of dam structure in flow model

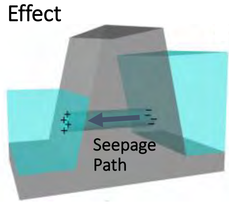
Applications

- Surface electrodes can locate internal dam or impoundment seepage paths for remediation
- Embedded electrodes for monitoring seepage
- Modelling software now exists to model effects of dam structure on surface SP response

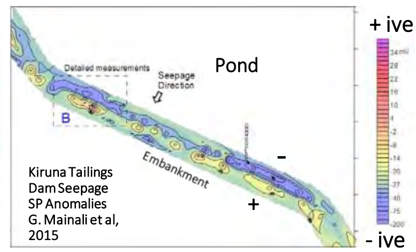
Limitations

- Undissipated pore pressures from dam raising and embedded pipes and cables can cause spurious anomalies

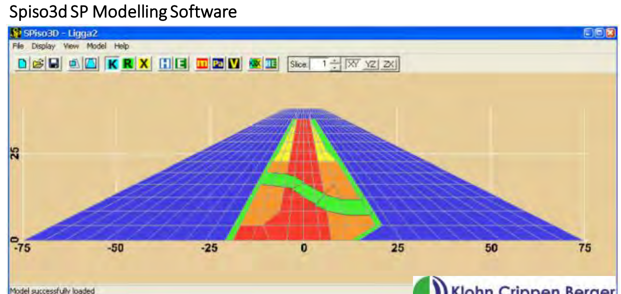
Streaming Potential Effect



After A. Berube, 2004



Spiso3d SP Modelling Software



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Case History: Filtered Tailings Pile Investigations

- Excessive seepage experienced. Asked if geophysics could identify seepage pathways and confirm parameters for design of pile expansion.
- Refraction seismic established bedrock elevation vs original surface. MASW provided shear wave velocity of foundation and tailings pile. Bedrock elevations used in hydrogeological model. Shear wave velocities input to seismic stability assessment.
- A quasi 3d ERT grid identified resistive windows in till layer. These windows exposed fractured rock seepage paths.
- Tailings pile removed where no till present and liner placed to successfully remediate sources of seepage, tailings replaced. Expanded facility continues to operate satisfactorily.

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Other Dam and Foundation Assessment Methods

- **TEM Conductivity** for seepage plumes, deep overburden and bedrock at depths beyond range of ERT.
- **Optical and Acoustical Televiewer** for structural and hydrogeological assessments.
- **GPR** for investigations of karst, saprolites, alluvials and buried decant pipes.
- **Magnetic Gradiometry and EM** for locating steel decant pipes beneath dams.
- **Seismic Cone Penetration Testing (SCPT)** with pressure, seismic and resistivity sensors for assessment of seismic and static liquefaction in upstream constructed tailings dams.
- **Borehole Geophysics** for more intensive studies of embankment failures, saturation levels, surface to borehole P+S wave, borehole to borehole P+S wave, neutron, gamma.
- **Nuclear Magnetic Resonance** via surface soundings and borehole tools to measure percent free and bound water in embankments and tailings.
- **Marine Seismic in ponds** high resolution imaging of layering, leakage pathways and detection of workings beneath tailings ponds.

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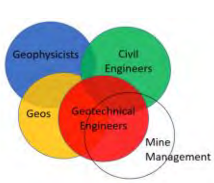
Why isn't more Geophysics done on Dams?

Because of the nature of Engineer-Geophysicist Communications!

e.g. *"Can surface resistivity detect a 15 cm clay layer at 25 m depth?"*

- **Correct Answer is** "*No*", Result is often no further investigation occurs beyond maybe another drillhole or two (at cost of many metres of geophysics).
- **Better Answer:** *"Well, the best way to establish if the geological environment is likely to include a clay layer is to establish the structure of the overburden with resistivity and seismic, checking for continuity of layers with known elevations of clays in the area, etc. etc.".* Outcome – Geophysics properly employed as a <u>change detection tool</u> to test for anomalies between drillholes <u>and to develop better overall geological understanding</u>.



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Questions?

"May I ask where you studied engineering?"

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