Outline

- Purposes of geo-modelling of tailings in an impoundment
- State-of-the-practice in tailings modelling
- FLAC-based modelling approach
- Validations of the modelling approach
- Example case
Main Purposes of Tailings Geo-Modelling

Mine operation planning

- To predict capacity of the impoundment for tailings storage (> geometric volume), = function of tailing properties and deposition scheme.

Mine closure

- To predict surface settlement after rock/sand backfilling;
- To estimate the amount of water to be discharged out of the tailings during consolidation;
Main challenges in modelling tailings deposition

- Continuous tailings deposition during consolidation process.
- Tailings large compressibility at small stress.

\[ e = A \cdot (p')^b \]

Fitting parameters:
- \( A = 7.72 \)
- \( b = -0.22 \)

\[ k = 2.536 \times 10^{-7} \times e^{4.65} \]
State-of-the-practice

Pseudo 3D Approach (main state of practice)
- Based on 1D large-strain consolidation theory
- Uses a series of annulus to model pit geometry

Quasi 3D Approach
- 3D flow analysis
- 1D (Vertical) consolidation

Modified from: Miller (2012)
<table>
<thead>
<tr>
<th>Comparison</th>
<th>Interaction between the columns; $\delta_{p3D} &gt; \delta_{3D}$</th>
<th>Deformation pattern</th>
<th>Non-vertical flow</th>
<th>Modelling of wick drains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-3D</td>
<td><img src="image1.png" alt="Diagram of Pseudo-3D" /></td>
<td><img src="image2.png" alt="Diagram of Deformation" /></td>
<td><img src="image3.png" alt="Diagram of Non-vertical flow" /></td>
<td><img src="image4.png" alt="Diagram of Modelling" /></td>
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<tr>
<td>Multi-dimensional modelling (~ Reality)</td>
<td><img src="image5.png" alt="Diagram of Multi-dimensional modelling" /></td>
<td><img src="image6.png" alt="Diagram of Deformation" /></td>
<td><img src="image7.png" alt="Diagram of Non-vertical flow" /></td>
<td><img src="image8.png" alt="Diagram of Modelling" /></td>
</tr>
</tbody>
</table>
Outline

- Purposes of geo-modelling of tailings in an impoundment
- State-of-the-practice in tailings modelling
- FLAC-based modelling approach (Multidimensional 2D/3D)
- Validations of the modelling approach
- Example case
FLAC-Based Modelling Approach

Modelling gradual tailing deposition (fish subroutine)

- Staged filling approach: (i) undrained slurry deposition ($\sigma'_v \approx 0$) followed by a (ii) stage of consolidation (under self weight).
- Update top boundary conditions after each stage of deposition.
- New level of horizontal surface ($z_{i+1}$) calculated based on tailing discharge rate ($\Delta v_{i+1}$) and actual settled surface.

Activation of layer ‘i’

Newly deposited volume $\Delta V_i$

Consolidation, $\Delta t_i$

Settled surface of layer “i”

Activation of layer ‘i+1’

Newly deposited volume $\Delta V_{i+1}$

Modified from: Zhou at all (2019)
Modelling of gradual tailing deposition (fish subroutine)

- Staged filling approach: (i) undrained slurry deposition ($\sigma'_v \approx 0$) followed by a (ii) stage of consolidation (under self weight).
- Update of boundary conditions after each stage of deposition.
- New level of horizontal surface ($z_{i+1}$) calculated based on tailing discharge rate ($\Delta v_{i+1}$) and actual settled surface.
FLAC-Based Modelling Approach

Constitutive model
- Non-linear relationships of e-σ' and k-e implemented in the Mohr-Coulomb model in FLAC.
- Voids ratio (e) for each element computed according to the volumetric strain (large strain) → update on the density, tangent stiffness and permeability.

\[ M = \left( \frac{(1+e_0)}{A \cdot b} \right) \cdot \left( e \right)^{\left( \frac{1}{b-1} \right)} \]

- Fitting parameters: 
  - Fitting parameters: 
  - A = 7.72, b = -0.22

\[ k = 2.536 \times 10^{-7} \times e^{6.65} \]

- M = Tangent constrained modulus
- e_0 = void ratio at deposition
- e = void ratio < e0
- A and b = fitted parameters as per e-σ’v relationship

\[ K = \frac{\delta \varepsilon_v}{\delta p} = \frac{M \cdot (1 + \nu)}{3 \cdot (1 - \nu)} \]

- K = tangent bulk modulus
- \( \delta \varepsilon_v \) = incremental volumetric deformation
- \( \delta p \) = incremental isotropic stress
- \( \nu \) = Poisson ratio
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Validation of the deposition process (against Gibson, 1958): Consolidation in a clay layer increasing in thickness with time

- \( T = \frac{m^2 t}{c_v} \) = normalised deposition rate.
- \( m \) = deposition rate.
- \( t \) = total deposition time.
- \( c_v \) = coefficient of consolidation.
- \( h \) = thickness at the end of deposition.
- \( \gamma' \) = soil/tailings effective unit weight.

Results for \( T = 4 \)

Excess pore pressure at the end of deposition / \( \gamma'h \)

 Modified from: Amodio at all (2019)
Comparisons with Predictions in Townsend and McVay (1990)

Scenario A

$S_i = 16\%$

$e_0 = 14.8$

Scenario B

$S_i = 16\%$

$e_0 = 22.8$

$S_i = 16\%$

$e_0 = 14.8$

3.3 ft (1 m)

11.8 ft (3.6 m)

11.8 ft (3.6 m)

1.0

0.5

0

0.0

0.5

12

18

TIME (months)

POND HEIGHT (%)

$k = c(e)^D (m/d) \Rightarrow k = (0.2532 E - 06) e^{4.65}$

Scenario C

$e = A(\bar{\sigma})^B (kPa) \Rightarrow e = 7.72(\bar{\sigma})^{-0.22}$

$k = c(e)^D (m/d) \Rightarrow k = (0.2532 E - 06) e^{4.65}$

Scenario D

$e = 7.72(\sigma''_{v})^{-0.22}$

Clay properties
Validation against Townsend and McVay (1990)

Scenario C

Validation against Townsend and McVay (1990)

Scenario D

Results after 1 year

Void Ratio

Excess Pore Pressure

Modified from: Amodio at all (2019)
Scenario B

Modified from: Amodio at all (2019)
Scenario B

Modified from: Amodio at all (2019)
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Modelling Details

Being activated layer-by-layer to model gradual tailings deposition and rock backfilling.

Pre-Designed FLAC Grid of Tailings & Rock Consolidation in a Pit (Half Cross-Section of the Axisymmetric Model)

Modified from: Amodio at all (2019)
Example Results

Variation in the elevation of tailings surface during deposition, rock backfilling and consolidation

![Graph showing variation in elevation over time]

Tailings consolidation and expression of excess water

![Graph showing volume changes over time]

Modified from: Zhou et al. (2019)
Concluding Remarks

- The presented multi-dimensional modelling approach explicitly captures all the key aspects associated with tailings consolidation in a multi-dimensional space.
- Built on FLAC, is reliable and powerful.
- Results have been validated against publications.
- There is also great potential in extending the capability of the modelling approach, such as linking the consolidation to the strength of the tailings and hence include stability calculations within the same framework.
Acknowledgment

I would like to acknowledge the Itasca team in Melbourne (and US) for the continuous support and my NGI’s colleagues in Perth and Oslo.
Thanks! & Question?