Assessment of Self-Weight Consolidation of Co-Deposition Deposits in the Geotechnical Beam Centrifuge

Dr. Gonzalo Zambrano, P.Eng
Yazhao Wang
Dr. Rick Chalaturnyk, P.Eng
Dr. Atoosa Zahabi, P.Eng
Dr. Dave Rennard

Geotechnical Centrifuge Experimental Research Facility (GeoCERF)
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GeoREF
Geomechanical Reservoir Experimental Facility

GeoCERF
Geotechnical Centrifuge Experimental Research Facility

GeoPRINT
3D Printing for the Geosciences

GeoRMT
Geomechanical Reservoir Modelling Technology

GeoREF
GeoCERF
GeoPRINT
GeoRMT

Experimental Studies

Field Studies

Numerical Studies
GeoCERF

Geotechnical Centrifuge Experimental Research Facility
Geotechnical Centrifuge Experimental Research Facility

- Located in NREF building, U of A campus
- A 2m radius platform 50 g-ton beam centrifuge
- Maximum acceleration of 280 rpm (~150 g)
- Maximum payload of 500 kg
- First of its kind in Western Canada
Beam Centrifuge

Rotation Speed **RPM** *(Round per Minutes)*

\[ N = r \frac{RPM^2}{895} \]

This is the magnitude of gravity that a centrifuge produces in the test platform.
Centrifuge Testing in Geotechnical Engineering

The world of PHYSICAL MODELING

Investigation/development of new processes
Parametric studies
Verification of analytical or numerical method

Prototype / field behaviour

Numerical and Analytical model  Physical model

After Mikasa et al., 1973
Advantages of Centrifuge Testing

- The same magnitude of stress levels is maintained in models as in full-scale prototypes
- Displacement and pore pressure boundary conditions are well-defined
- Observations of the complete cross-section of a model can be made
- Self-weight consolidation and other diffusion processes can be studied in a short period of time.
- Centrifuge modelling is comparatively cheap, better controlled, more easily and accurately instrumented, and has more uniform soil conditions than prototype scale testing.
- Isolates gravity-dependent from gravity-independent phenomena.
- Has a technique for checking the scale effect and consistency of the test results and is particularly useful when no prototype is available for verifying the model test results.
- Has theoretically derived and some experimentally proved scaling laws
- Can extend from one-dimensional to two- or three-dimensional modelling
- The effects of various stress histories, stress paths, and geometry conditions can be easily studied.
- Inhomogeneity, layering, and sequence of deposition can be modelled
- Can provide insight into important aspects and mechanisms of the new phenomena.
Limitations of Centrifuge Testing

- The vertical stress distribution in a centrifuge model is non-linear
- The radial acceleration field creates a horizontal stress component
- The effect of friction and adhesion between the soil and model container can be significant in some cases
- These three above effects are minimized by using a model height and width of less than 20% of the effective radius of the centrifuge.
- Centrifuge modelling requires different time-scale factors for different forces to govern a problem.
- Centrifuge testing may enhance the segregation of particles
Scaling Prototype / Model

• Gravitational field “n” induced by the centrifuge

Prototype

$n-g$ field

$
\gamma : \text{Unit weight of soil}
$

Model

Gravity field

$r \omega^2 = ng$

• Scaling laws

Kimura and Kusakabe 1987
Most Common Scaling Criteria

Dimensions:

\[ H_p = N \times H_m \]

\( H_p \) is the height of the deposit being modeling

\( H_m \) is the equivalent model height in the testing apparatus

\( N \) is the number of G-forces the model is subject to.

- For example, a 14 cm sample model height would need to be subjected to 15 G-forces to scale to 2.1 m.

Time:

\[ t_p = t_m \times N^2 \]

\( t_m \) is the time in the model

\( t_p \) is the time in the deposit (prototype).

- 1.7 years of consolidation could be modeled in approximately 65 hours at 15 G.
Other Scaling Relationships

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Prototype</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$N$</td>
<td>1</td>
</tr>
<tr>
<td>Area</td>
<td>$N^2$</td>
<td>1</td>
</tr>
<tr>
<td>Acceleration</td>
<td>1</td>
<td>$N$</td>
</tr>
<tr>
<td>Weight force</td>
<td>$N^2$</td>
<td>1</td>
</tr>
<tr>
<td>Stress</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Strain</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mass density</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Time (consolidation)</td>
<td>$N^2$</td>
<td>1</td>
</tr>
<tr>
<td>Mass</td>
<td>$N^3$</td>
<td>1</td>
</tr>
<tr>
<td>Velocity</td>
<td>$N$</td>
<td>1</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>$N$</td>
<td>1</td>
</tr>
<tr>
<td>Time (creep)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Centrifuge Modelling

- A centrifuge can model any large-scale nonlinear problem for which gravity is the primary driving force.
- Modelling is based on the stress similarity between a prototype (field or laboratory tests) and a centrifuge model.
- Scaling factors for stress, time, height and density are chosen for the centrifuge operation.

Basic principle of the centrifuge modelling (Taylor 1995)

\[ h_m = \frac{h_p}{N} \]
\[ t_m = \frac{t_p}{N^2} \]

Centrifuge scaling laws
GeoCERF
Tailings Consolidation Test Package

High-Resolution Camera

Centrifuge Test Package

Consolidation Cell

In-Flight Penetrometer

Pore Pressure Transducers
Tracking Interface Settlement In-Flight

Prototype Settlement (m) vs. Prototype Time (Years)

Centrifuge Starts Acceleration
10X Speed

Flight Time 0 minutes
Prototype Time 0 Years

High Resolution In-Flight Camera
The Kearl oil sands project

- The Kearl flotation tailings treatment facility deposits flocculated Fluid Fine Tailings (FFT) with the Thickened Tailings (TT) in the tailings area.
- Due to the difference in nature of the two tailings streams, the co-deposition of FFT and TT needs to be evaluated at large laboratory scale.
**Tailings Co-Deposition**

**Segregation**
- Particle segregation is not well-understood in the centrifuge environment;
- Dynamic segregation boundary could be different for different materials.

**Consolidation**
- The long-term self-weight consolidation behavior of the co-deposition of F-MFT and TT is not well understood;
- Co-deposition deposit performance would take years to assess in the field
### Segregation Modelling

<table>
<thead>
<tr>
<th>Stage</th>
<th>G level</th>
<th>Incremental Hours</th>
<th>Incremental Prototype Time (Hour)</th>
<th>Cumulative Prototype Time (yr)</th>
<th>Samples on payload</th>
<th>Samples taken out from payload at the end of each stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>19</td>
<td>475</td>
<td>0.05</td>
<td>1,2,3,4</td>
<td>Sample 1</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>2</td>
<td>49</td>
<td>0.06</td>
<td>2,3,4</td>
<td>Sample 2</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1</td>
<td>100</td>
<td>0.07</td>
<td>3,4</td>
<td>Sample 3</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>1</td>
<td>225</td>
<td>0.10</td>
<td>4</td>
<td>Sample 4</td>
</tr>
<tr>
<td>5*</td>
<td>30</td>
<td>1</td>
<td>900</td>
<td>0.20</td>
<td>-</td>
<td>Sample 5</td>
</tr>
</tbody>
</table>

*Sample 5 was tested separately.*

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Table 1: Centrifuge test plan for segregation modelling.
Transitions between TT and MFT were observed visually and marked here.

Initial Solids Content

Initial SFR

Sample 1 - 5G  20 days

Sample 2 - 7G  21 days

Sample 3 - 10G  26 days

Sample 4 - 15G  35 days

Sample 5 - 30G  2.5 months
Segregation Index

\[ I_s = \sum_{i=1}^{n} \left\{ \frac{1}{2} \left[ \frac{S_i}{S_{avg}} - 1 \right] \left[ \left( \frac{H}{H_f} \right)_{i+1} - \left( \frac{H}{H_f} \right)_{i-1} \right] \right\} \times 100\% \]

Fundamentals of Segregation, Teklu-Mihiret 2009

<table>
<thead>
<tr>
<th>G-level</th>
<th>Segregation Indices, (I_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>0.96 2.30 0.82 2.20 0.98</td>
</tr>
<tr>
<td>F-MFT</td>
<td>0.71 1.13 0.24 0.75 0.18</td>
</tr>
<tr>
<td>Sample #</td>
<td>1 2 3 4 5</td>
</tr>
</tbody>
</table>

SFR ratio and Solids content distributions did not prove any segregation happened up to 30G
Consolidation Modelling

<table>
<thead>
<tr>
<th>Sample 6</th>
<th>Sample 7</th>
<th>Sample 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cm TT</td>
<td>2 cm F-MFT</td>
<td>5.8 cm TT</td>
</tr>
<tr>
<td>2 cm TT</td>
<td>2 cm F-MFT</td>
<td>4 cm F-MFT</td>
</tr>
<tr>
<td>2 cm TT</td>
<td>2 cm F-MFT</td>
<td>4 cm TT</td>
</tr>
<tr>
<td>2 cm TT</td>
<td>2 cm F-MFT</td>
<td>4 cm F-MFT</td>
</tr>
<tr>
<td>2 cm TT</td>
<td>2 cm F-MFT</td>
<td>4 cm TT</td>
</tr>
<tr>
<td>2 cm TT</td>
<td>2 cm F-MFT</td>
<td>4 cm F-MFT</td>
</tr>
</tbody>
</table>

29.8 cm TT/F-MFT Mixture
Sample 7 was built upon Sample 6 configuration by manually shearing it with shear blades.
Photos of consolidation modelling samples

Before

After 19 Prototype Years
Sample 6 & 7

Initial Prototype Height  9 m
Final Prototype Height   4.8 m

Sample 6 and Sample 7 shared an overlapping consolidation curve
Sample 6

30G

Graph showing Solids Content (%) vs. Prototype Depth (m) and SFR.
Sample 7

29.8 cm
TT/F-MFT
Mixture

Solids Content (%)
The layered structure was preserved and captured in Sample 8
Conclusions

• The dynamic segregation boundary for TT and F-MFT co-deposition deposits is above 30G;

• “Layered” and “homogenized” co-deposition techniques have negligible impact in terms of long-term consolidation behavior;

• the layered structures exist after large-strain consolidation in centrifuge environment;

• Centrifuge modelling is proven to be an effective and highly-efficient experimental tool in assessing tailings treatment techniques.
Thank you!

Dr. Gonzalo Zambrano, P.Eng - gonzalo@ualberta.ca
Dr. Rick Chalaturnyk, PEng - rjchalaturnyk@ualberta.ca
Consolidation (diffusion) and seepage

\[ T_v = \frac{c_v t}{H^2} \]

\( T_v \): Dimensionless time factor; \( c_v \): coefficient of consolidation; \( H \): distance to the drainage path

For the same degree of consolidation, \( T_v \), will be same in model and prototype and so:

\[ \frac{c_{vm} t_m}{H_m^2} = \frac{c_{vp} t_p}{H_p^2} \]

\( H_p = N \cdot H_m \)

\[ t_m = \frac{1}{N^2} \frac{c_{vp} t_p}{c_{vm}} \]

Hence, if same material is used in model and prototype the scale factor for time is \( 1:N^2 \)