Physical modelling of revitalization options for reclamation of high-plasticity spoil dumps

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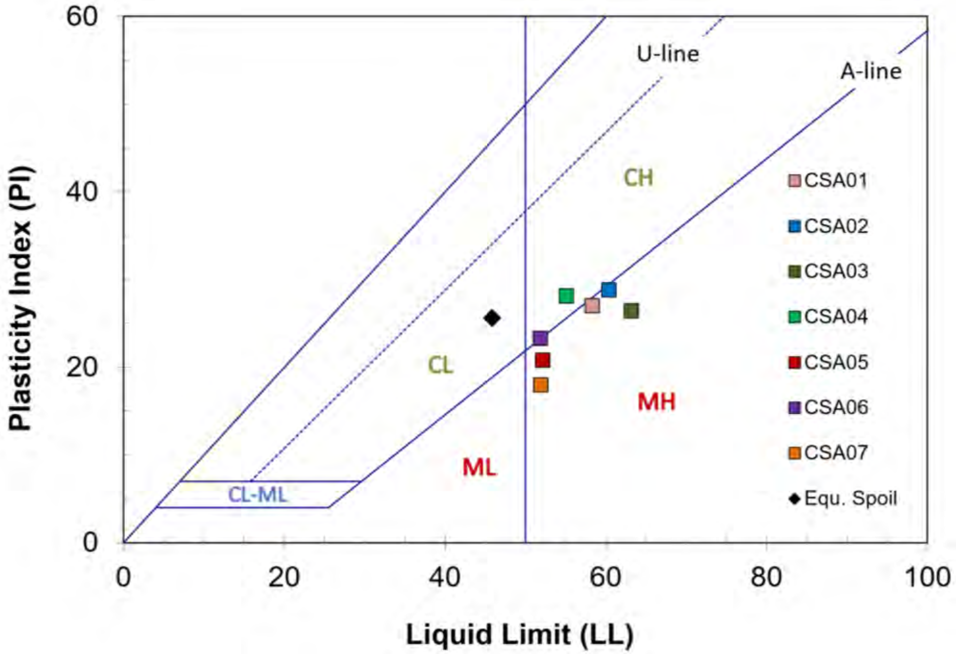
Introduction

- Premise: open-pit mine overburden soil (or spoil) materials are heterogeneous and can contain large proportions of high-plasticity clay.
- Challenge: use of spoil for revitalisation of open-pit mine areas

Image source: photocase.com



Data from testing of samples from CSA Open Pit mine

Introduction

- Premise: open-pit mine overburden soil (or spoil) materials are heterogeneous and can contain large proportions of high-plasticity clay.
- Challenge: use of spoil for revitalisation of open-pit mine areas
- Objective: Physical modelling of spoil response to loading for 2 revitalisation options:

Creation of pit lakes using mine spoils

Image source: imagelinkglobal.com

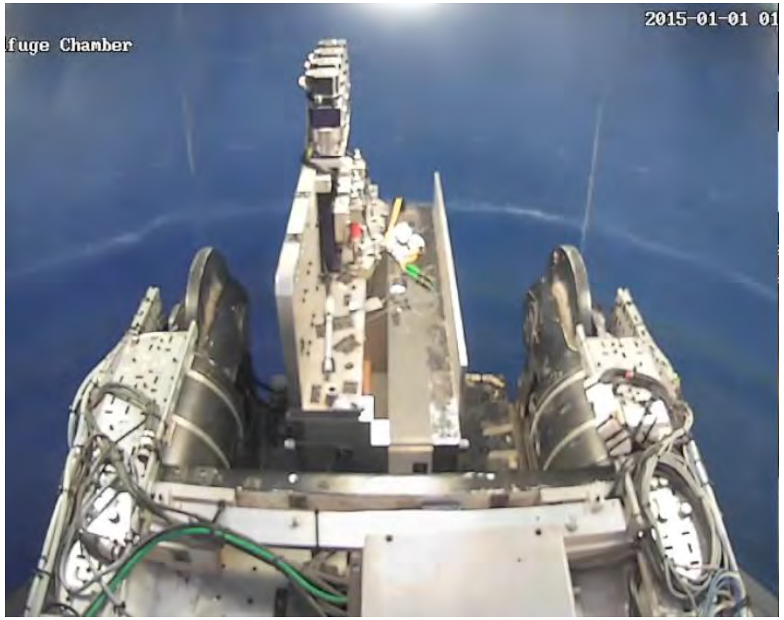
Wind turbines on mine spoils

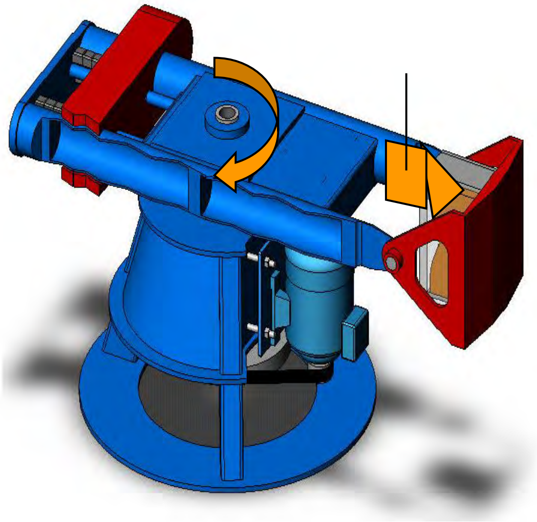
Image source: windeurope.org

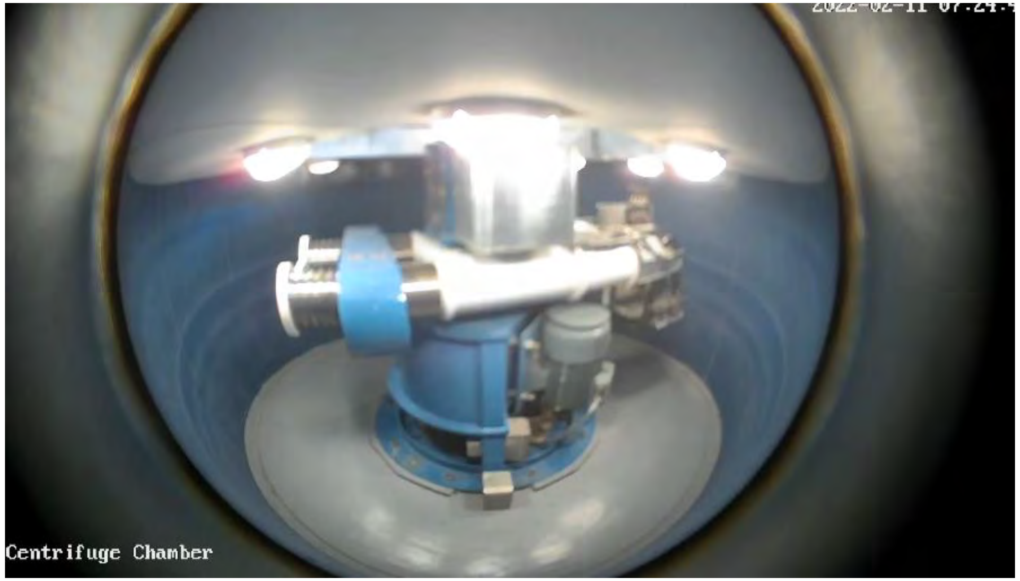
Introduction

Nottingham Centre for Geomechanics

- Geotechnical Centrifuge:
  - 50g-tonne
  - 2.0m platform radius
  - Max 150g
  - Max 500kg payload





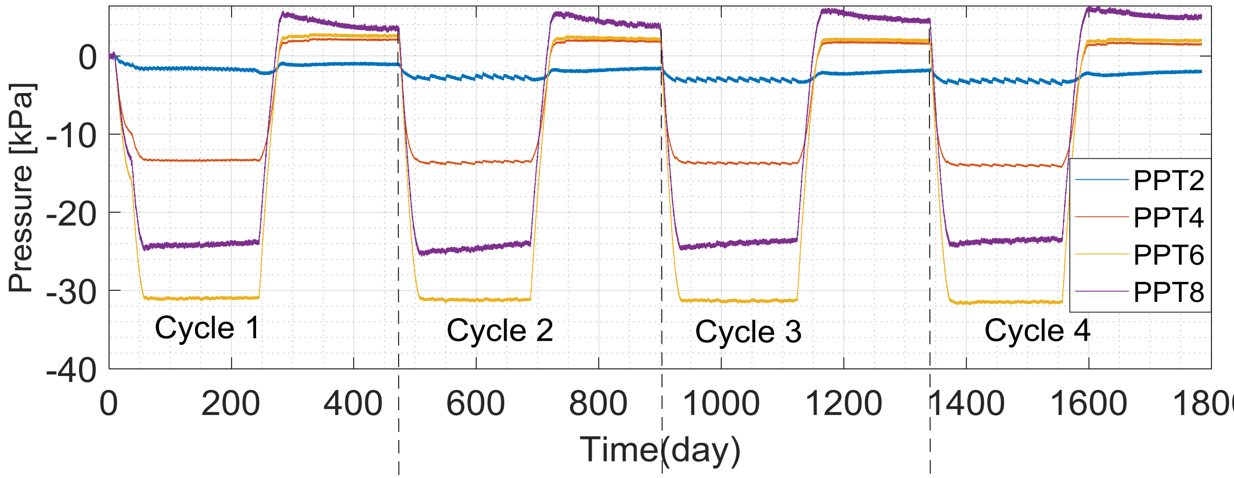


Option 1 – Use of mine spoils for pit lakes - RAFF

Option 1: Use of mine spoils for creation of pit lakes (RAFF project)

<u>Methodology</u>

- Centrifuge tests conducted at a scaling factor of N=80 times gravity (80g)
  - dimensions scaled down by factor N compared to a full-scale prototype
  - Time of centrifuge test reduced by factor N^2 compared to full-scale prototype
    - 6 months of full-scale prototype can me modelled in 41 minutes in the centrifuge



Full-scale prototype time ~5 years

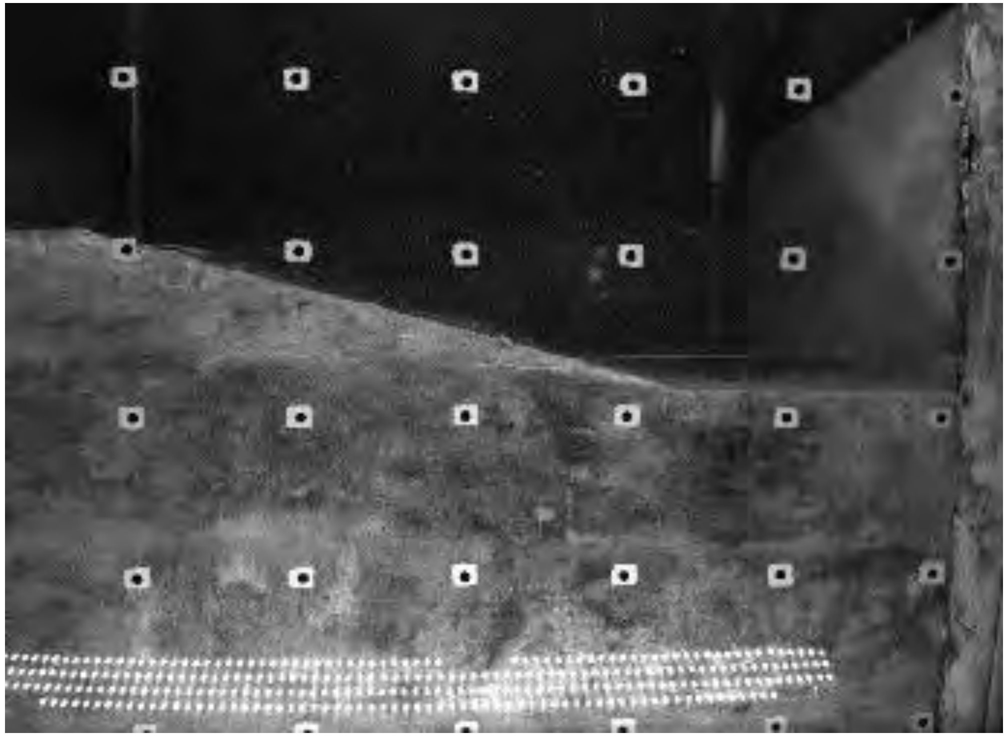
Model-scale time 0 45 90 135 180 225 270 315 360 405 ~7 hours

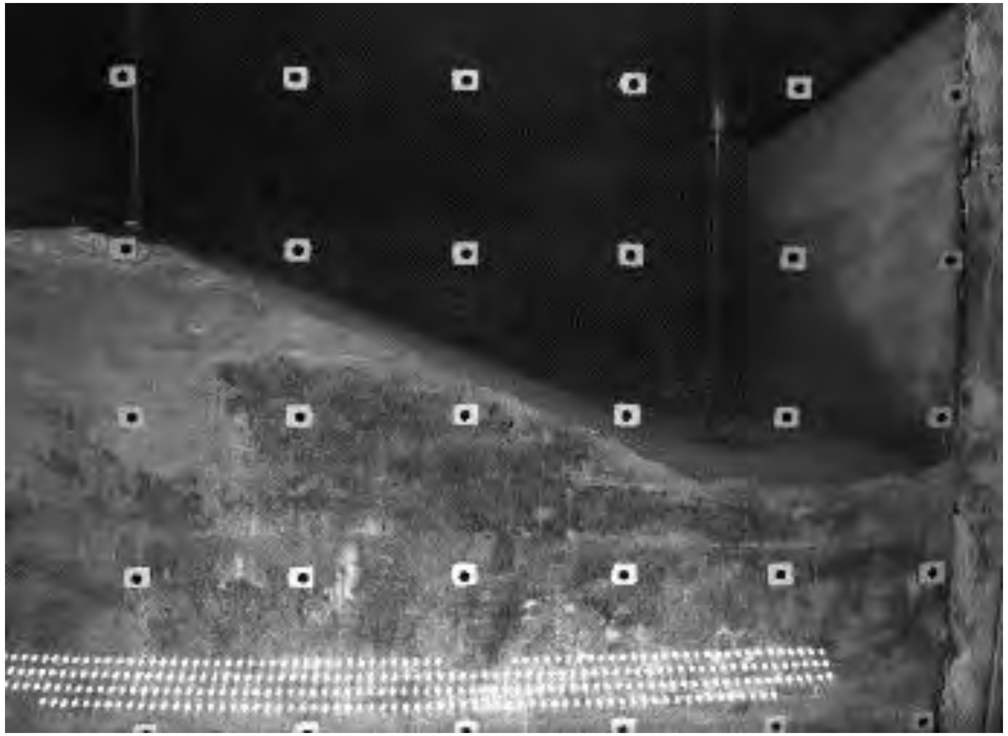
Time (minutes)

Option 1 – Use of mine spoils for pit lakes - RAFF

<u>Methodology</u>

- Two slope geometries:
  - 15 degrees
  - 24 degrees

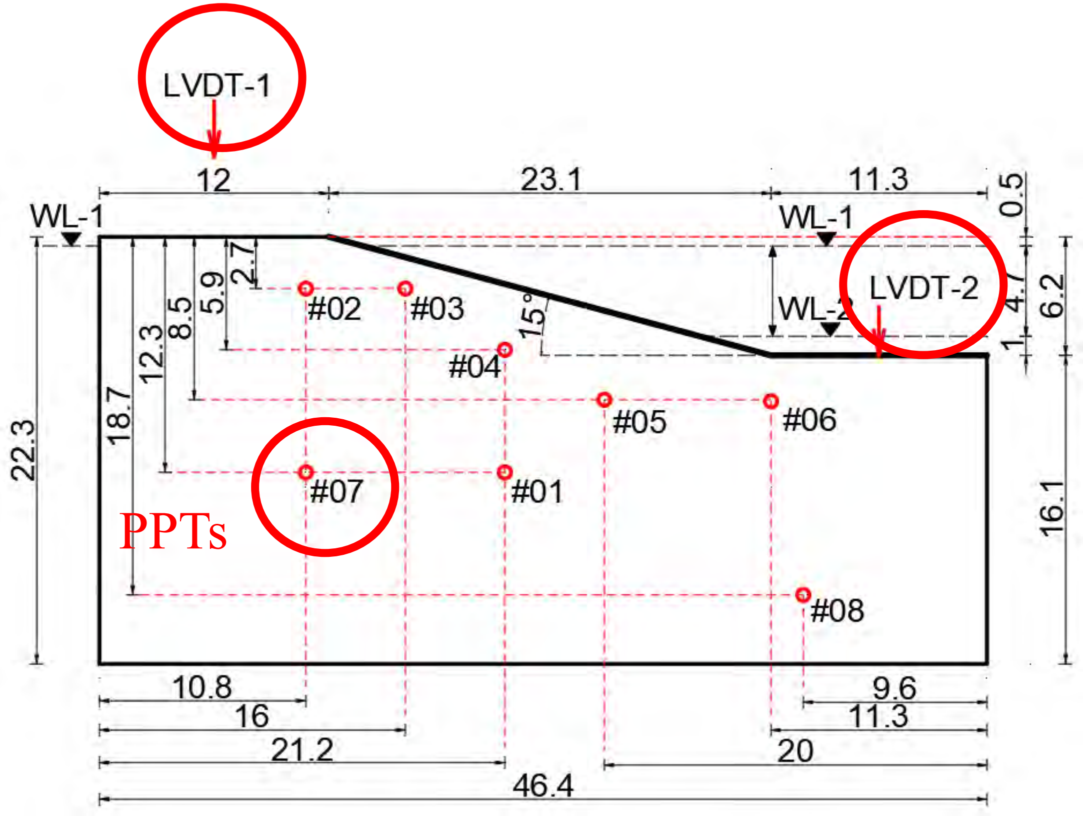


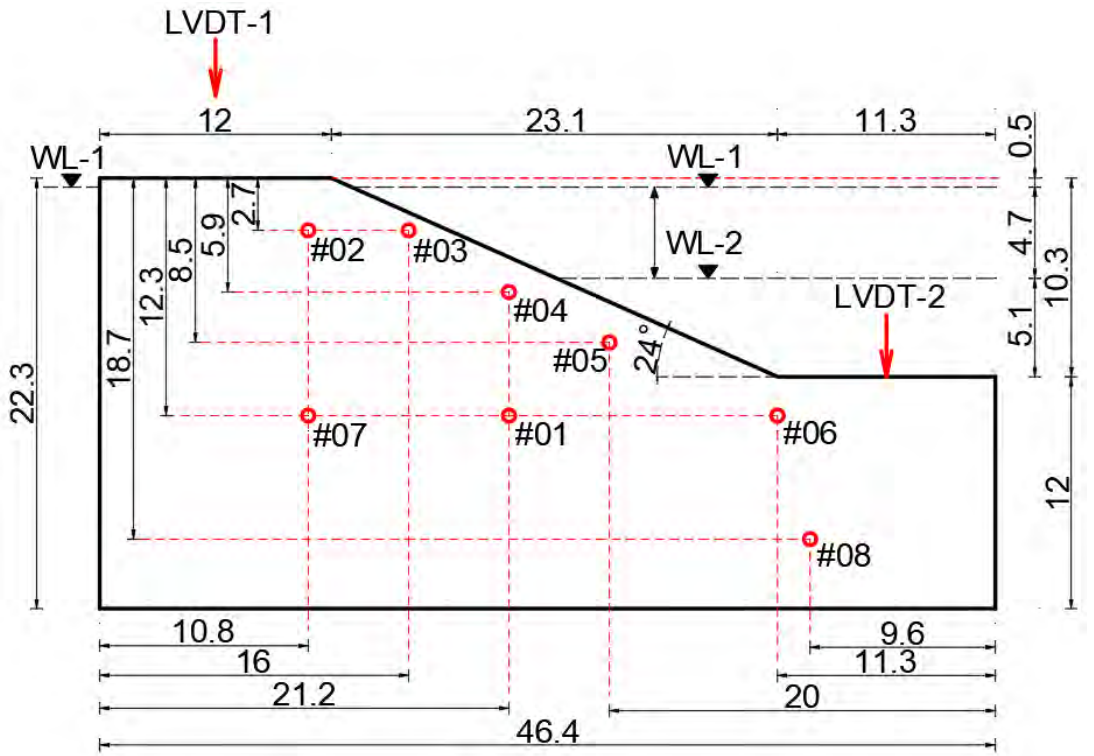


Option 1 – Use of mine spoils for pit lakes - RAFF

Instrumentation

- PPTs to measure pore water pressure within the soil
- LVDTs to measure displacements at discrete locations: crest and toe

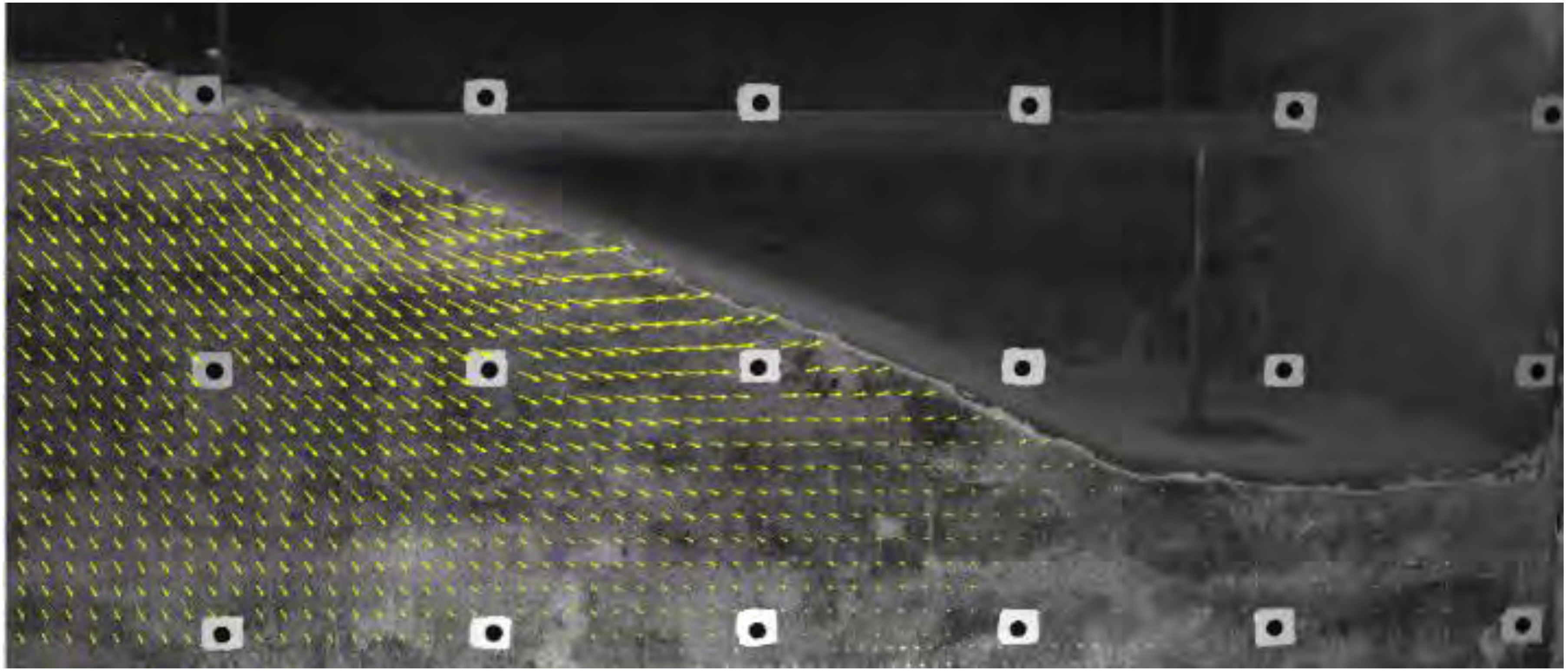




Option 1 – Use of mine spoils for pit lakes - RAFF

Instrumentation

- Image analysis to measure full displacement field at transparent front wall of centrifuge container

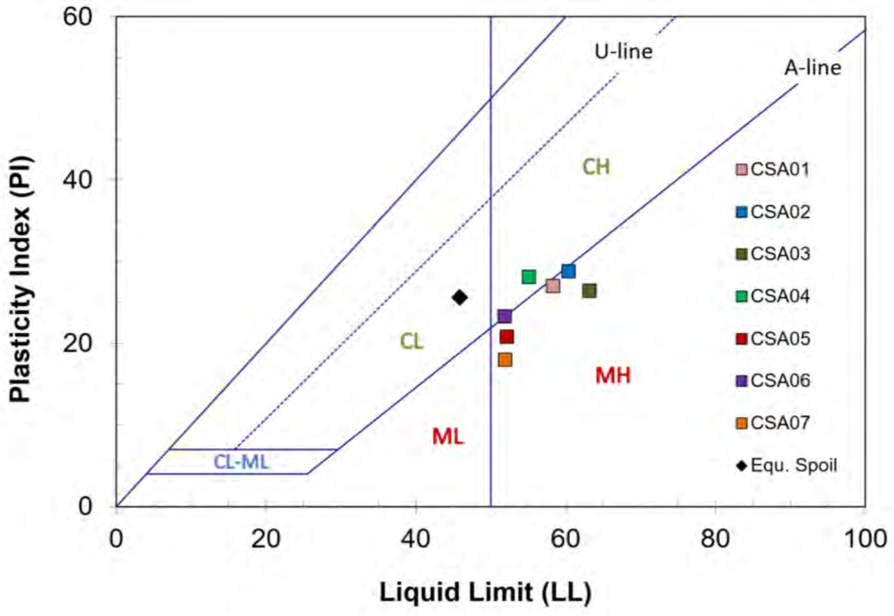


Option 1 – Use of mine spoils for pit lakes - RAFF

Equivalent spoil

- Centrifuge models used an equivalent spoil material
  - Needed a consistent material (i.e. could not use real spoils) to achieve repeatable and reliable experiments
  - 50% silt + 30% bentonite + 20% kaolin mixture
  - Developed to replicate the physical and mechanical characteristics of spoil materials obtained from spoil heap sites near Lake Most in the Czech Republic.

Geotechnical Property	Value
Specific gravity, G_s	2.52
Sand fraction (%)	0
Silt fraction (%)	50
Clay fraction (%)	50
Liquid limit, LL (%)	46
Plasticity index, PI (%)	25.6
Compression index, C_c	0.545
Recompression index, C_r	0.07
Effective friction angle, φ' (degrees)	28
Undrained shear strength, (kPa)	26
Air entry value, AEV (kPa)	280 (drying curve), 130 (wetting curve)

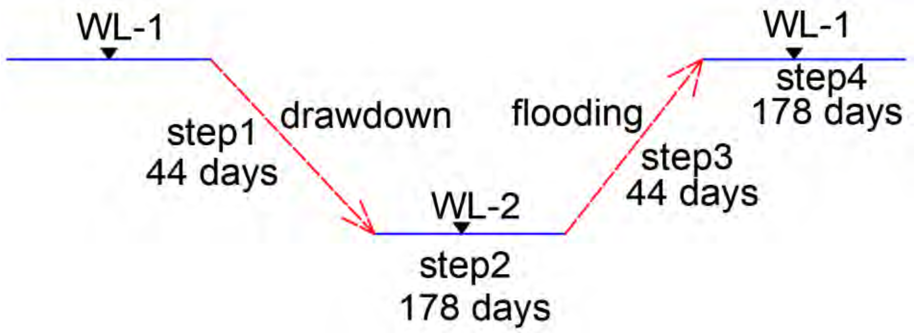


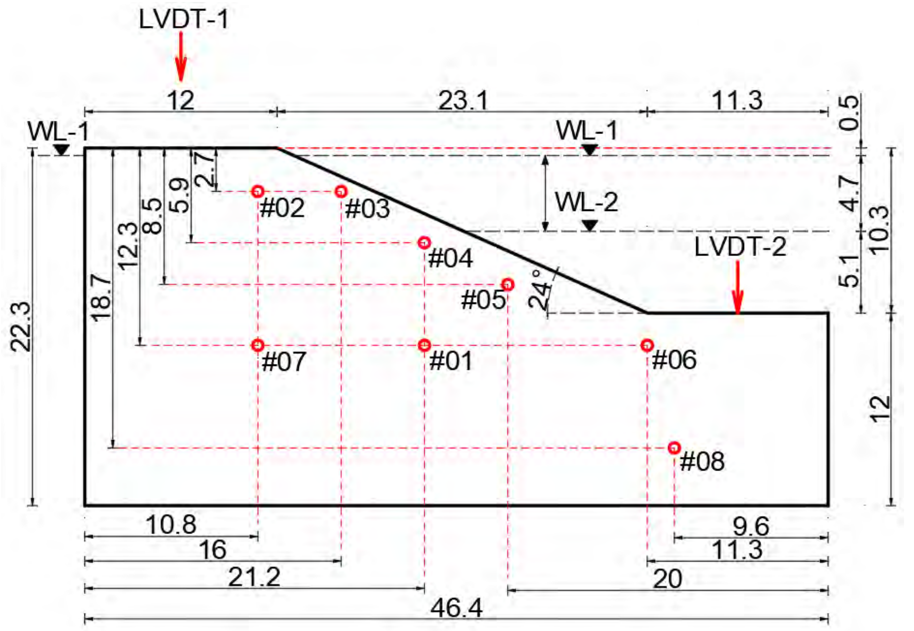
Data from testing of samples from CSA Open Pit mine

Option 1 – Use of mine spoils for pit lakes - RAFF

<u>Modelling process</u>

- Water level varied between water level 1 (WL-1) and water level 2 (WL-2)
- Water level fluctuation cycle (full-scale prototype times)
  - Reduce water from WL-1 to WL-2 (4.7 meters drawdown) within approximately 44 days
  - maintain at WL-2 for 178 days (half a year)
  - increase from WL-2 to WL-1 (4.7 meters flooding) within 44 days
  - Maintain at WL-1 for half a year.
- Water level on the left side of the slope maintained at WL-1 throughout.
- For the 15° slope, four water level fluctuation cycles were carried out while five water level fluctuation cycles were performed on the 24° slope





Option 1 – Use of mine spoils for pit lakes - RAFF

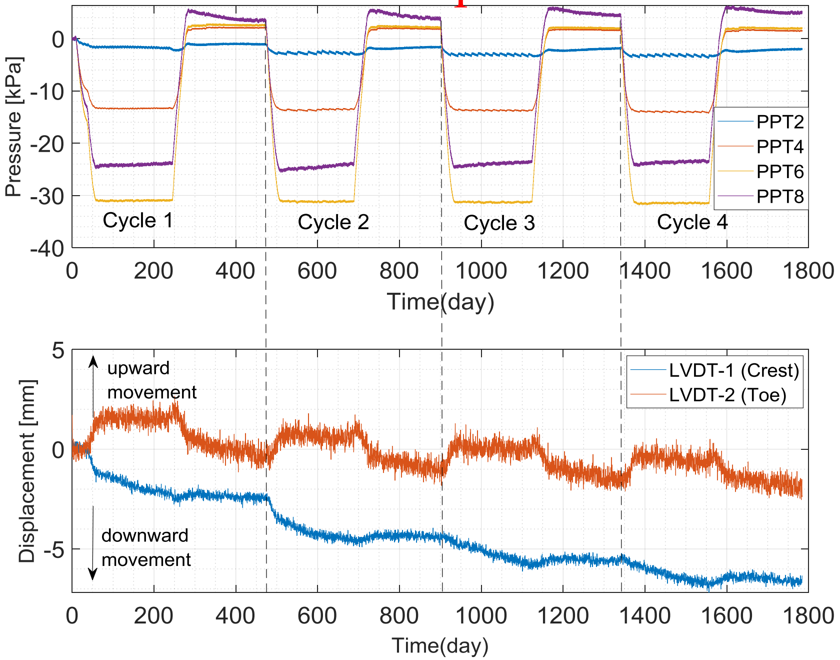
Results - PPTs and LVDTs

- Pore pressures remain relatively stable while water levels are constant
- Ratcheting (upwards/downwards) movement of the crest and toe during seasonal water level fluctuations
- Settlement magnitude at crest increases with each seasonal fluctuation (seasonal increment decreases)
    - 15^{o} slope: cycle 1=2.5mm 1; cycle 2=4.5mm; cycle 3=5.5mm; cycle 4=6.5mm
    - Similar values for 24^{o} slope
- No evidence of collapse

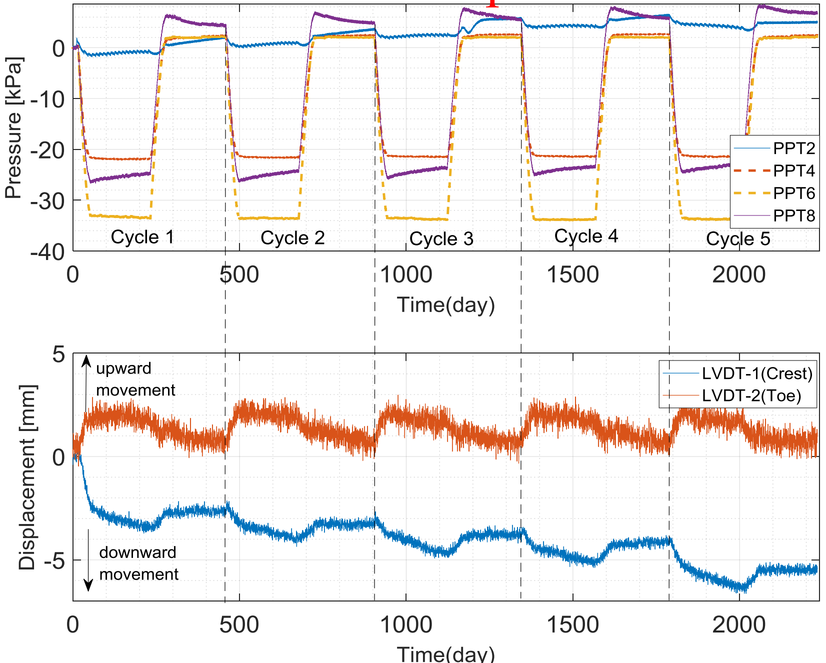
Pore pressures

Displacements

15^{o} slope



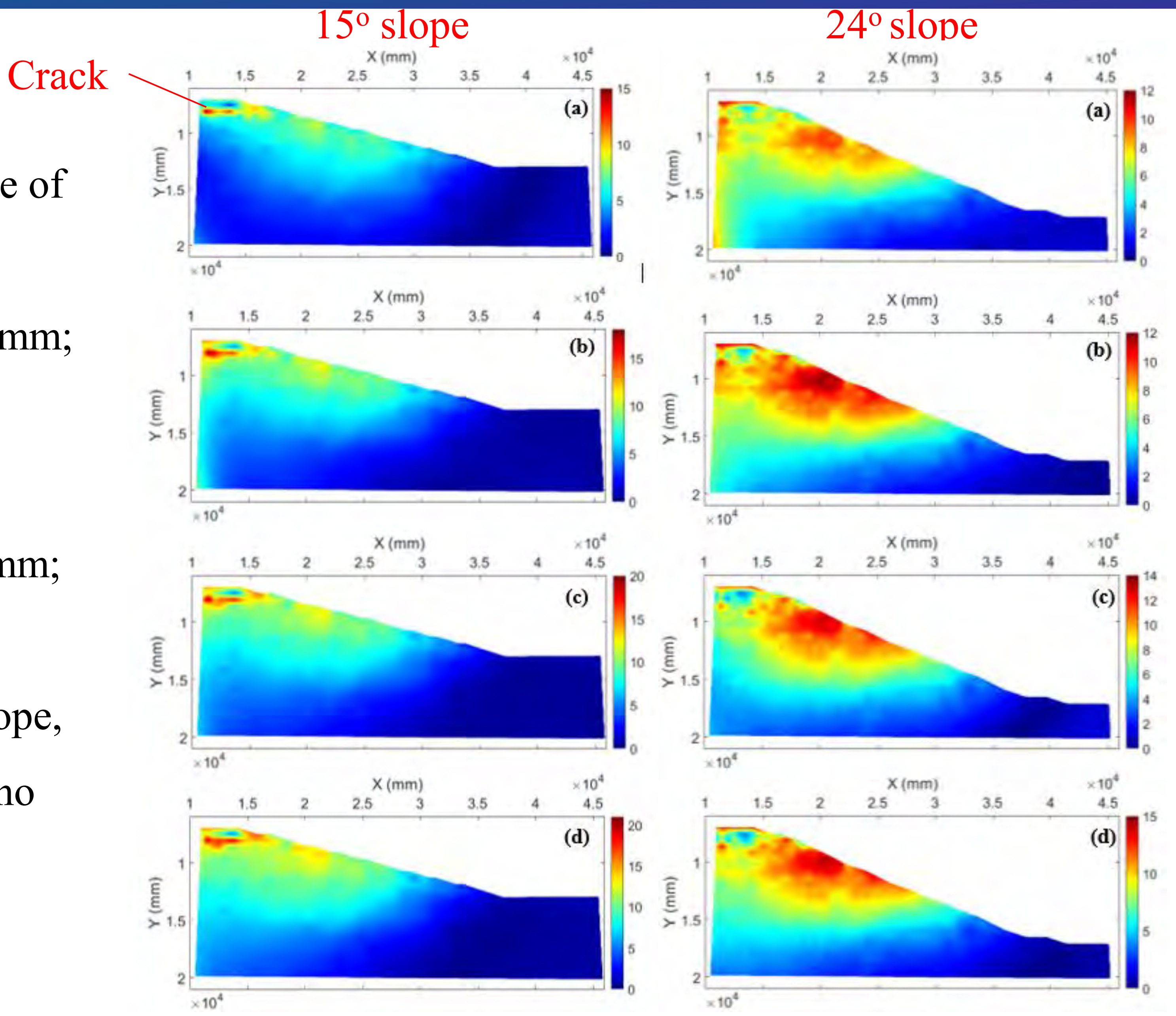
24^{o} slope



Option 1 – Use of mine spoils for pit lakes - RAFF

<u>Results – Image analysis</u>

- Largest displacements localised near middle of the slope
  - 15° slope: cycle 1=7mm 1; cycle 2=11mm; cycle 3=12mm; cycle 4=14mm
  - 24° slope: cycle 1=10mm 1; cycle 2=12mm; cycle 3=13mm; cycle 4=15mm; cycle 5=16mm
- Slightly larger displacements for steeper slope, involving larger area of soil mass, but still no indication of collapse



Option 1 – Use of mine spoils for pit lakes - RAFF

Conclusions: Option 1 – Use of mine spoils for pit lakes - RAFF

- Physical modelling with a geotechnical centrifuge is a viable option for studying the stability and serviceability of spoil slopes as they are affected by environmental factors.
- A replica spoil was developed that could effectively capture the characteristics of real spoil materials containing high levels of mid-high plasticity fines.
    - This introduced significant challenges in terms of timescales for sample preparation and testing.
- Ratcheting mechanisms (upwards/downwards movements) were observed and quantified for two slope angles (15^o and 24^o) resulting from seasonal variation of lake water elevation.
- Displacements were relatively low (~7mm during one seasonal cycle); these accumulated with seasonal cycle, reaching 16mm for the 24^o slope after 5 seasonal cycles.
    - Incremental accumulated displacement per cycle stabilised at about 1mm/season
    - No evidence of collapse in these tests
- Longer duration tests could be achieved – technical challenges prohibited longer tests during this project.

Option 2 – Wind turbines on mine spoils - SUMAD

Option 2: Installation of wind turbines on mine spoils heaps (SUMAD project)

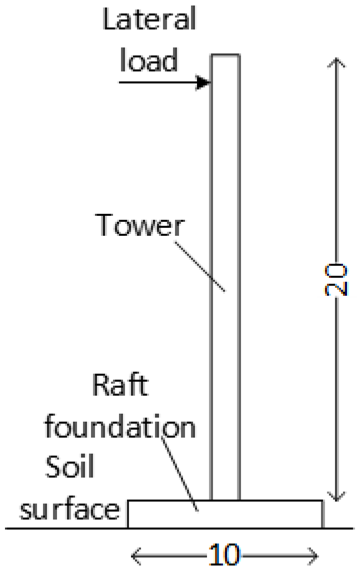
- Specific challenge: long-term response of spoil-foundation systems on mid-high plasticity spoils, including
  - long-term cyclic loading of the foundation system, and
  - climatic condition variations (change in ground water level – affecting effective stresses in soil)

Image source: windeurope.org

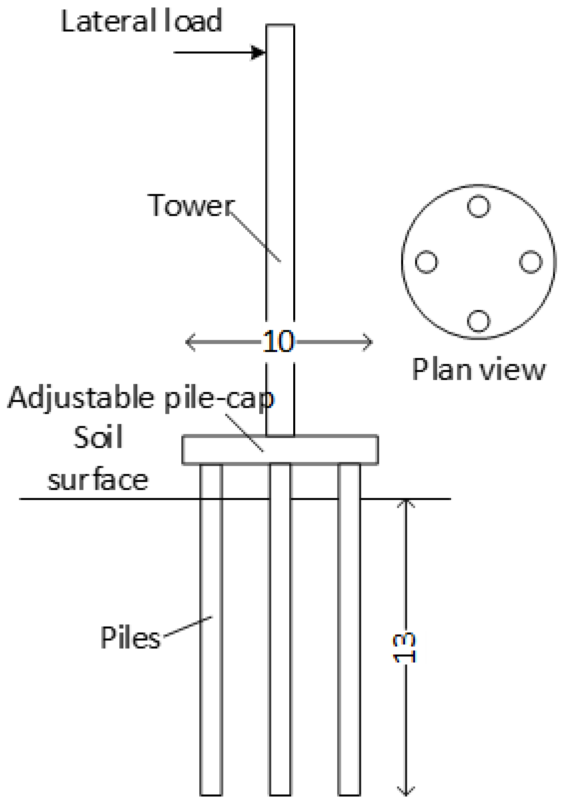
Option 2 – Wind turbines on mine spoils - SUMAD

<u>Methodology</u>

- 3 feasible wind turbine foundation designs considered:
  - Raft, pile-group, pile-raft
- Foundation designs conducted according to standard methods
- Centrifuge tests conducted of the designed foundation systems
  - Centrifuge scaling factor of N=65 times gravity (65g)
  - dimensions scaled down by factor N compared to a full-scale prototype
- Used same equivalent spoil material as previously described



Raft



Pile-group
(pile-raft when raft in contact with soil)

Full-scale dimensions in m

Option 2 – Wind turbines on mine spoils - SUMAD

<u>Test plan</u>

- 8 tests conducted
- For piles, four holes corresponding to the pile locations were first excavated, followed by insertion of the piles.
- Pile-group and pile-raft experiments conducted using same foundation model and same spoil sample.
  - Pile-cap fabricated so it could be lowered and put in contact with the soil surface for the pile-raft foundation experiment.
- Tests parameters included:
  - Max cyclic load
  - Ground water elevation: at ground level GL and below ground level BGL
- Loading frequency sufficiently high for undrained soil response

Table 2. Experimental plan for centrifuge testing foundation systems

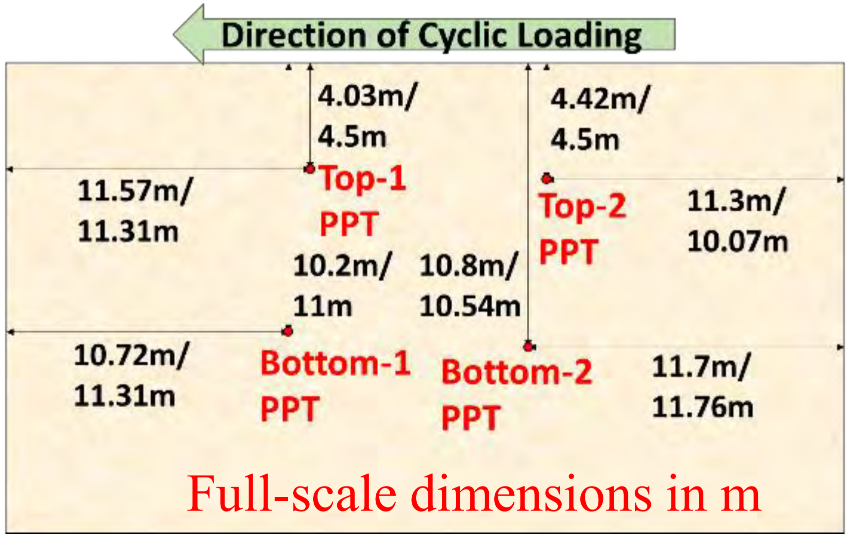
Foun. Type	Exp No	Water Table[a]	Max. Cyclic Load (kN)	N[b]	f (Hz)
Raft	1	GL	87	1000	0.2
	2	GL	171	210	0.1
	3	7.5m BGL	87	1000	0.2
	4	7.5m BGL	171	175	0.1
	5	7.5m BGL	460	5	0.02
Pile-Group	6	GL	501	980	0.06
	7	6m BGL	501	350	0.06
Pile-Raft	8	GL	501	930	0.06

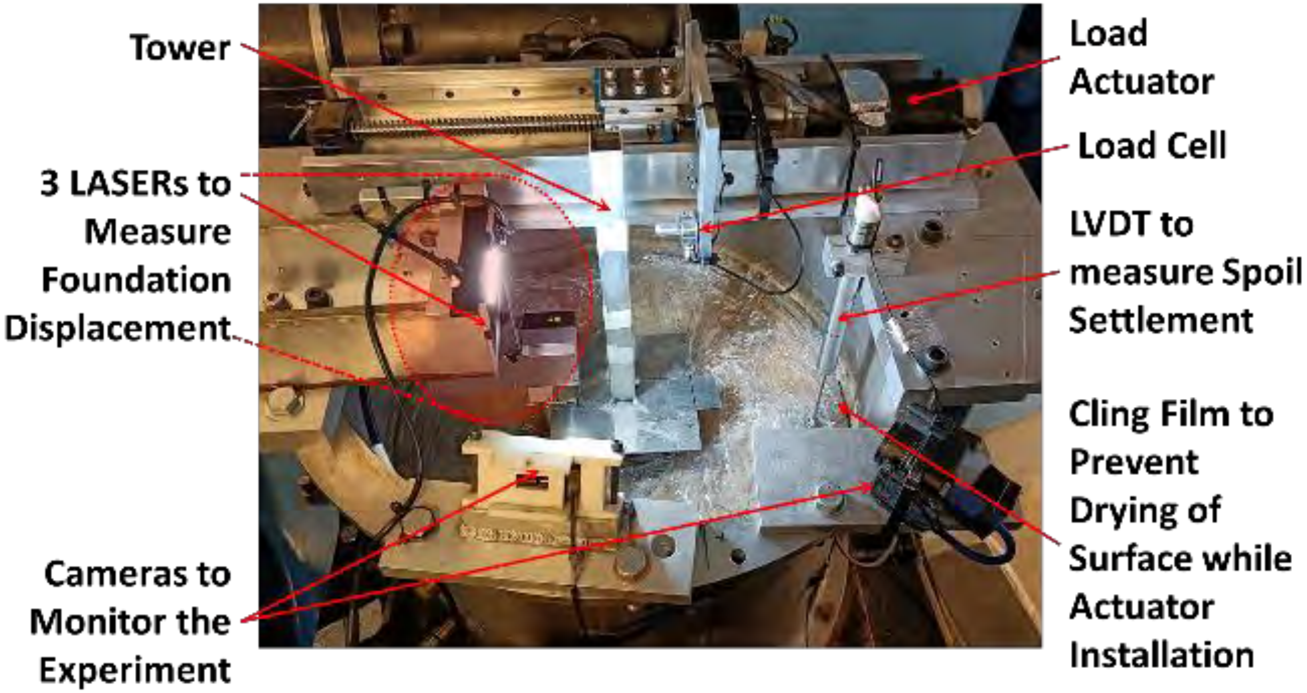
Notes: [a]GL = at ground level, BGL = below ground level; [b]N = maximum number of cycles

Option 2 – Wind turbines on mine spoils - SUMAD

Model layout and instrumentation

- Pore pressure transducers used to measure pore water pressure in soil beneath the foundations
- LVDT used to measure soil settlement (to assess degree of consolidation)
- Lasers used to measure tower horizontal and vertical movements (to calculate rotation)
- Load actuator used to cyclically load tower, with load cell installed to measure loads





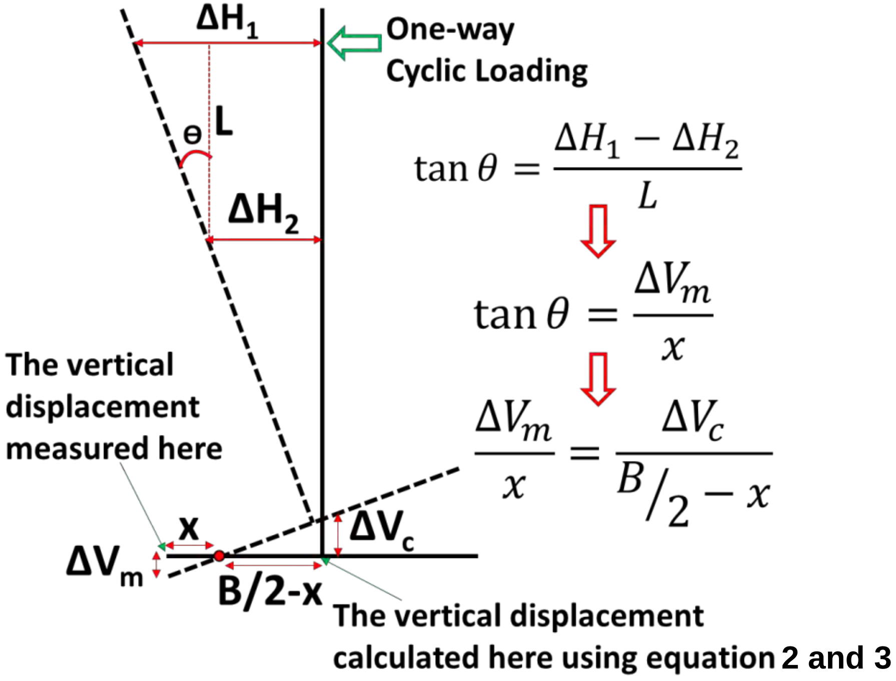
Option 2 – Wind turbines on mine spoils - SUMAD

<u>Results</u>

- Focus on moment-rotation and load-displacement data
- Moment at centre of foundation base = force x distance of load application above ground level
- Rotation θ determined from laser data

$$\theta = \tan^{-1}\left(\frac{\Delta H_1 - \Delta H_2}{L}\right)$$

- Vertical displacement measured at side of foundation and calculated at centre of foundation base



Option 2 – Wind turbines on mine spoils - SUMAD

Results – cyclic loading

- Water table at ground level: Exp 1 and 2
  - Max rotation = ~0.07° for 87 kN (Exp=1) and ~0.1° for 171 kN (Exp=2).
  - Predominately elastic for both loading conditions: rotation was reversible for each cycle.
  - Results expected as this loading intensity is based on the serviceability limit state.
  - Indicate low degradation of cyclic stiffness of the spoil material.

Indicates good performance of foundation system under expected serviceability level loads.

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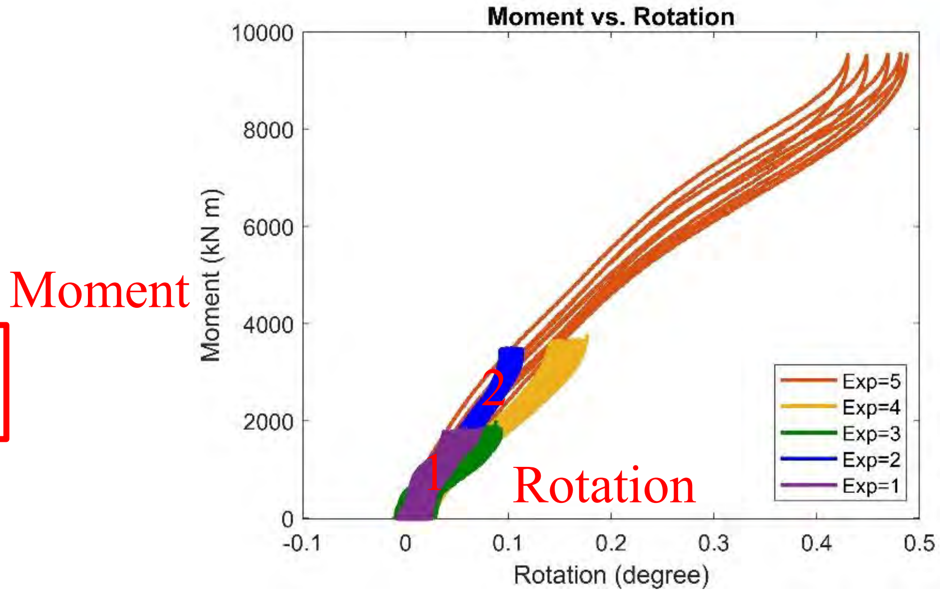
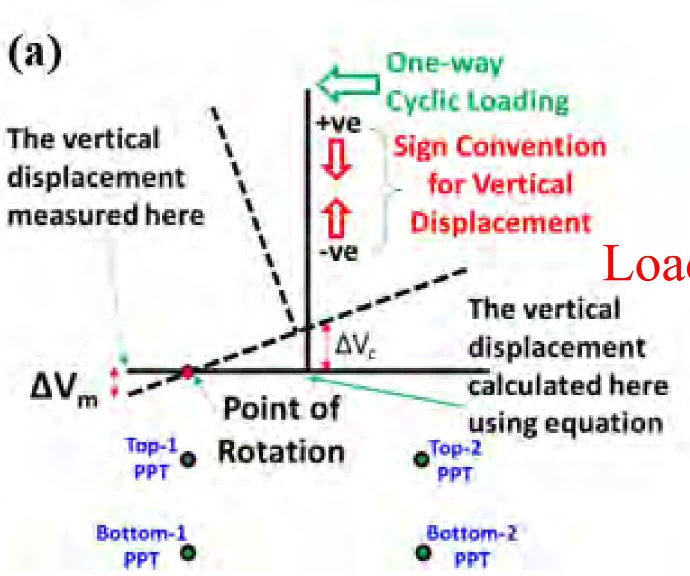
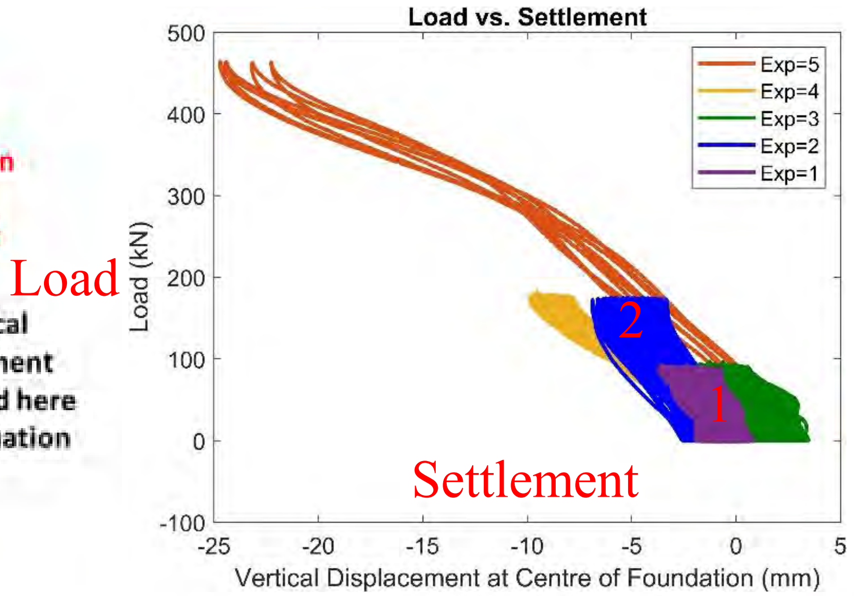


Option 2 – Wind turbines on mine spoils - SUMAD

Results – cyclic loading

- Water table at ground level: Exp 1 and 2
  - Max vertical displacement = -3mm for 87 kN (Exp=1) and -6mm for 171 kN (Exp=2).
  - Upwards displacements at foundation centre due to point of rotation of foundation.
  - Minimal residual settlements of -0.5mm and -1.7mm for 87kN and 171kN loading cases.





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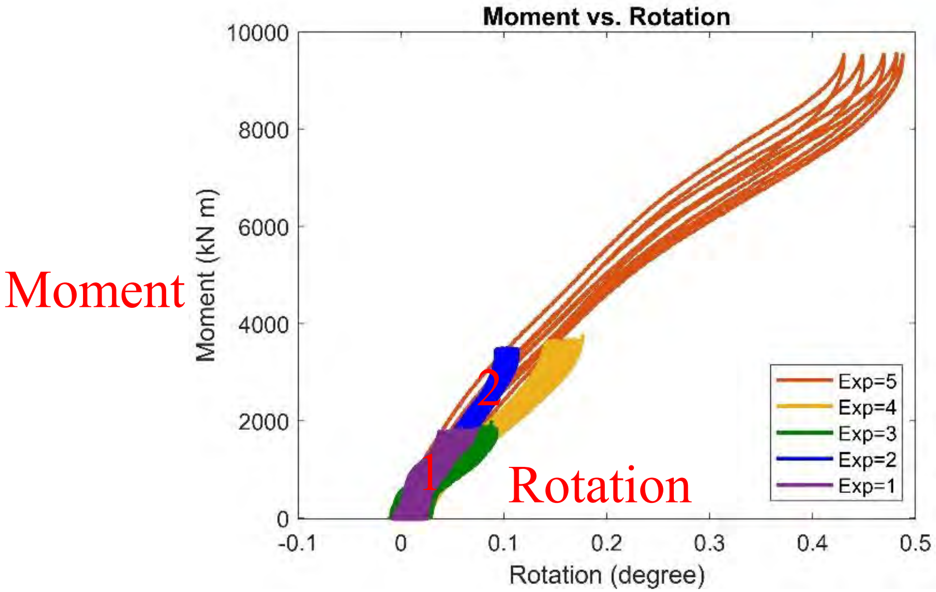
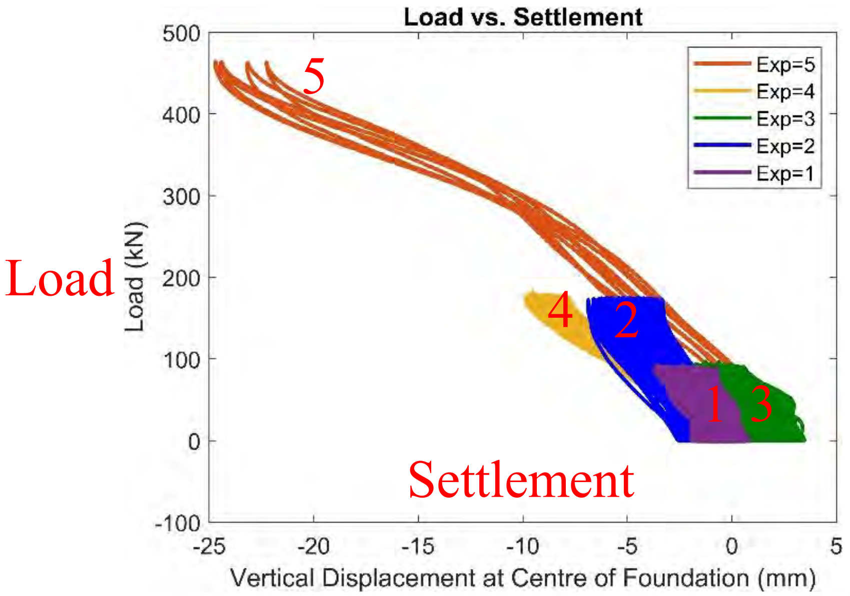
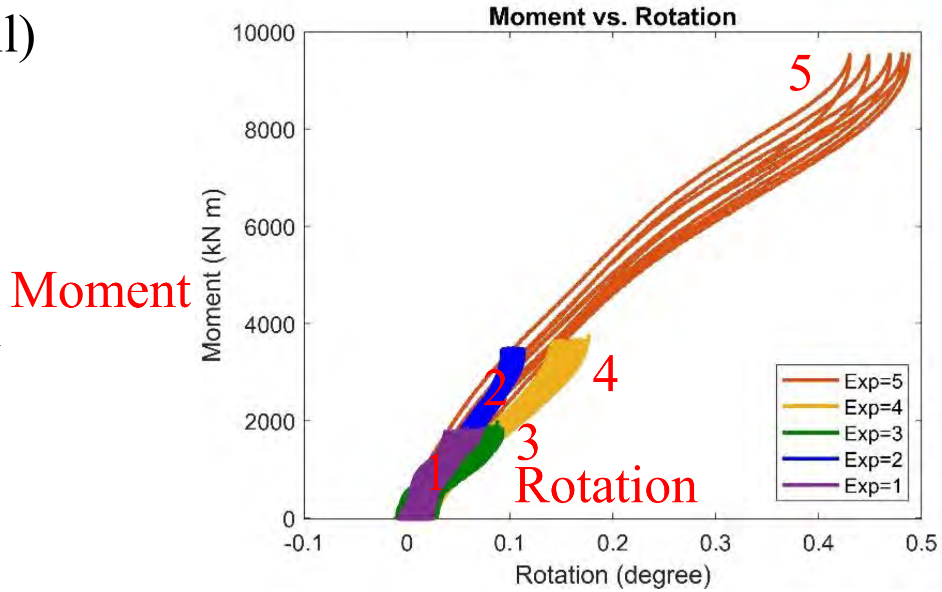


Option 2 – Wind turbines on mine spoils - SUMAD

Results – cyclic loading: raft foundation

- Water below ground level: Exps 3-5:
  - Max rotation = ~0.09° for 87 kN (Exp=3), ~0.17° for 171 kN (Exp=4), and 0.48° for 460kN (Exp5).
  - Predominately elastic for lower loading cases (Exp 3 and 4)
  - Higher accumulation rates for high loading case indicates elasto-plastic response
  - Accumulated rotations: 0.007°, 0.018° and 0.027°
  - Higher rotations likely due to a change in rotational mechanism of foundation due to increased stiffness in Exps 3-4 (unsaturated soil) compared to Exps 1-2 (saturated soil).





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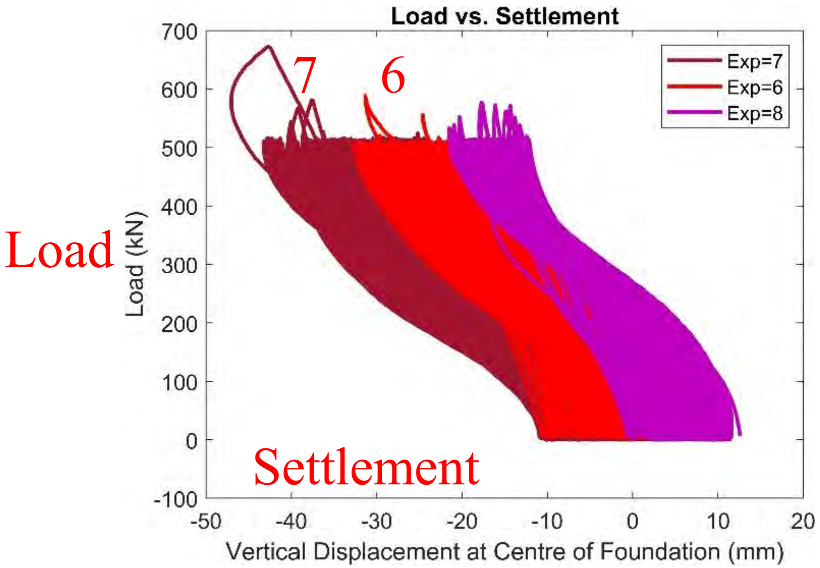
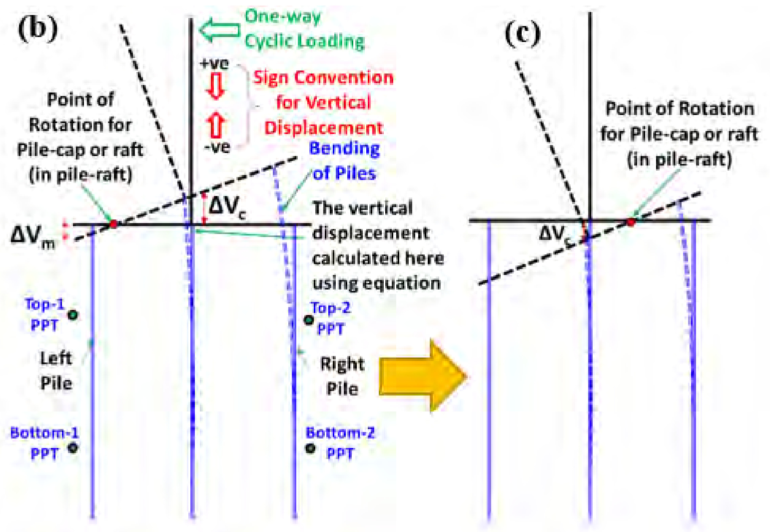
Option 2 – Wind turbines on mine spoils - SUMAD

Results – cyclic loading: pile-group

- Max rotation = ~1° for water at GL Exp 6, ~0.9° for water BGL Exp 7
- Showed considerable accumulated rotations: elasto-plastic soil response
- Rate of increase in foundation rotation was high for the first few cycles (N≈50-60), then progressively decreased.
- Complex history of vertical settlement (moving from initially positive settlement then towards negative uplift) due to movement of point of rotation with load cycle





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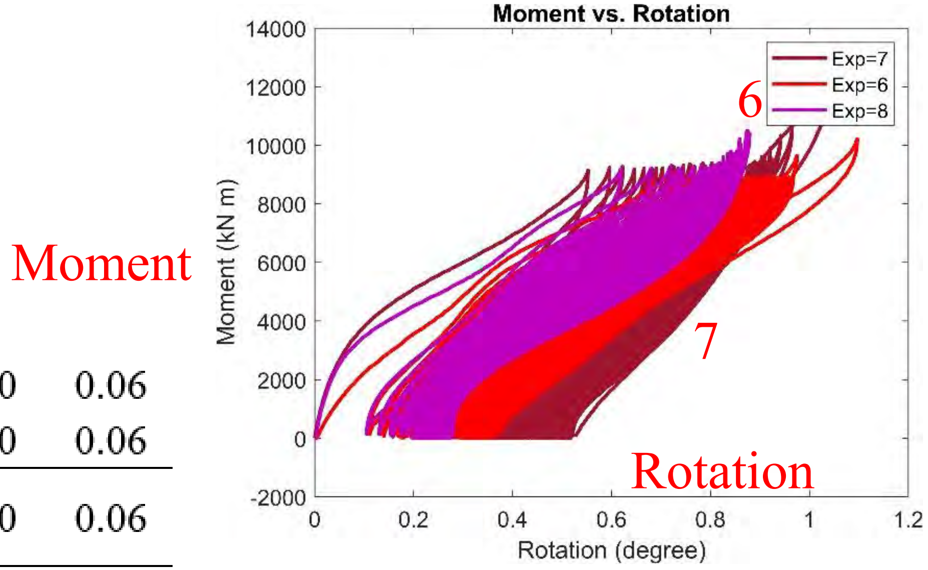

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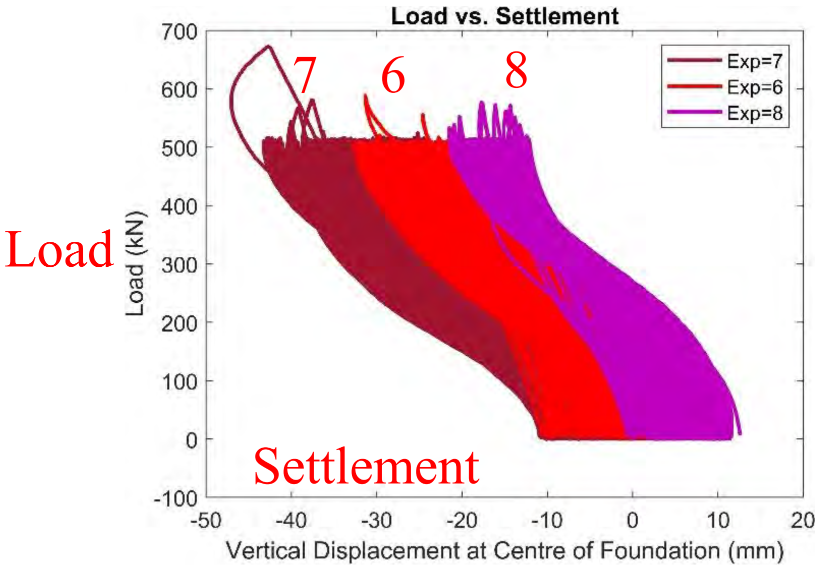
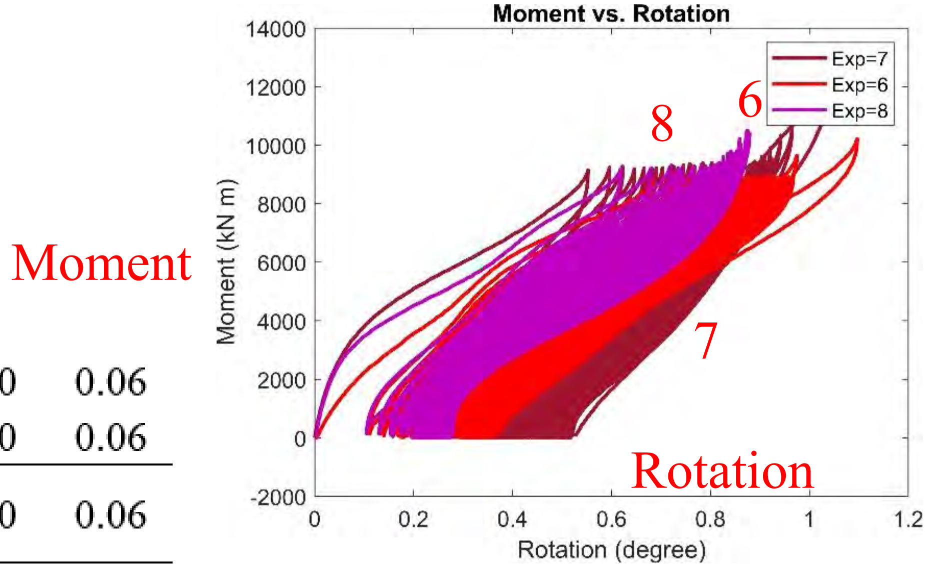
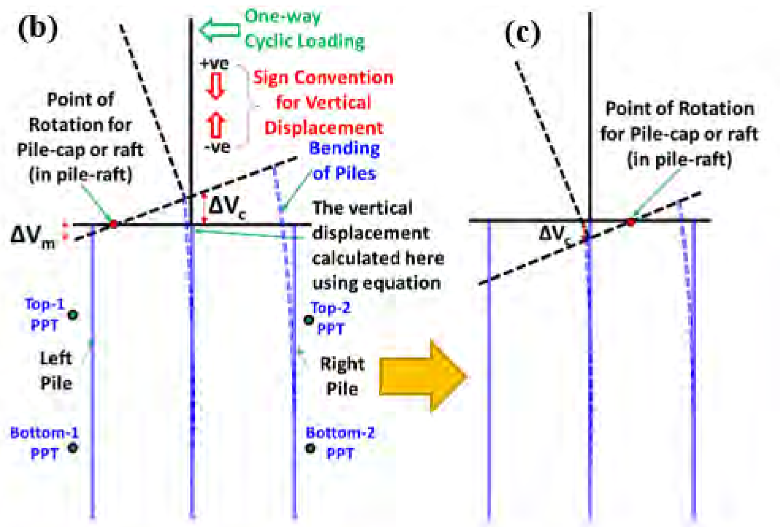
Option 2 – Wind turbines on mine spoils - SUMAD

Results – cyclic loading: pile-raft

- Max rotation = ~0.85° for water at GL Exp 8
- Showed better performance than pile raft







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Option 2 – Wind turbines on mine spoils - SUMAD

Conclusions: Option 2 – Wind turbines on mine spoils - SUMAD

- Physical modelling with a geotechnical centrifuge is a viable option for studying the performance of wind turbine foundations on mine spoil materials
- A replica spoil was developed that could effectively capture the characteristics of real spoil materials containing high levels of mid-high plasticity fines.
    - This introduced significant challenges in terms of timescales for sample preparation and testing.
- The accumulation of foundation rotation and vertical displacements were found to be within acceptable limits for lower lateral loading cases but, at higher loading cases, may be of concern.
- The vertical displacements were greater for partially saturated conditions (lower water table) compared to fully saturated (water table at ground level) – likely a result of a change in rotational mechanism of the foundation due to increased stiffness in unsaturated soil.
- Cyclic stiffness degradation of spoil material under continuous long-term loading led to changes in the deformation pattern and centre of rotation for the cases of deep foundations.
- The experimental data obtained from these centrifuge tests are being used in connection with numerical modelling to better understand results.

Thank you

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