Centrifuge modelling for geotechnical instruction & Visualisation modelling

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Centre for Energy & Infrastructure Ground Research

Sheffield Centrifuge Facilities

CEIGR

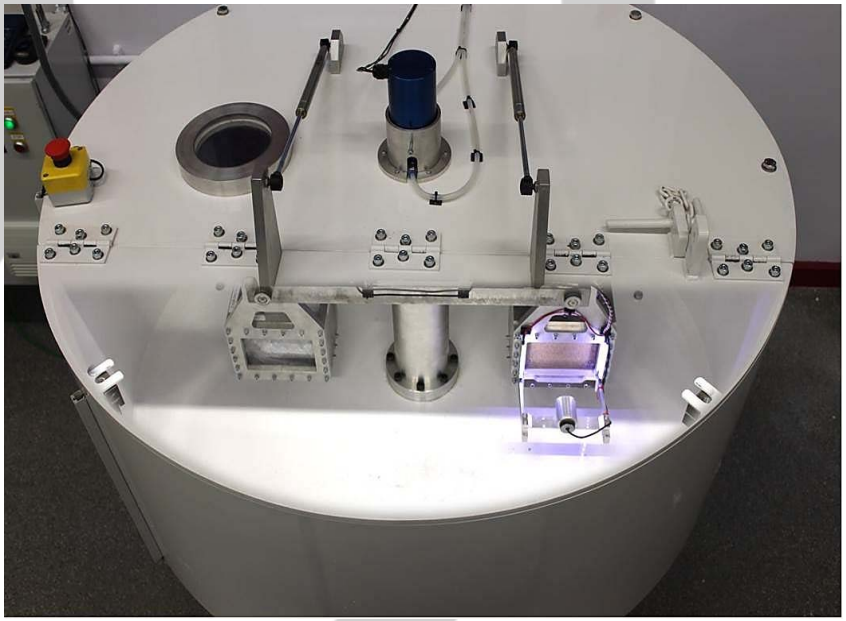
Centre for Energy & Infrastructure Ground Research

2012 – 1m centrifuge commissioned

2014 – £1.2m EPSRC grant to for CEIGR

2015 – 4m centrifuge commissioned

1m diameter



4m diameter – 50gT

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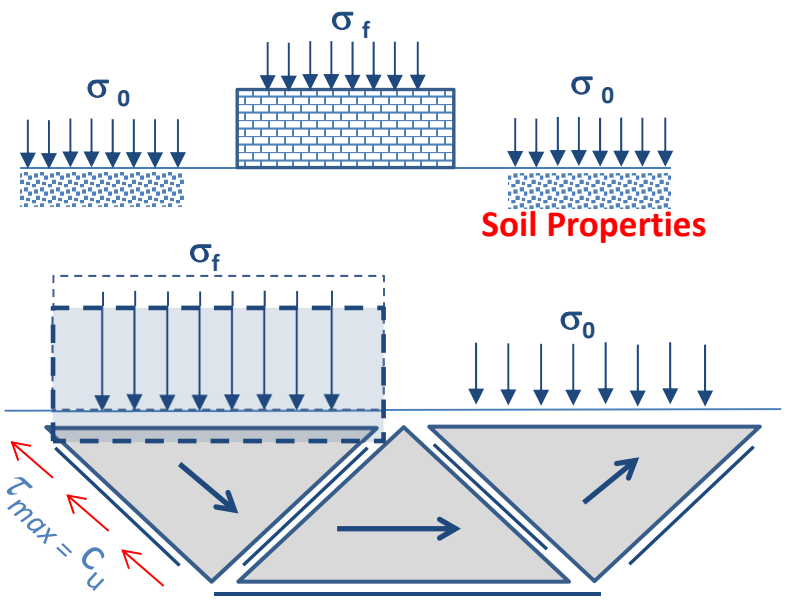
The laboratory is an essential learning environment

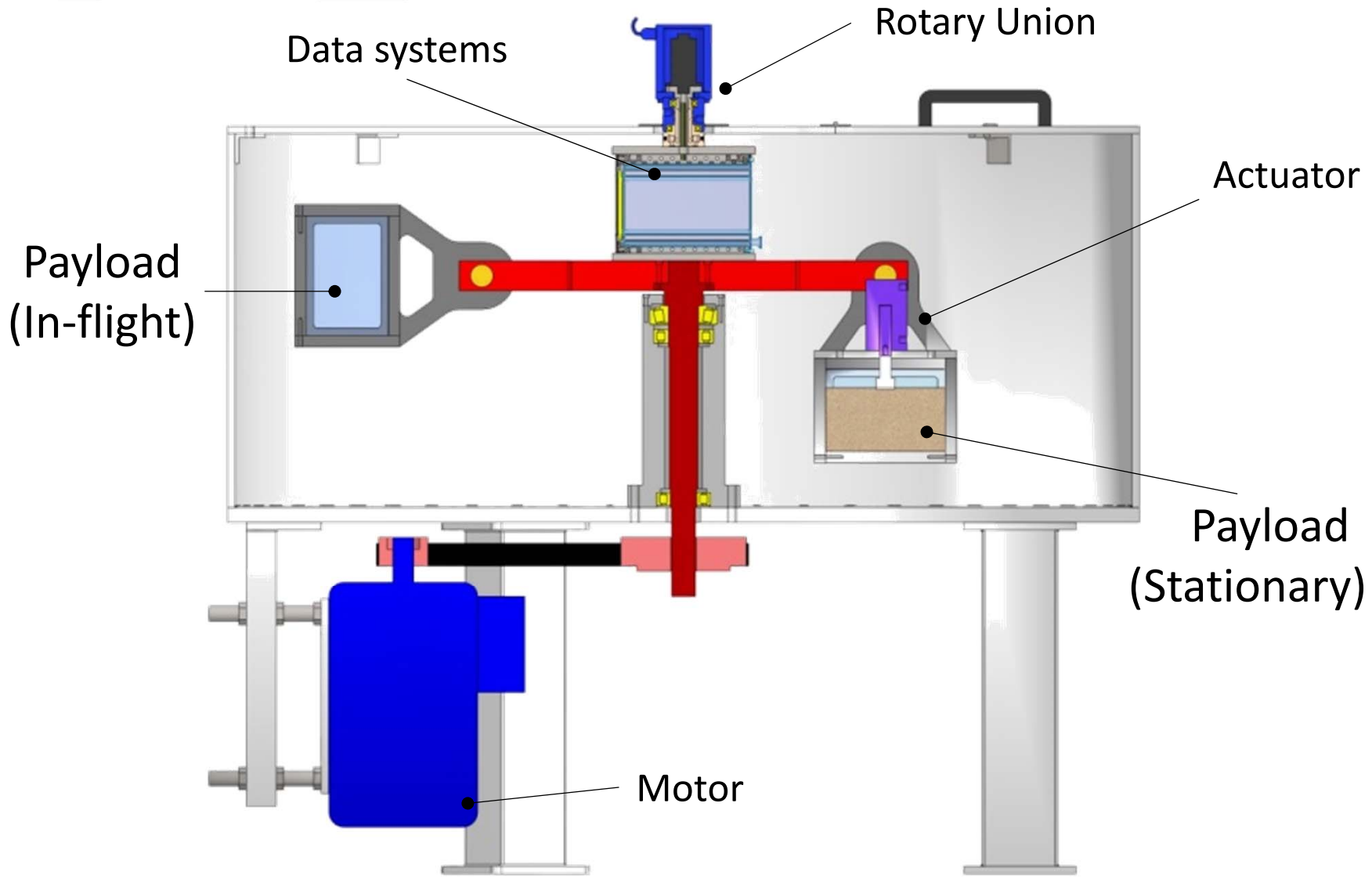
- Understanding of soil as an engineering material
- Reinforce & validate classical soil mechanics theory
- Develop laboratory skills - practical, data collection & appraisal



$$\sigma_f = c_u \cdot N_c + q_0$$

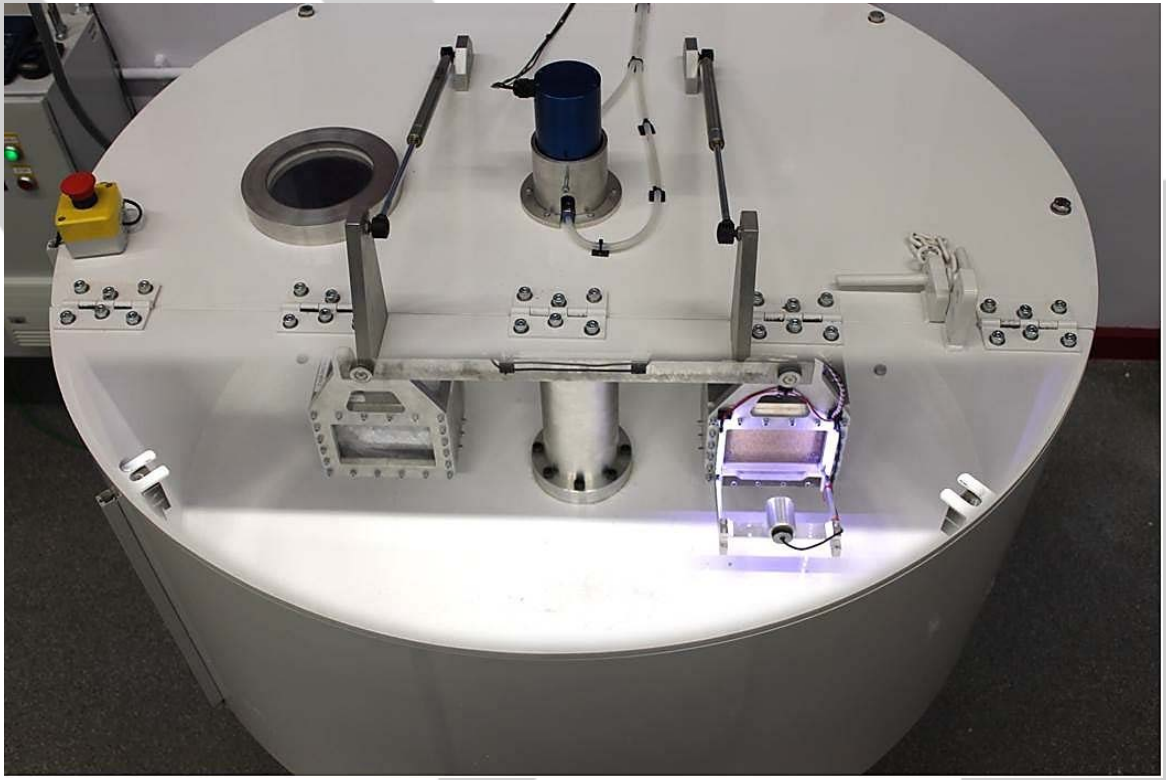
Centrifuge modelling in the UG curriculum

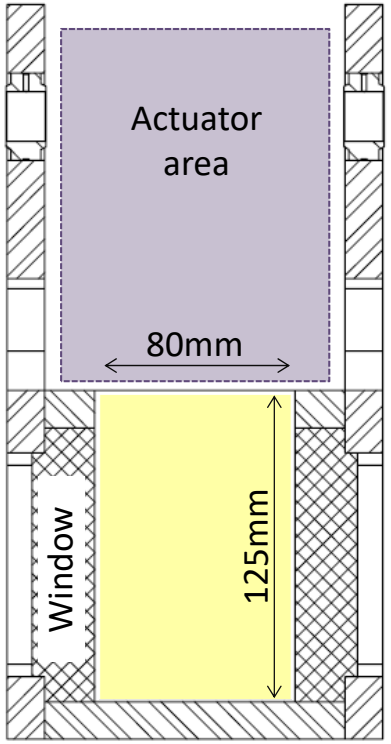
UoS2gT/1.0 educational centrifuge

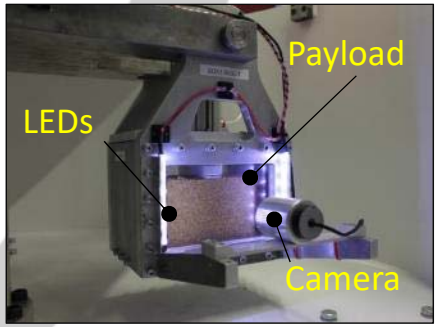


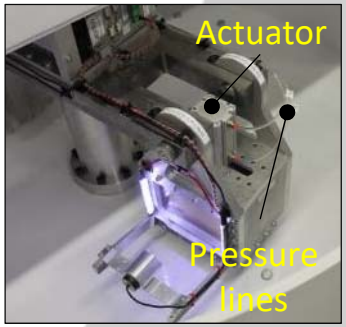
Centrifuge modelling in the UG curriculum

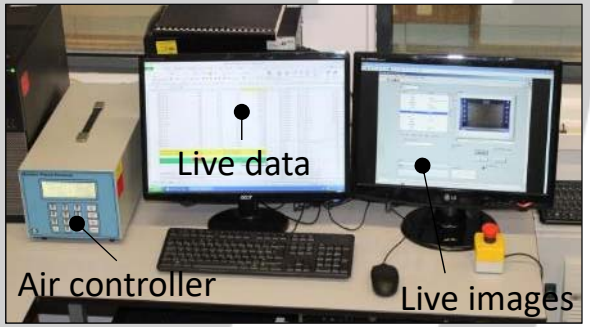
UoS2gt/1.0 teaching centrifuge





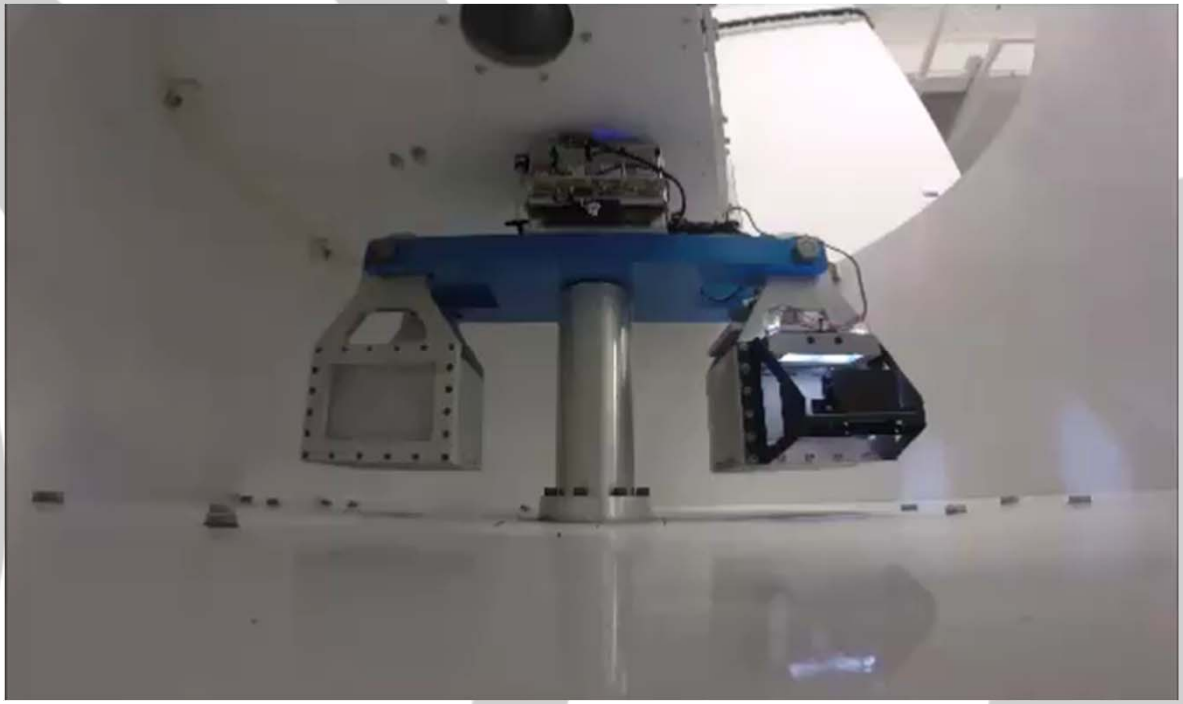


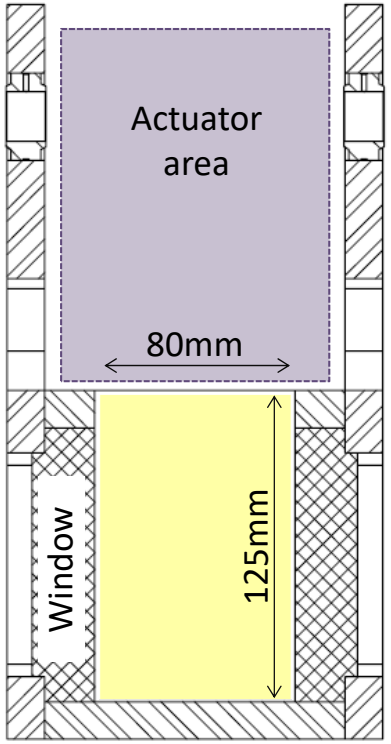


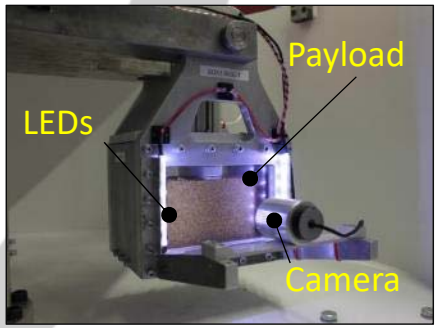


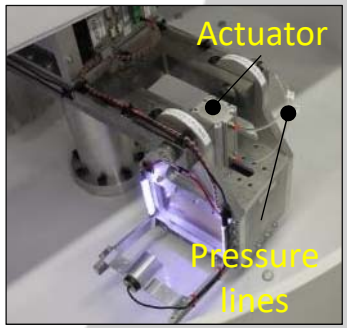
Centrifuge modelling in the UG curriculum

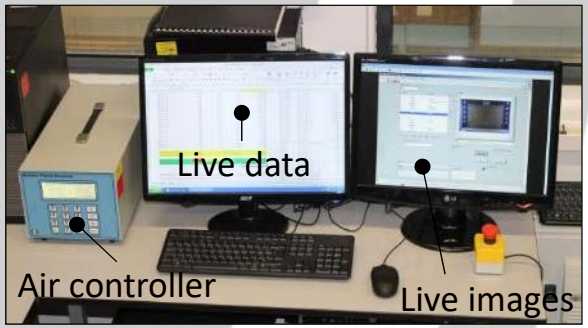
UoS2gt/1.0 teaching centrifuge





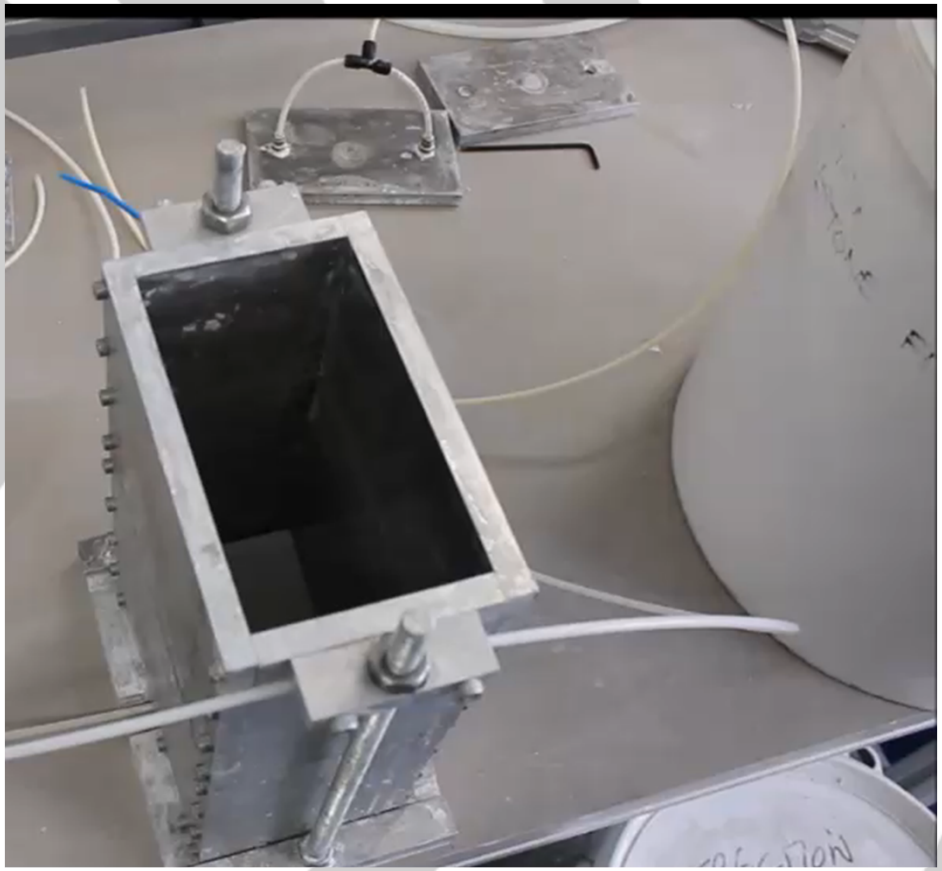






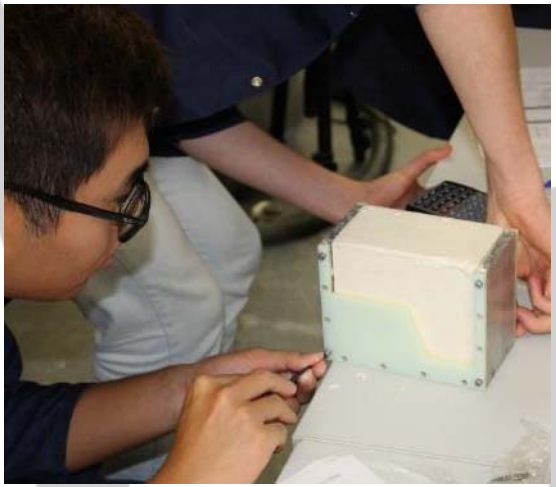
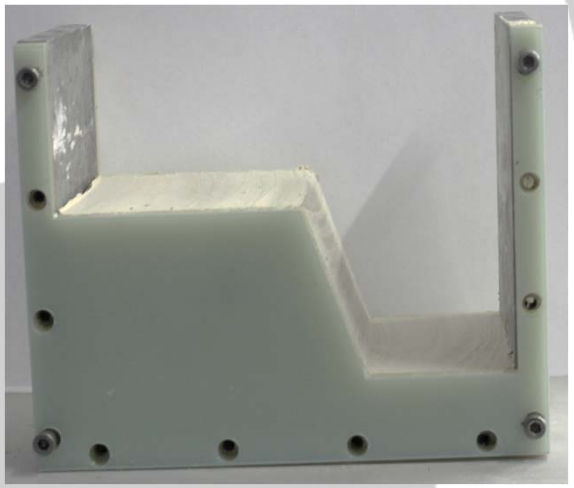
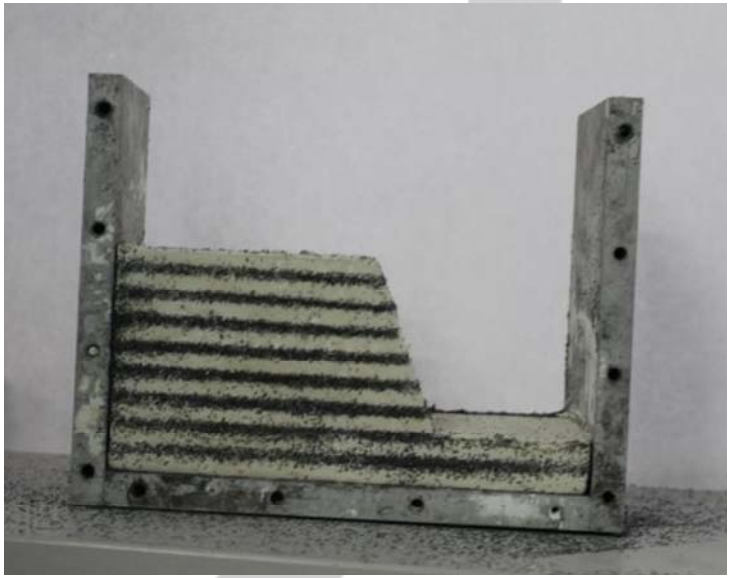
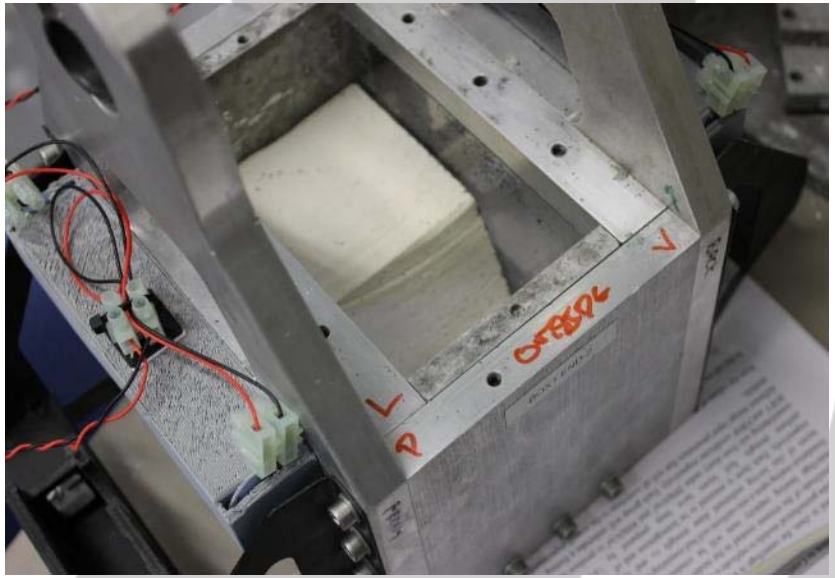
Model preparation

- Multiple samples is vital
- Repeatability important



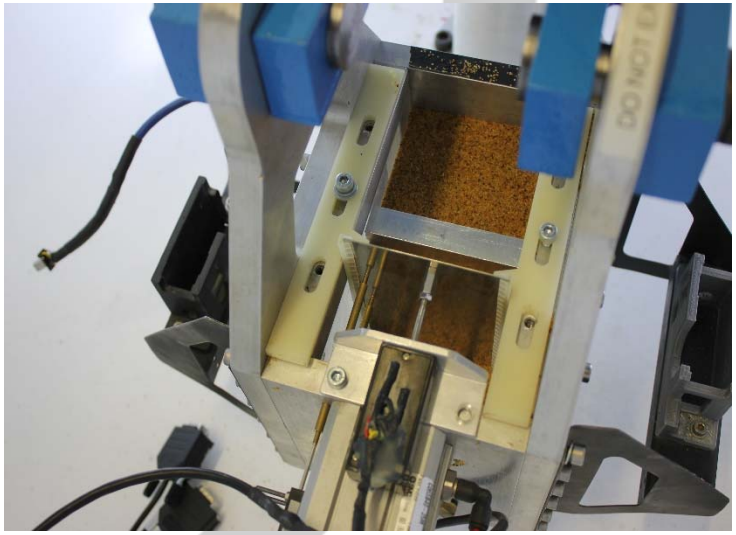
Centrifuge modelling in the UG curriculum

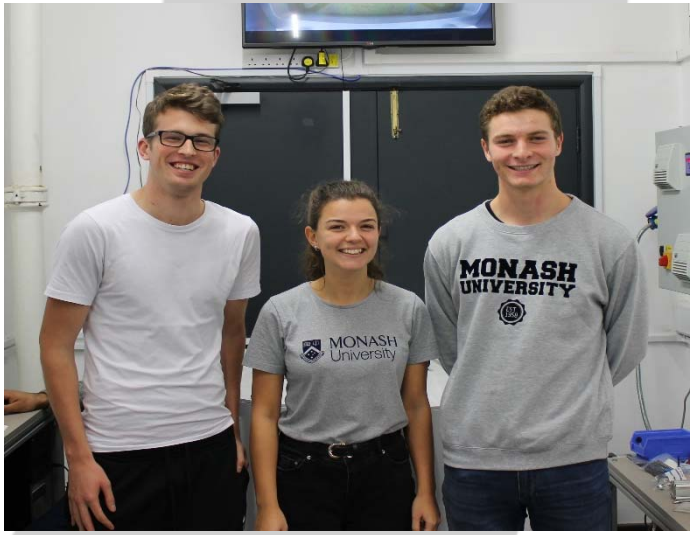
Model preparation

Centrifuge modelling in the UG curriculum

Model preparation





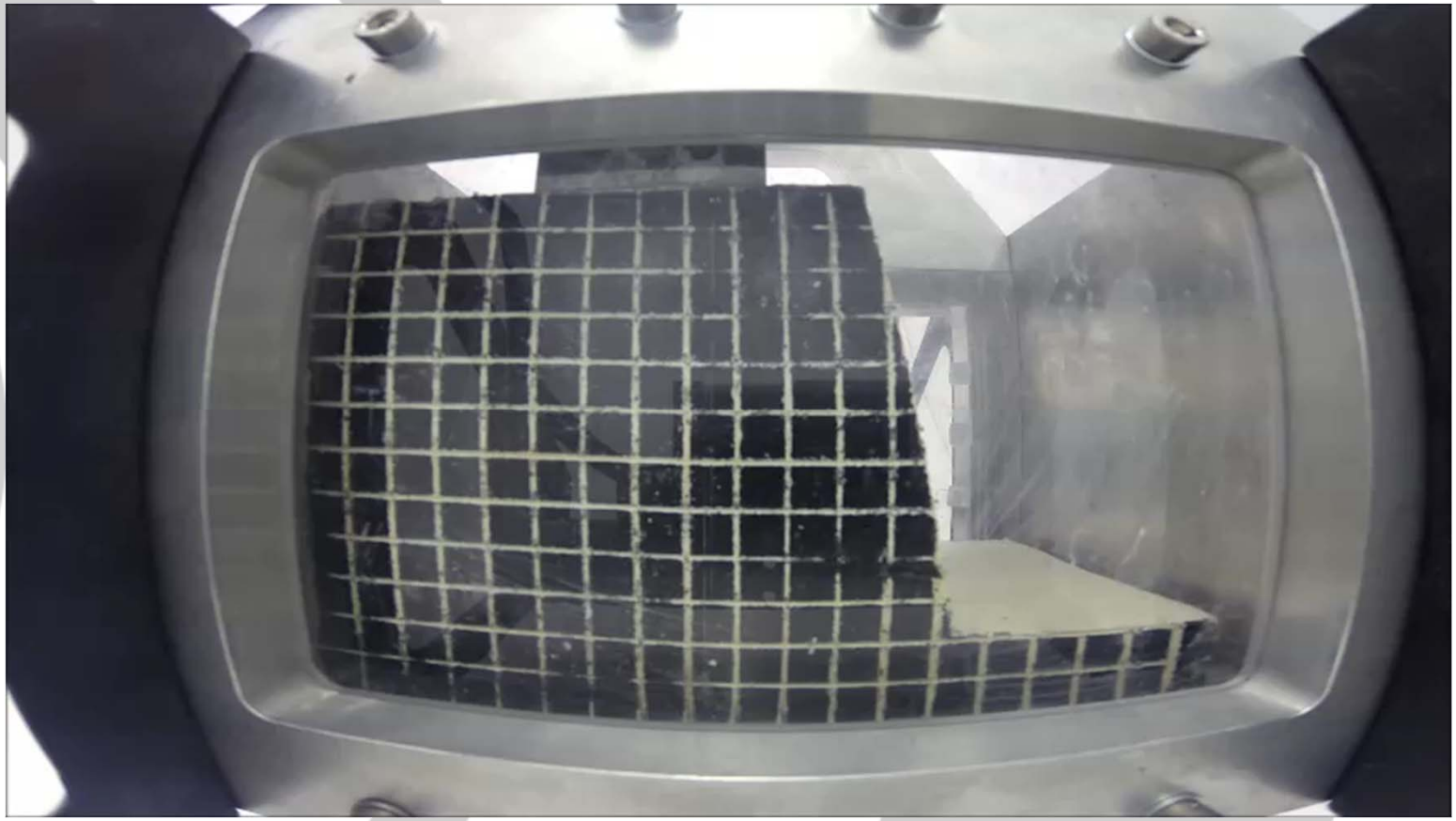
Centrifuge modelling in the UG curriculum

Model preparation

Resist the temptation to interfere !!
'Are you really sure you want to do that?'

Centrifuge modelling in the UG curriculum

Model preparation



Slopes

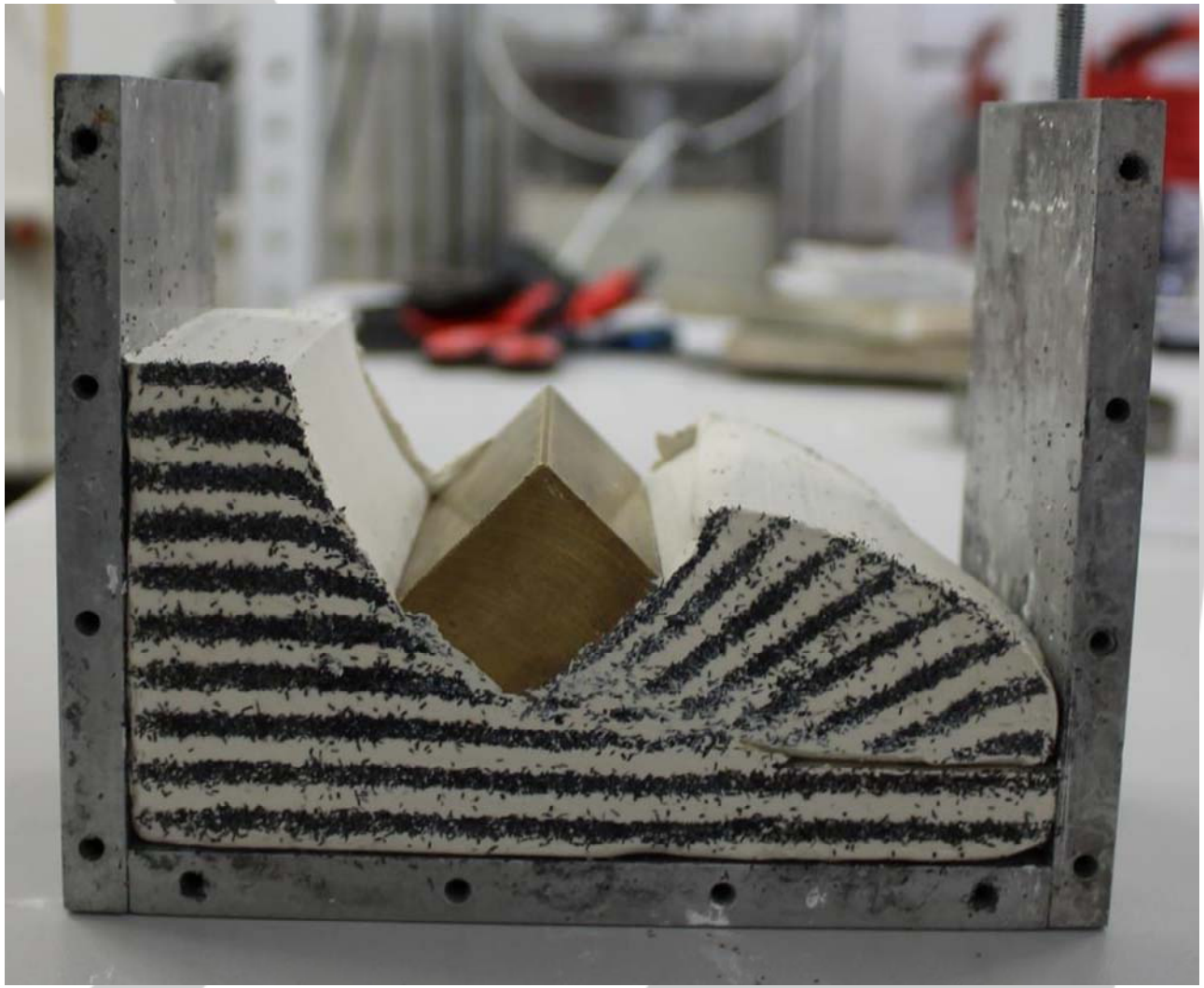
Retaining Walls

Footings

Flood embankments

Centrifuge modelling in the UG curriculum

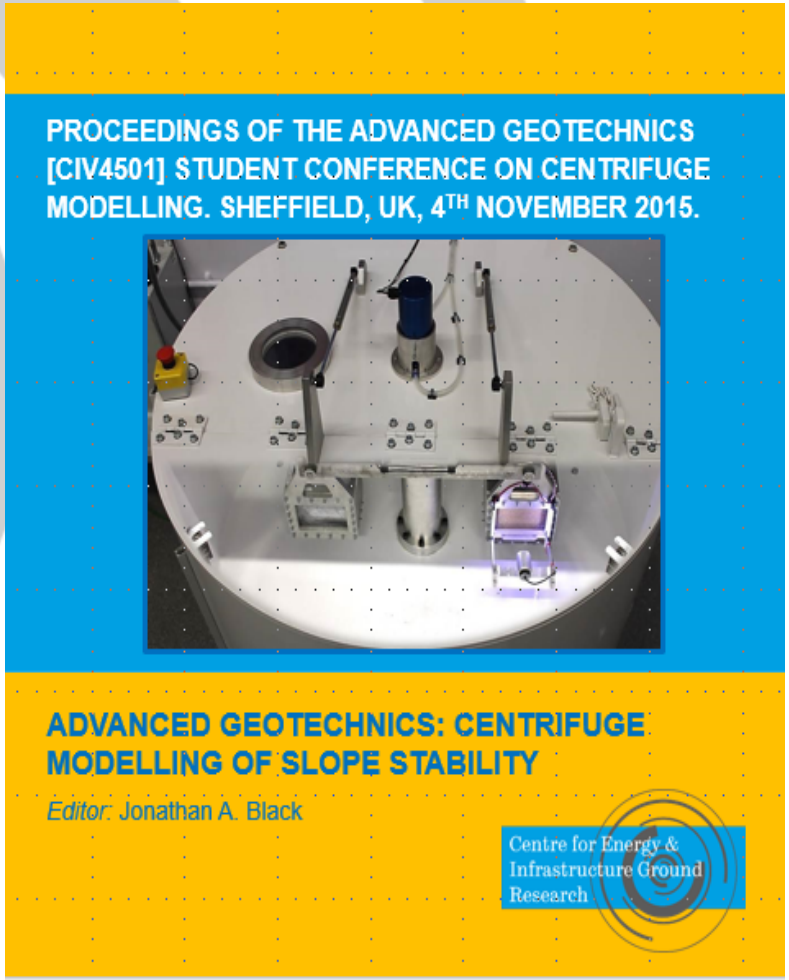
Model preparation

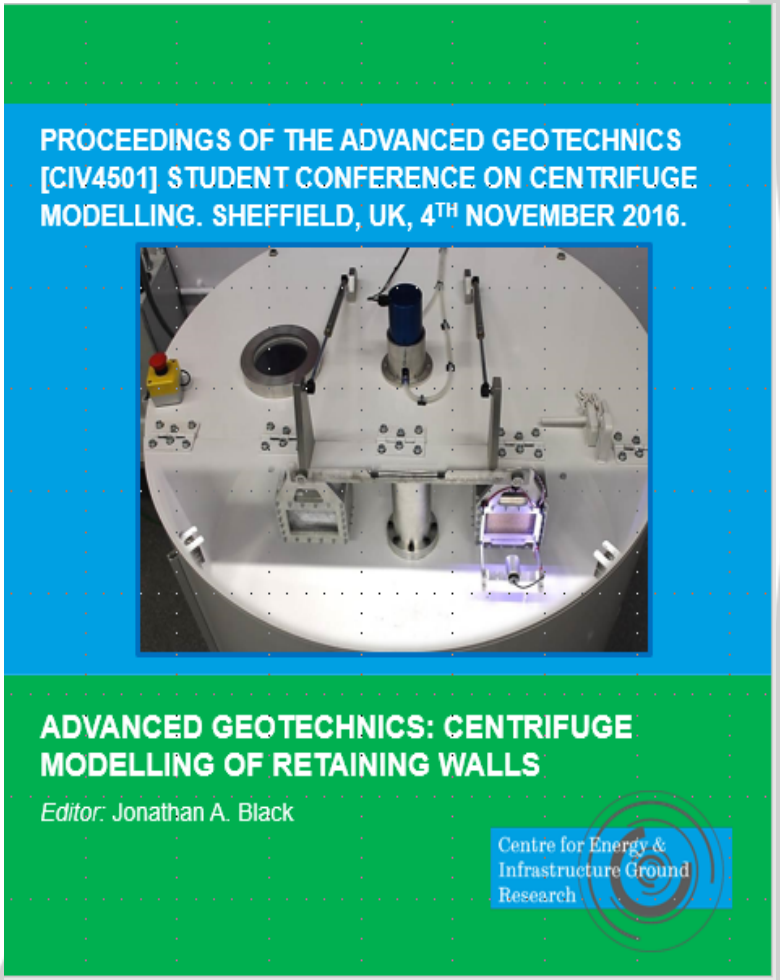


Bespoke centrifuge module

- Unfamiliar problem – investigative approach
  - Analytical, numerical and experimental
- Suite of experimental results – element & centrifuge
  - Strength properties of soil
  - Observe behaviour of model
- Shared sense of responsibility to achieve high quality test data
- Individual student paper for conference dissemination

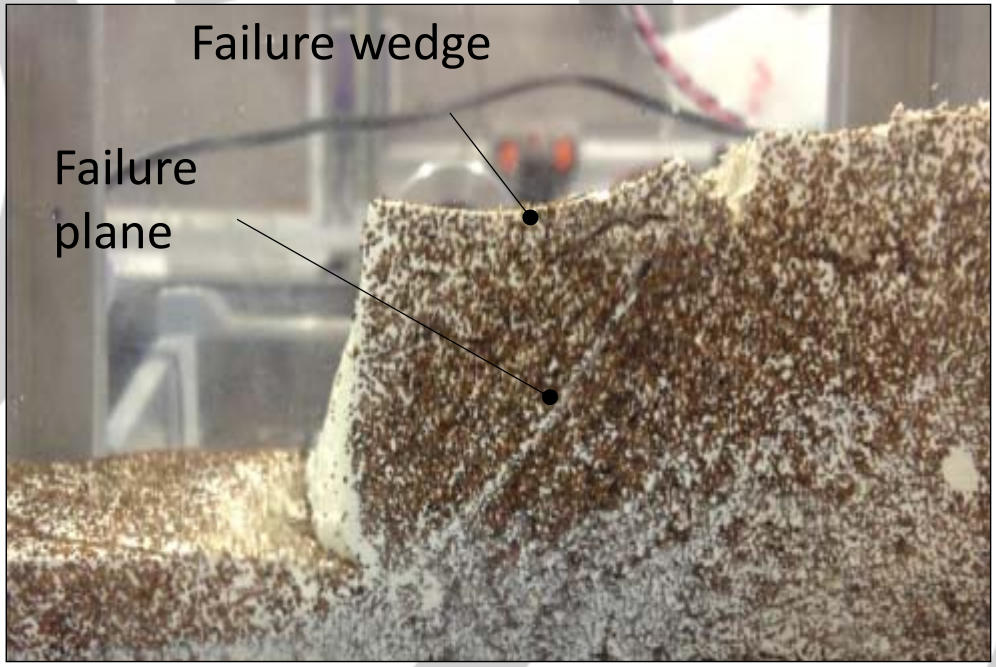
Student Conference

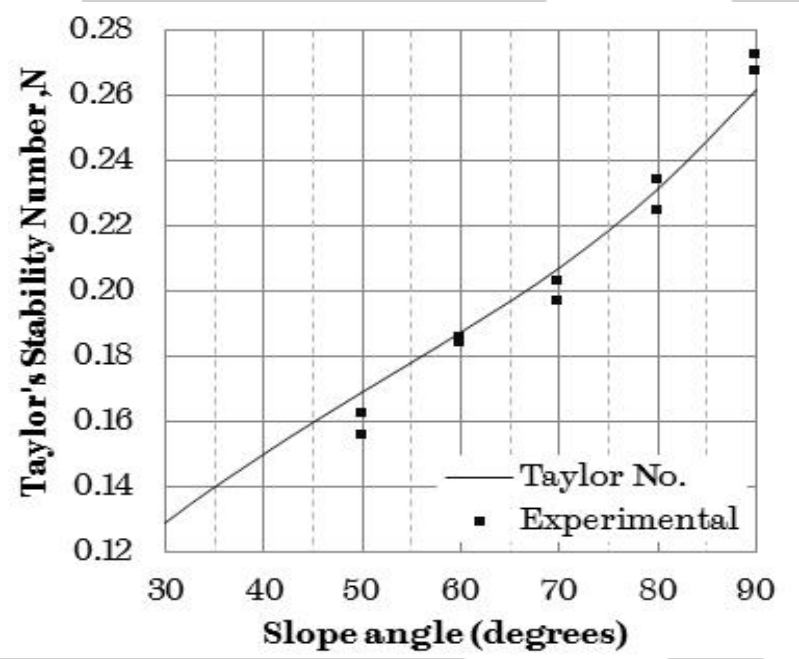




Gravity switch on

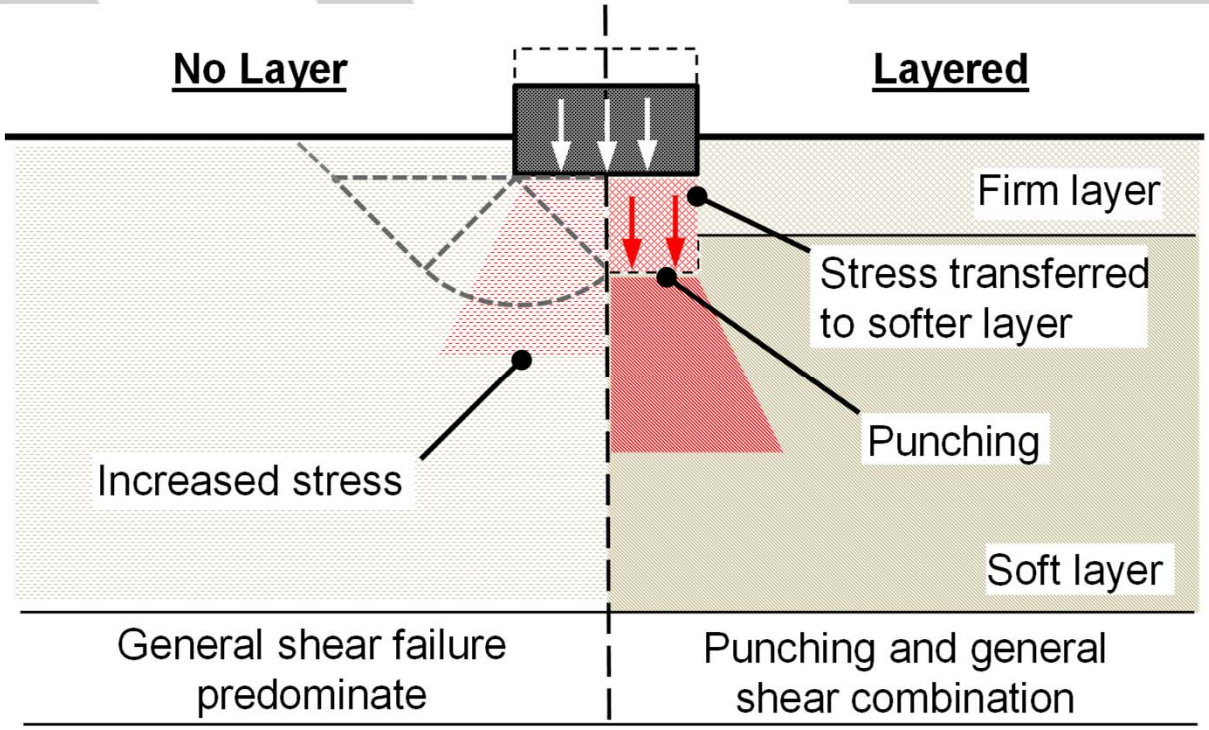
- Slope stability
- Comparison with limit equilibrium & empirical methods
- lope angle and soil strength considered





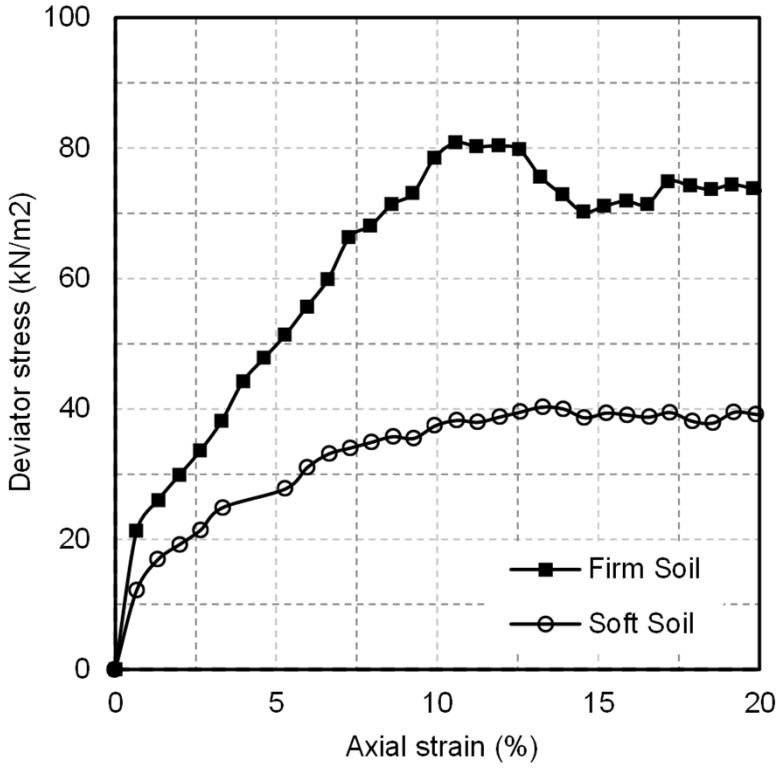
Shallow Foundation Project

- Shallow bearing capacity of layered soils



Shallow Foundation Project

- Clay pre-consolidated at 400kN/m^2 & 200 kN/m^2; c_u = 40 & 20 kN/m^2



Test No.	Layer 1		Layer 2	
	H_1 mm: [*m]	c_u1 kN/m^2	H_2 mm: [*m]	c_u2 kN/ m^2
1	80 [4.0]	40	0	N/A
2	40 [2.0]	40	40 [2.0]	20
3	20 [1.0]	40	60 [3.0]	20
4	15 [0.75]	40	65 [3.25]	20
5	10 [0.5]	40	70 [3.5]	20

Note: *prototype for acceleration N = 50g
Footing Width: B = 20mm [1.0]

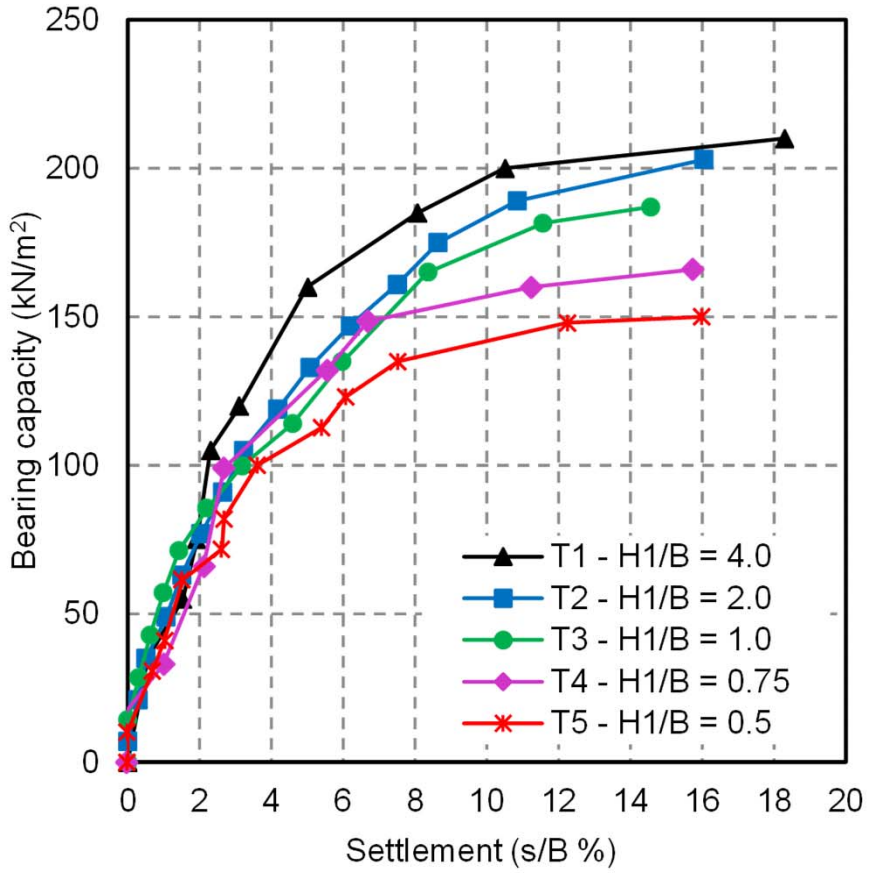
Centrifuge modelling in the UG curriculum

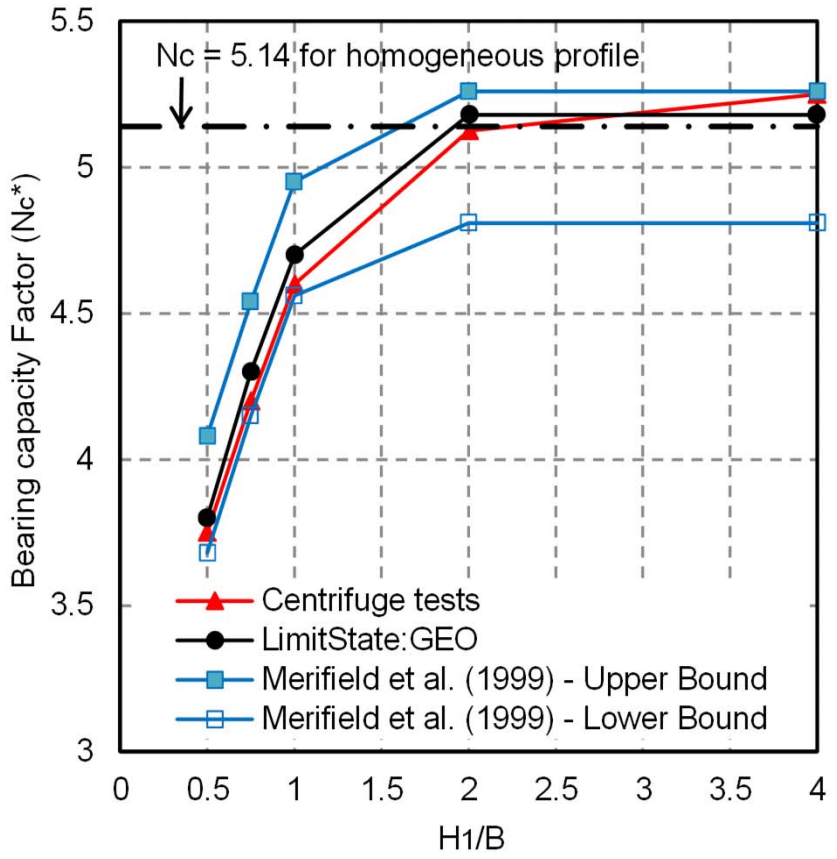
Design examples

Bearing Capacity response:

limitstate geo

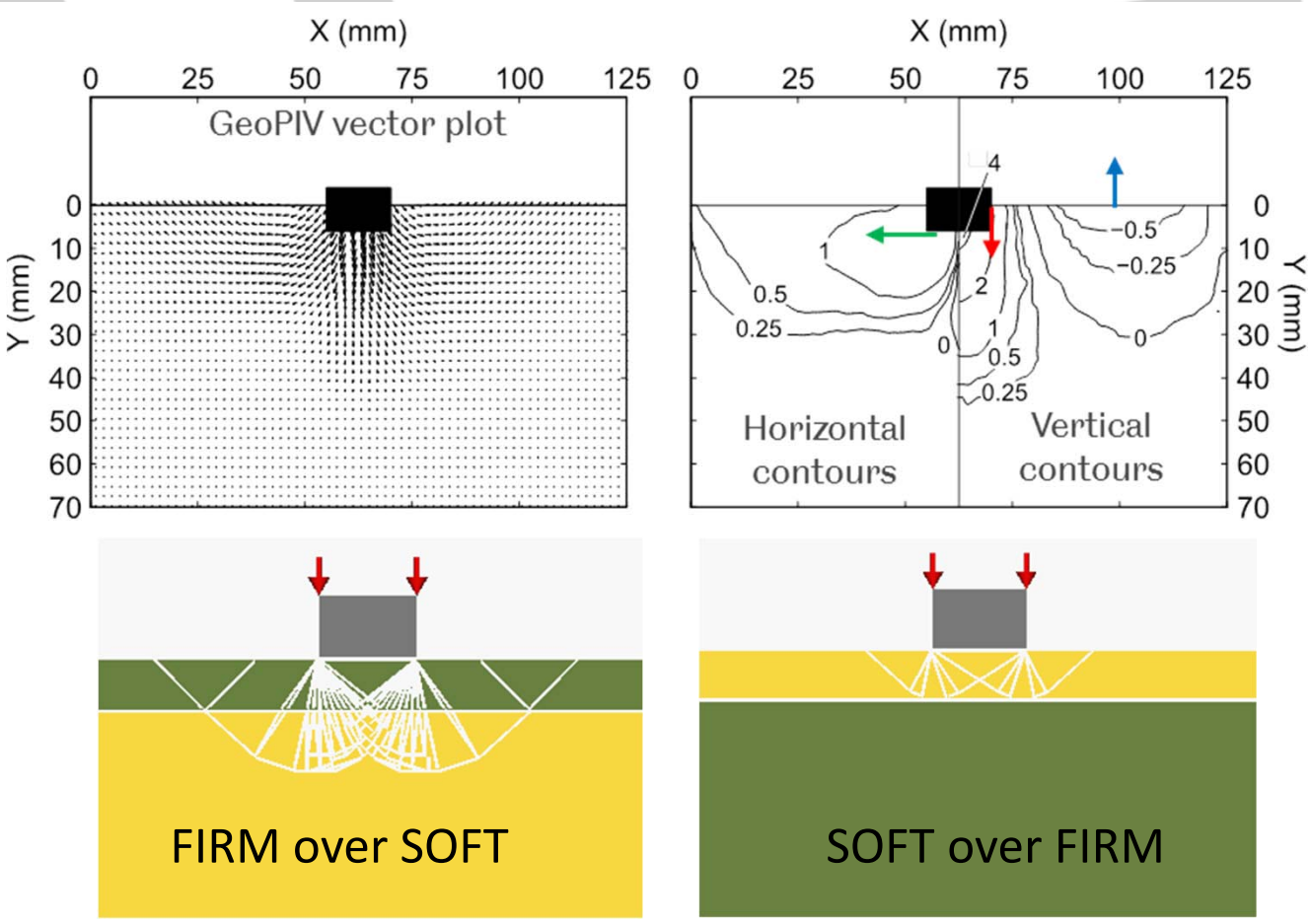
http://www.limitstate.com/geo



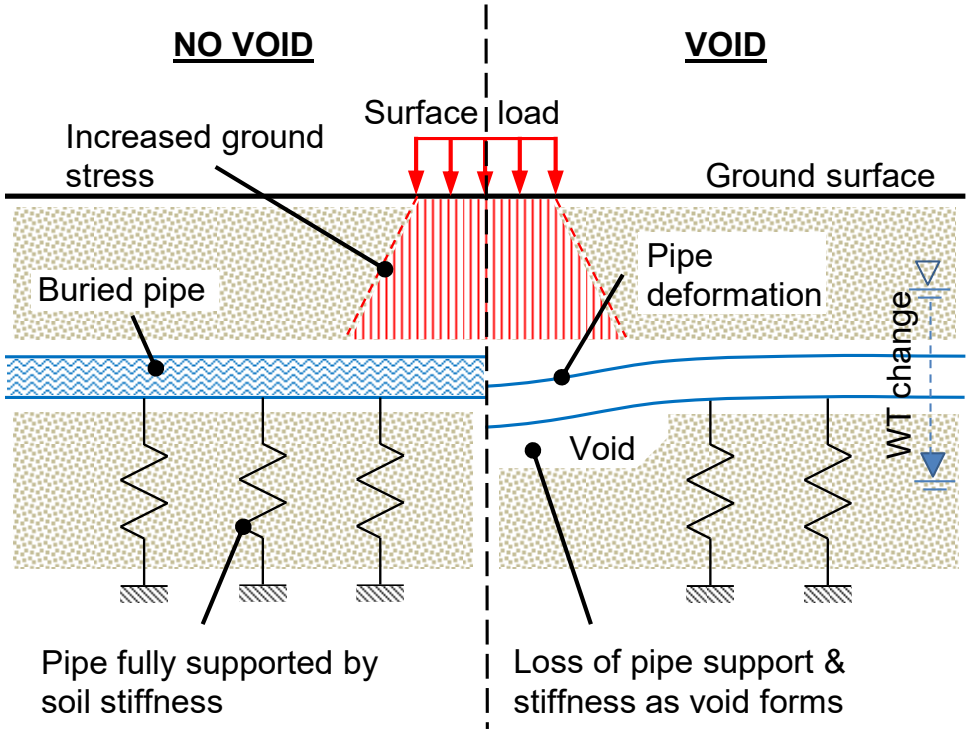


Performance compared to:

- GeoPIV soil velocity and displacement mechanics



- Effects of void formation on bending response of buried flexible utility pipes.

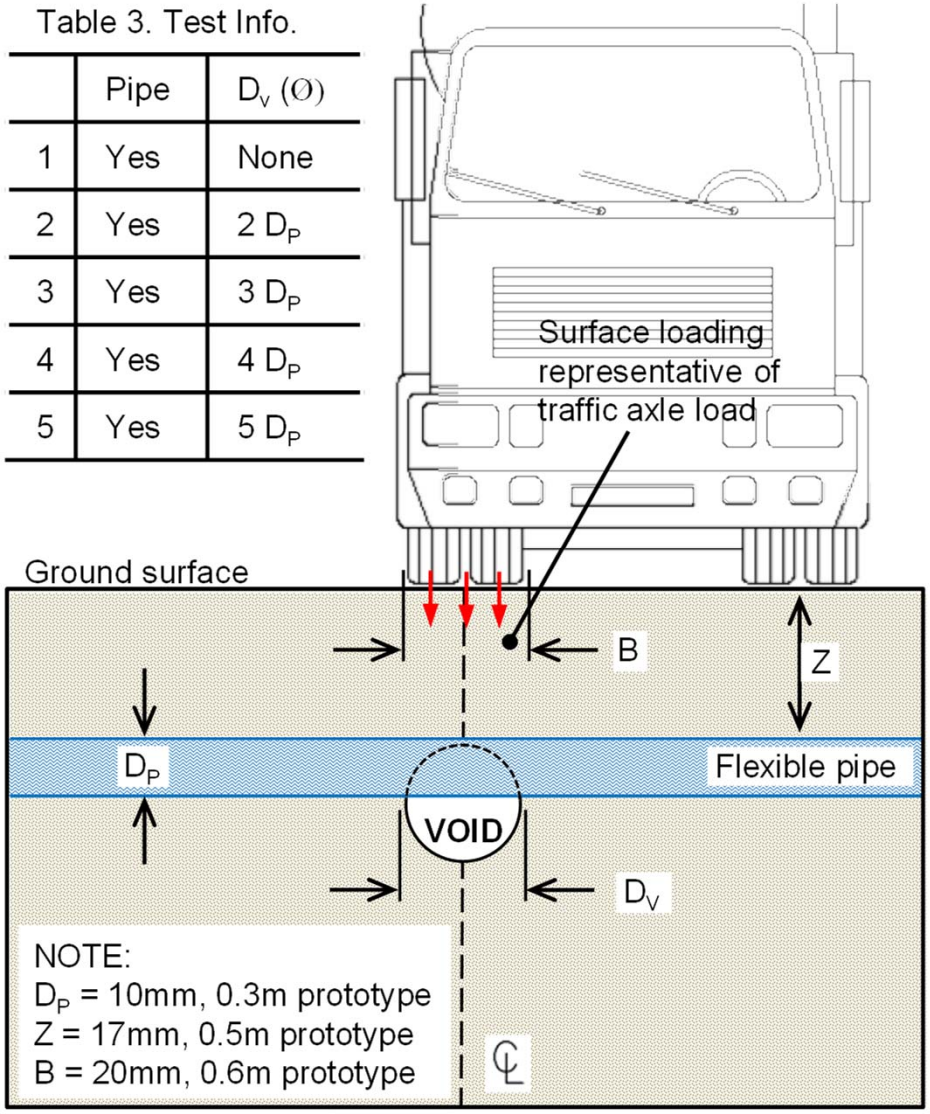


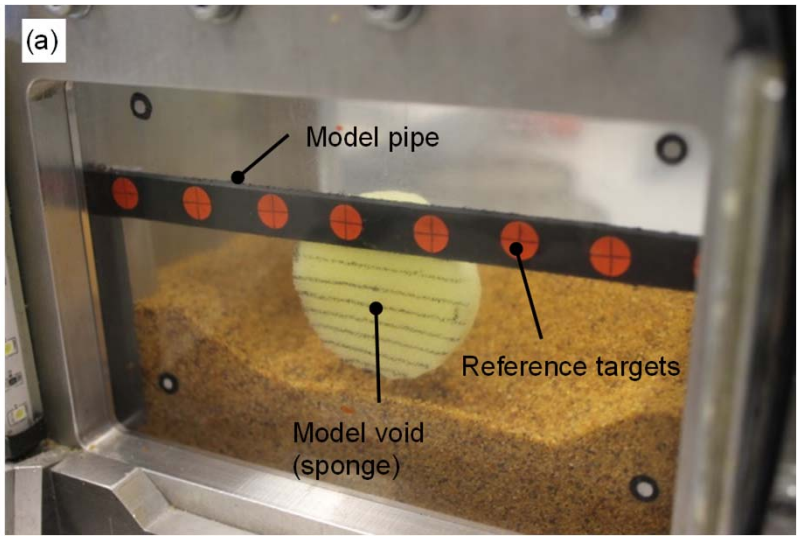
Centrifuge modelling in the UG curriculum

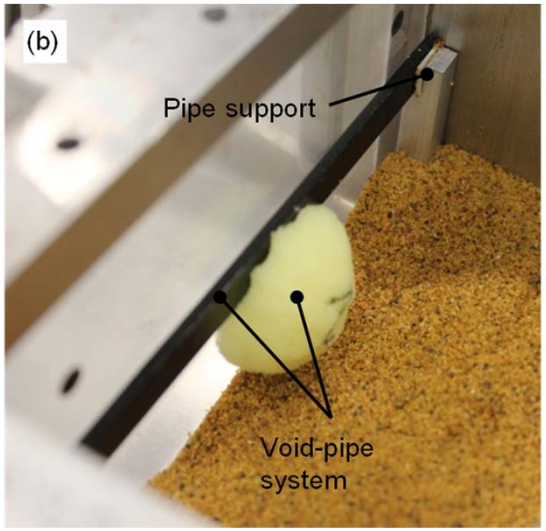
Presentation content

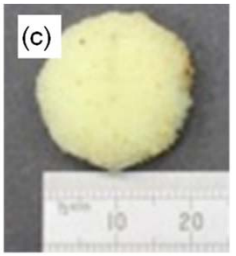
Table 3. Test Info.

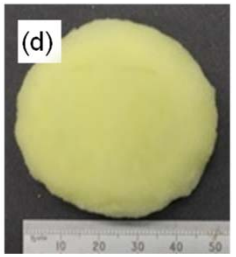
	Pipe	D_V (Ø)
1	Yes	None
2	Yes	2 D_P
3	Yes	3 D_P
4	Yes	4 D_P
5	Yes	5 D_P



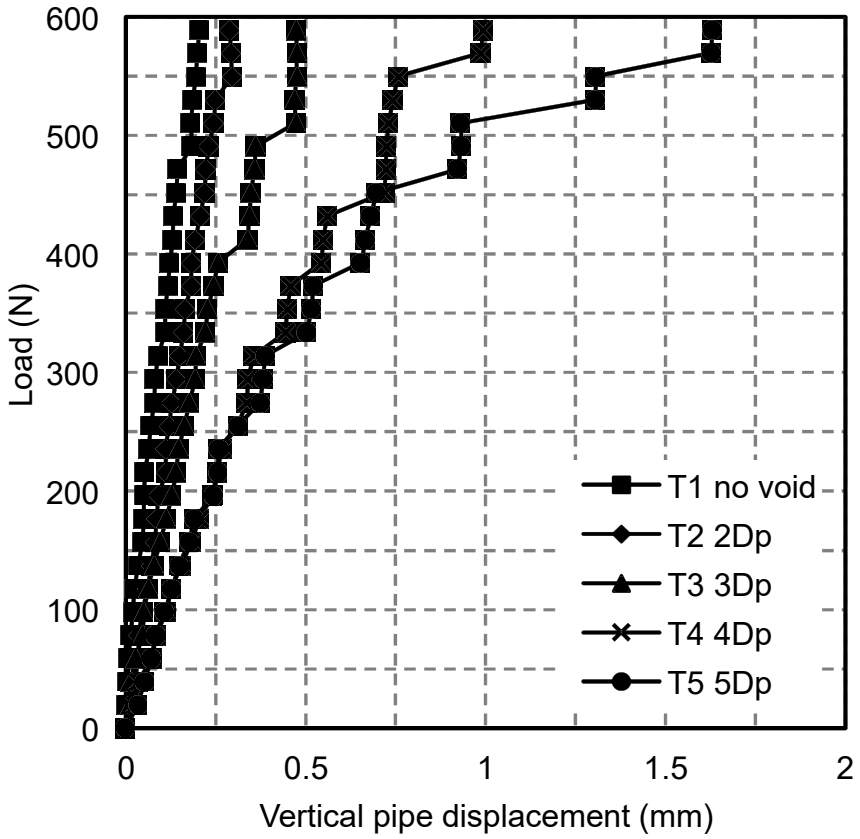


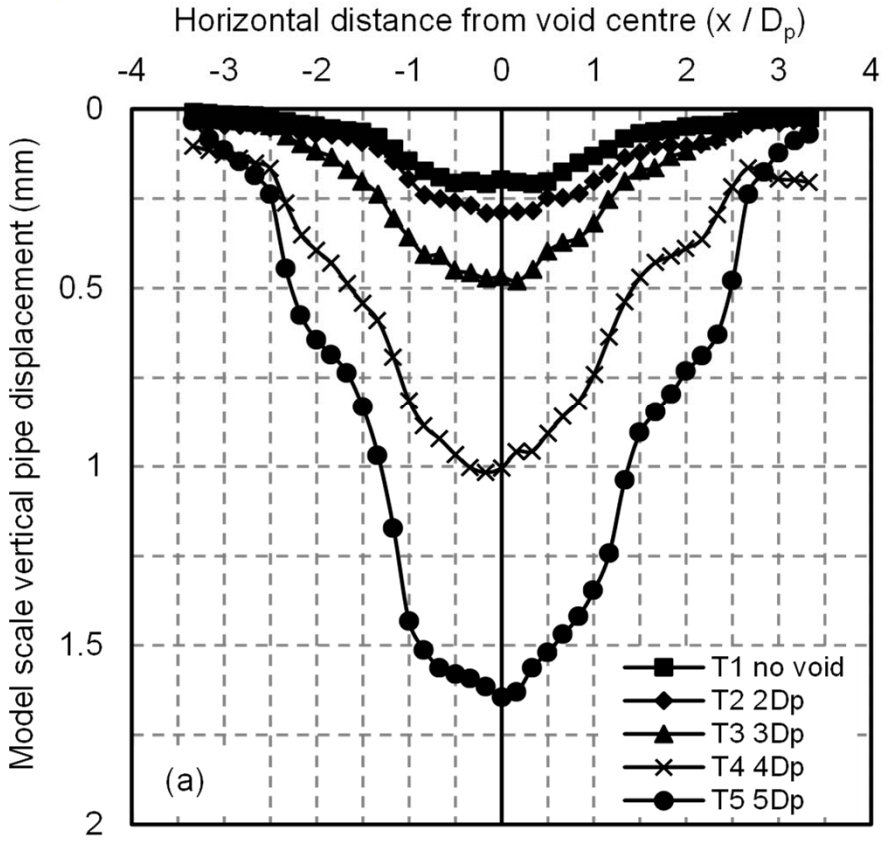






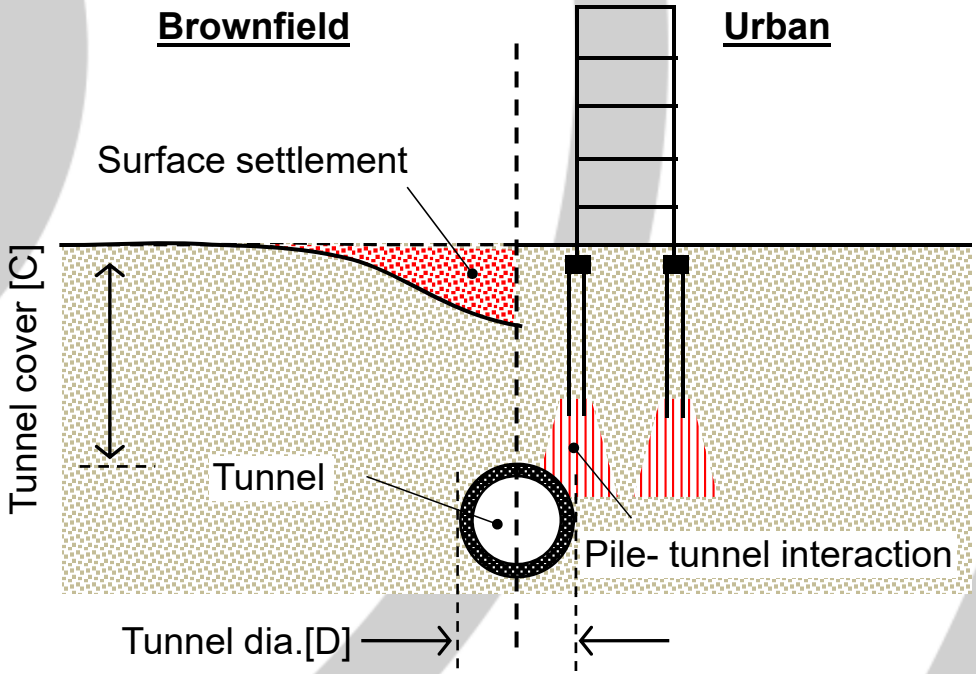
Pipe displacement & centre of void position

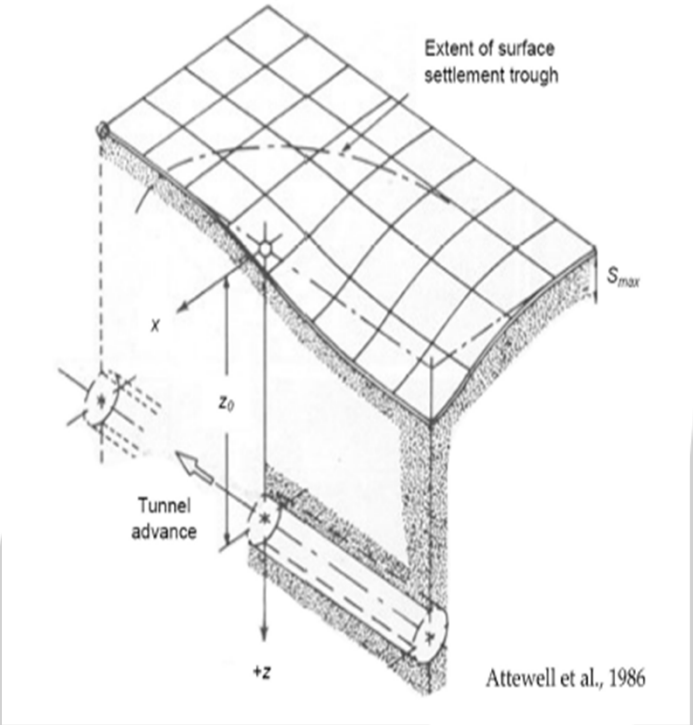




Impact of tunnelling on buried infrastructure

- Verification of surface settlement
- Interaction with existing infrastructure

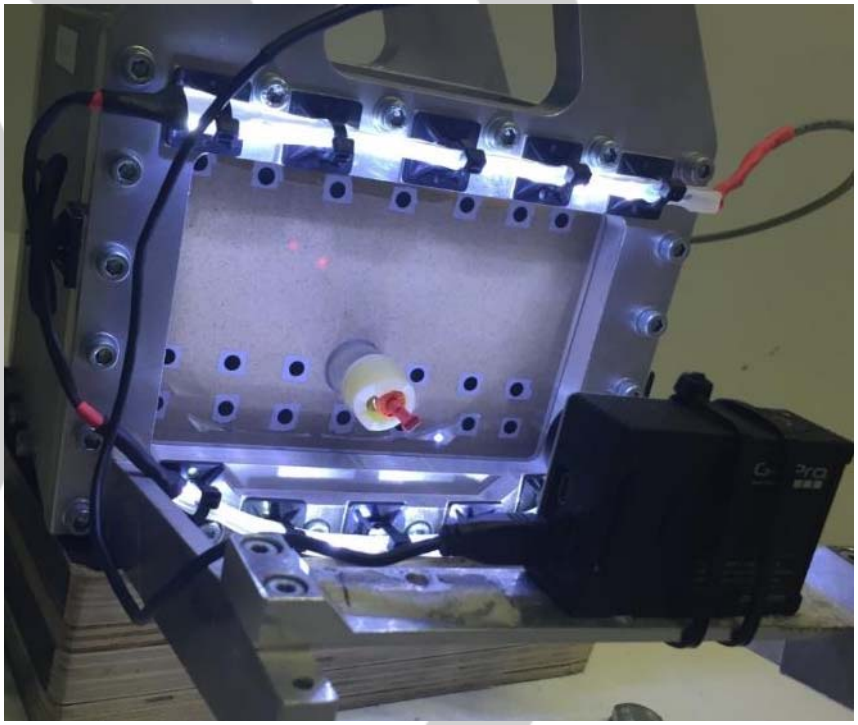


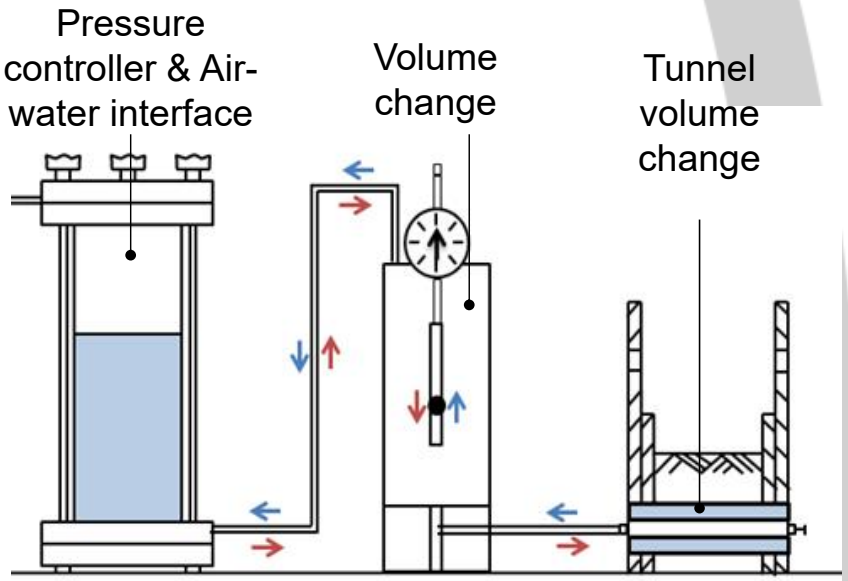


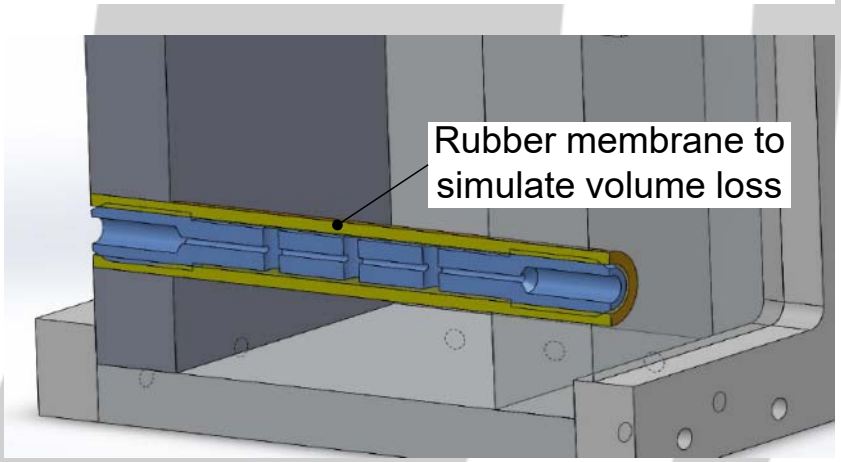
Centrifuge modelling in the UG curriculum

Design examples

Tunnel Vol. loss simulation



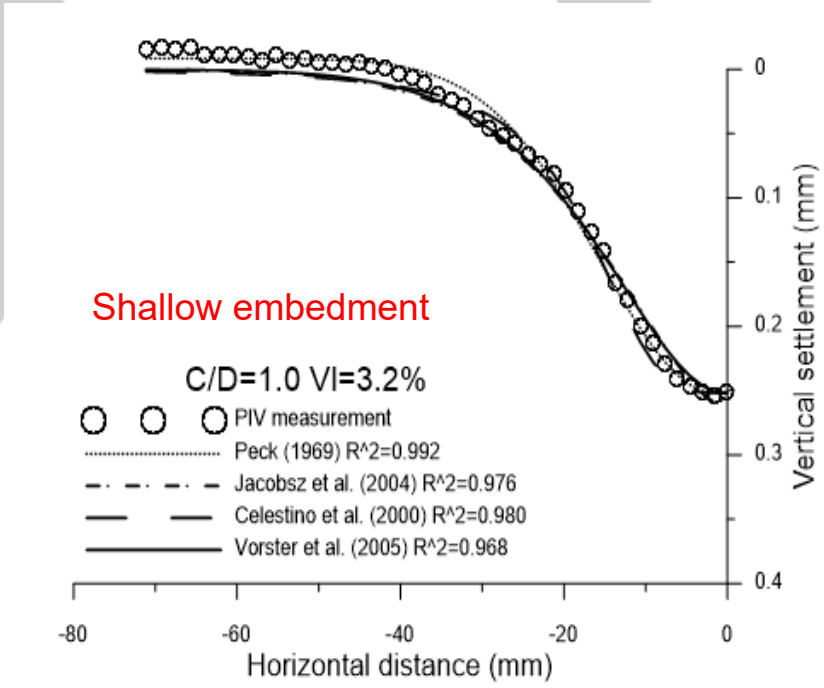


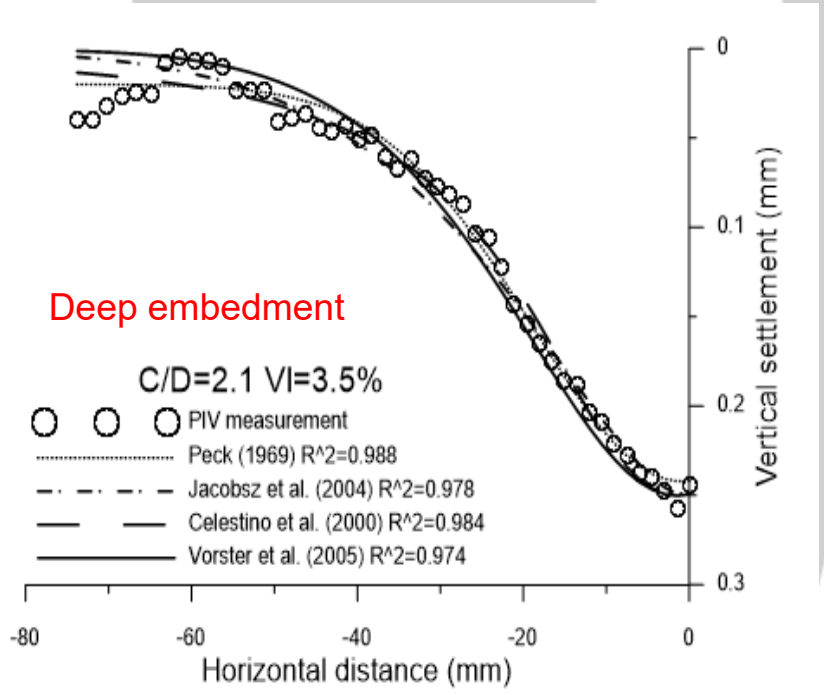


Impact of tunnelling on buried infrastructure

- Tunnel diameter to cover ratio C/D = 1.0; 1.6 and 2.1
- Comparison to classic theory [Peck 1969] & recent works

$$S_v(x) = S_{max} exp\left(\frac{x^2}{2i^3}\right)$$





Lessons to remember

1. **Keep it simple**
2. **Keep it simple!**
3. Allow students to make mistakes & learn from failures
4. Integration of preparation systems vital for throughput
5. Good things do come in small packages
6. **Remember to keep it simple !**

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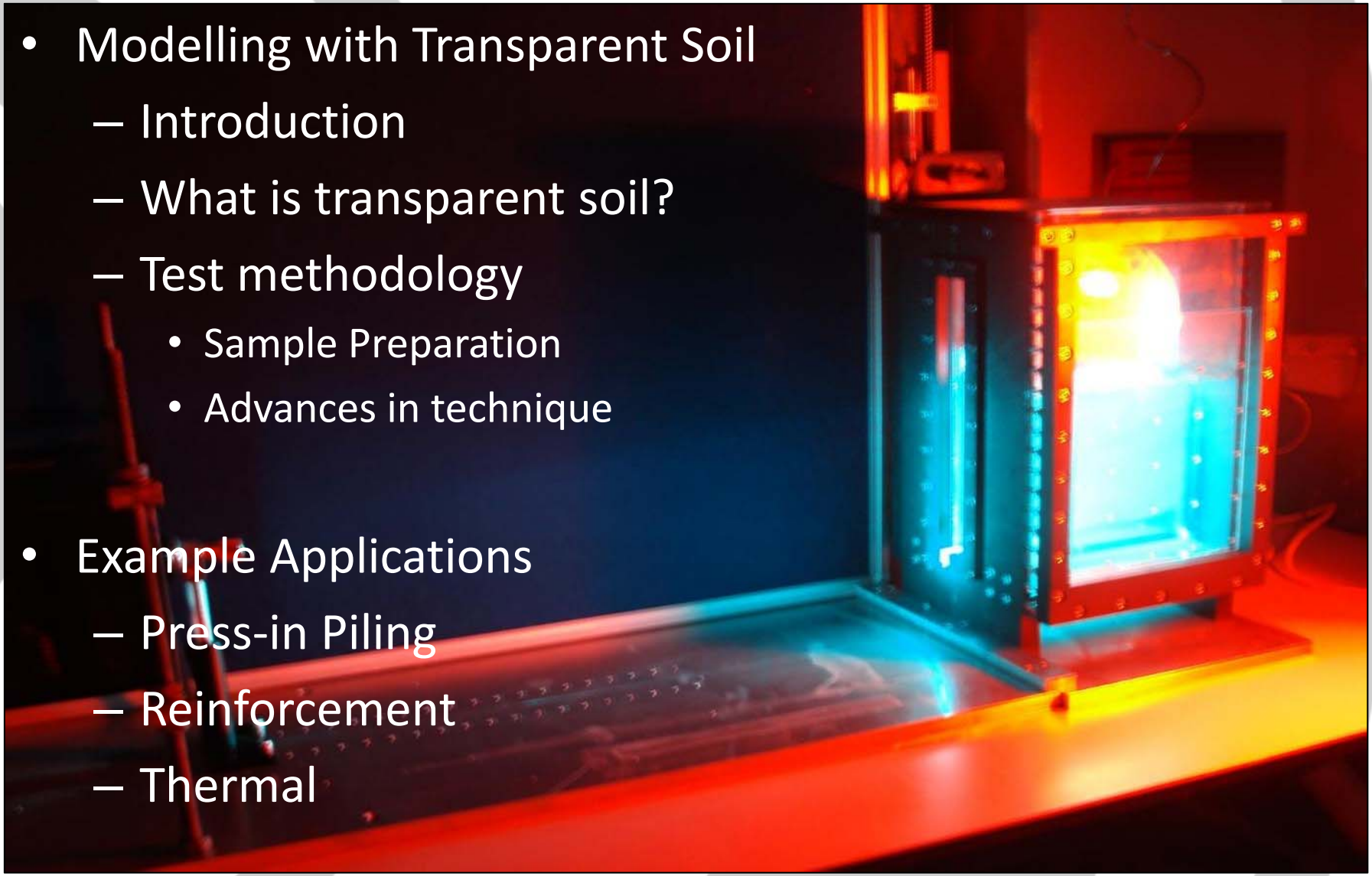
Impact to student learning

- Observation & validation of theory
- Connecting analytical, numerical, empirical methods
- Developing experimental research skills
- Promoting geotechnical research
- Test facility for scoping out larger studies

Visualisation modelling at Sheffield

Transparent Soil

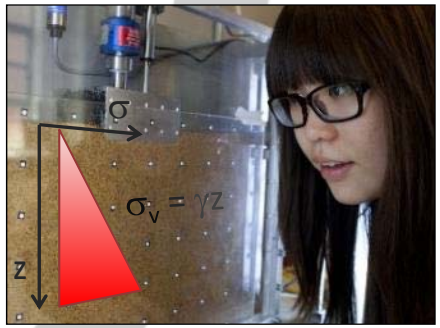


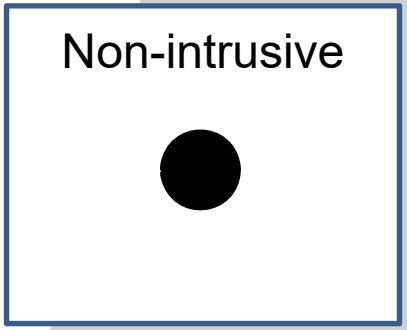
- Modelling with Transparent Soil
  - Introduction
  - What is transparent soil?
  - Test methodology
    - Sample Preparation
    - Advances in technique
- Example Applications
  - Press-in Piling
  - Reinforcement
  - Thermal

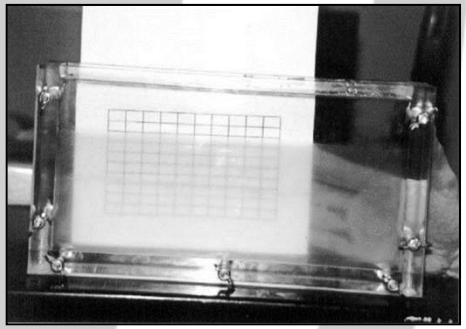
Modelling with Transparent Soil

Introduction to transparent soil

- Visualisation used extensively to gain greater insight
  - Medical, engineering, environmental
- Desire to visualize soil deformation to enhance understanding - interaction, failure mode, design codes
  - X-ray: discrete lead shot, low resolution, compliance errors
  - Photogrammetry: *Plane Strain* modelling – Stereo, PIV 'GeoPIV'
  - Limitations: Boundary effects, geometry & installation simplification



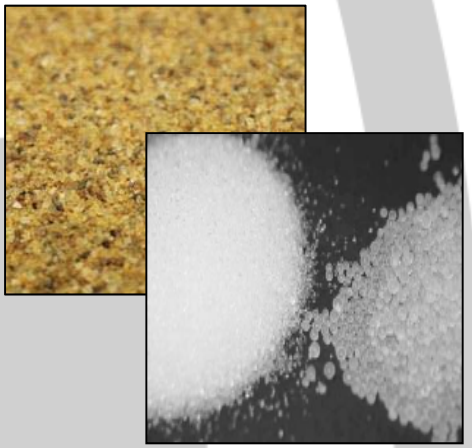




Modelling with Transparent Soil

Introduction to transparent soil

- Transparent ‘soil’ development
  - Range of analogue soil materials adopted
    - Coarse: glass, silica gels, fused quartz
    - Fine: Precipitated & Fumed amorphous silica
  - Aggregate & matched refractive index pore fluid
    - Blended mineral oils
    - Two phase (remove air)
  - Optical quality
    - Aggregate dependant
    - Oil quality & calibration
    - Temperature dependent
- Impact on sample size possible

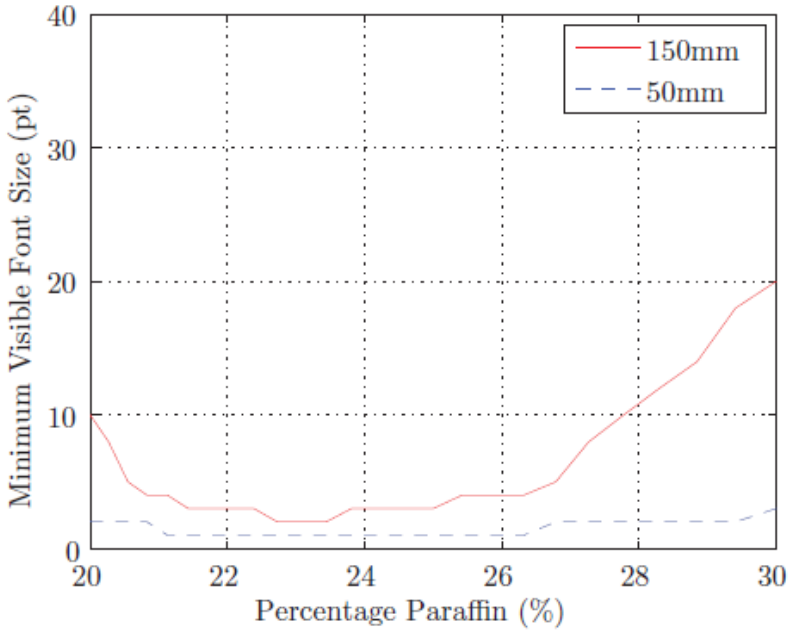


Modelling with Transparent Soil

Introduction to transparent soil

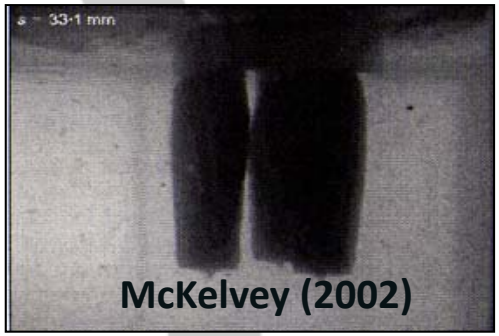
- Optical quality assessment
  - Eye test chart: ‘Snellen chart’ at opticians
  - Located behind specimen, ‘say what you see’
    - Calibration of optimum material blend
  - Subjective & operator dependent
  - Test chamber geometry

Test Card Example	Point Size
54521	72
21036	48
27147	36
78828	28
61638	26

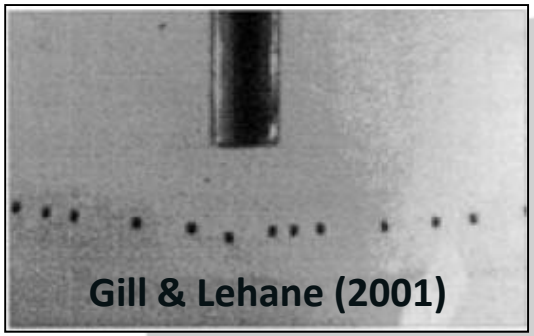


- Methods of observation in transparent soil

Silhouette tracking



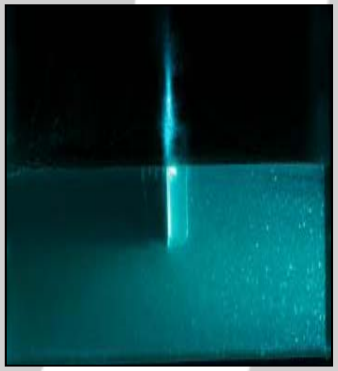
McKelvey (2002)


Gill & Lehane (2001)

Target beads

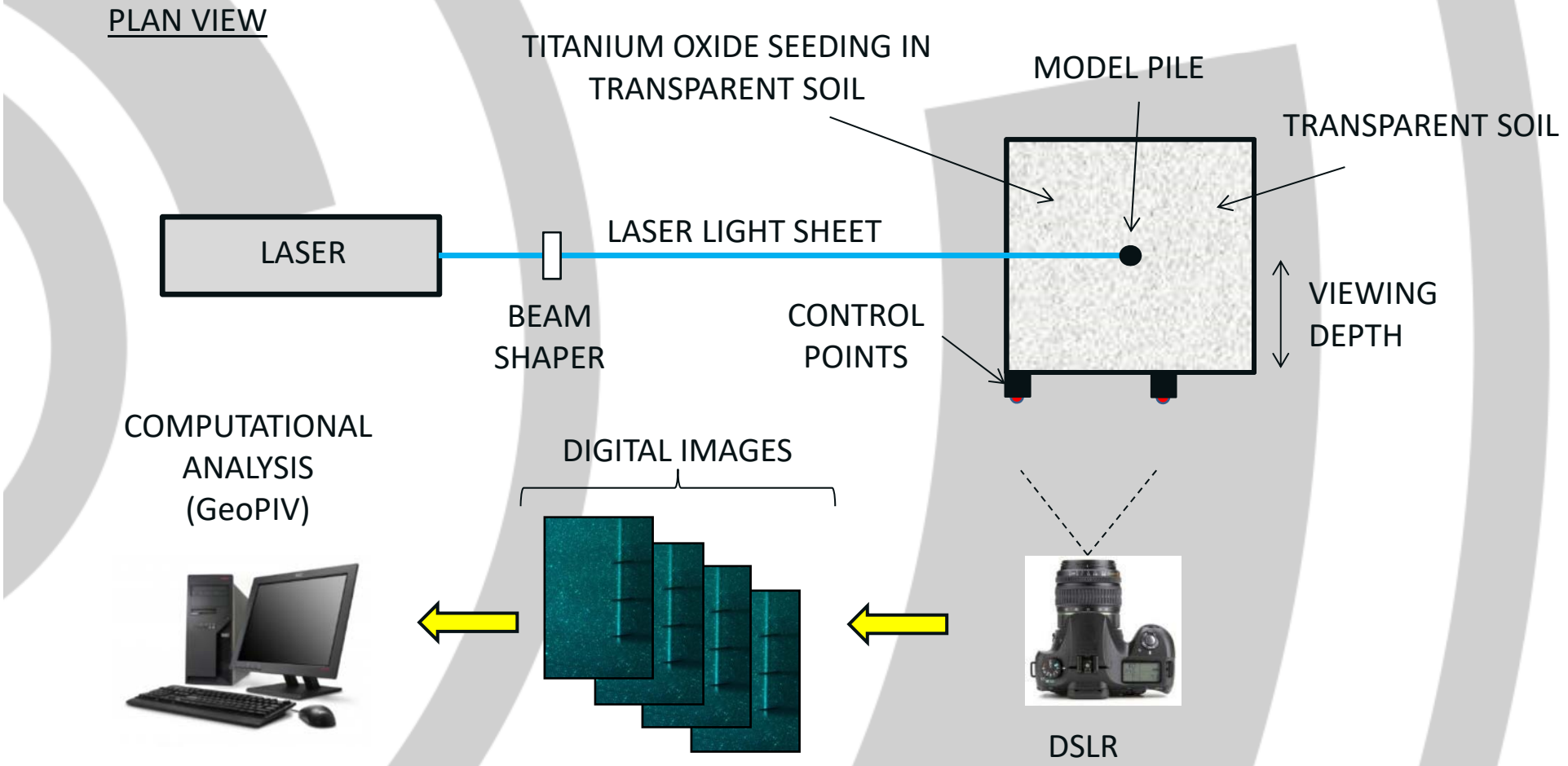
  - Material quality not as critical in all cases
    - Low resolution, compliance errors from inclusions
  - How to measure/record internal high-resolution displacements..?

  - PIV similar to fluid mechanics
    - Tracking of seeding particles
      - Laser aided imaging
      - Image correlation



Modelling with Transparent Soil

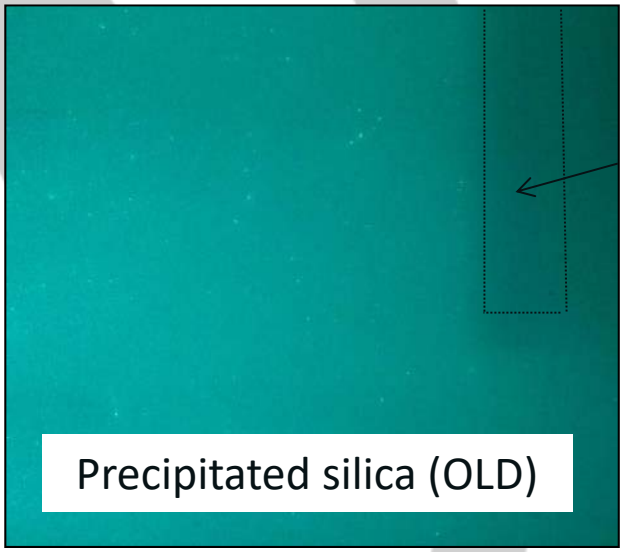
Experimental test configuration



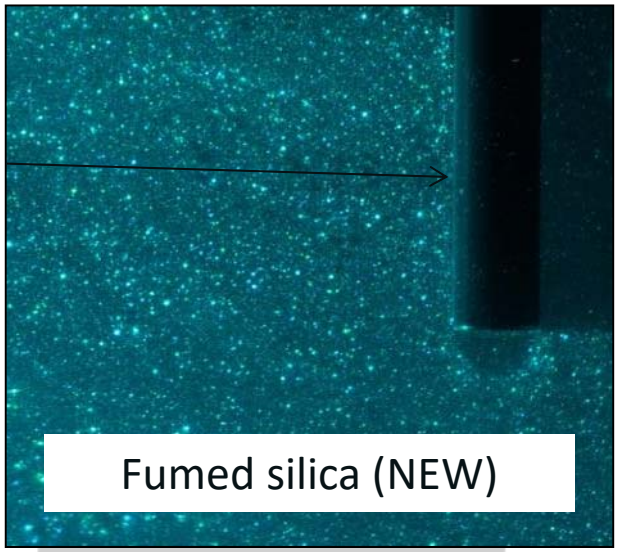
Modelling with Transparent Soil

PIV displacement measurement

- Laser aided imaging illuminates ‘soil’ texture



12 mm diameter model pile

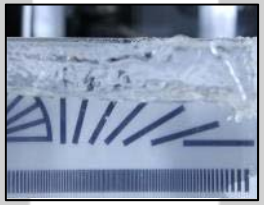


  - Impact of soil type & oil quality on optical clarity
    - Comparison above @ 100mm viewing depth
    - Precipitated: Iskander et al. 1994, Hird et al. 2008, Ni et al. 2010
    - Fumed: New UoS formulation of aggregate and oil

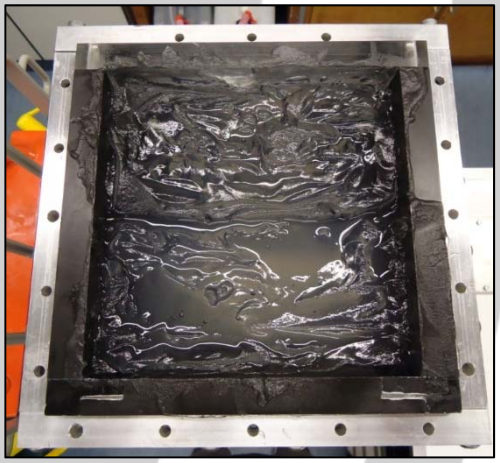
Modelling with Transparent Soil

Material preparation

- Transparent Soil: UoS formulation
  - Aggregate – fumed silica (D_{50}=14μm)
  - Pore fluid – matched Refractive Index
    - White oil (77%), Paraffin (23%)
  - Seeding texture for PIV analysis
    - Titanium Oxide particles (D_{50}=20μm)
    - In-lieu of discrete targets i.e. beads



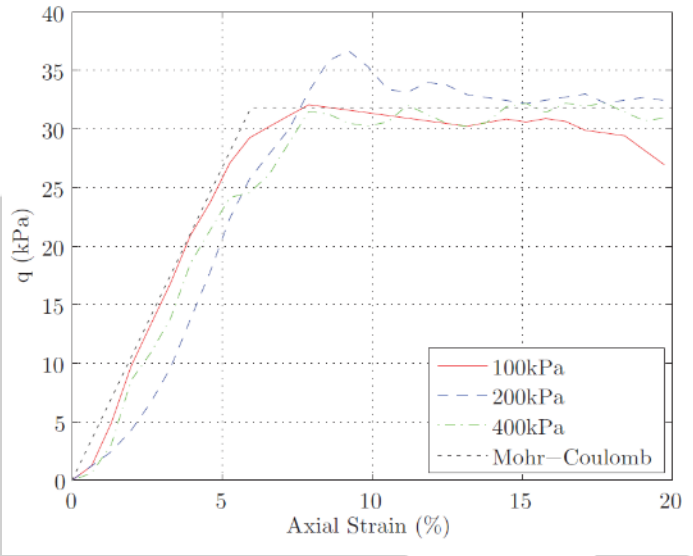
- Sample preparation:
  - Mixed in slurry form
  - De-aired under vacuum
  - Consolidated to desired stress

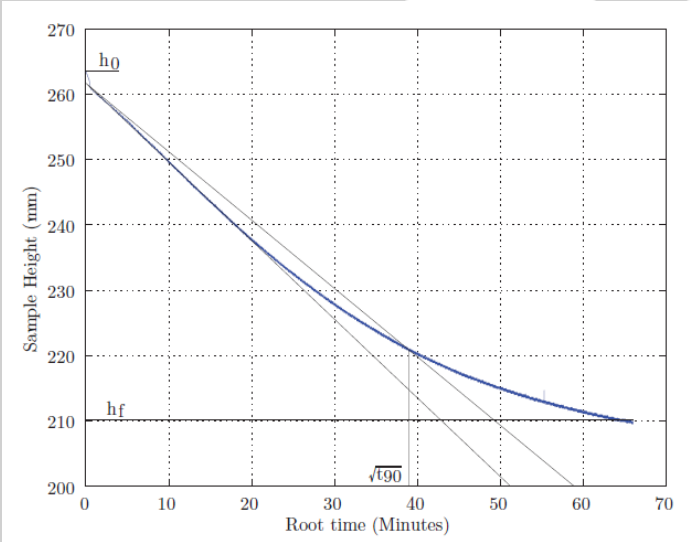


Modelling with Transparent Soil

Material preparation

- Stress – strain response
  - Consolidated to 100kPa
  - Undrained shear strength ~ 15-20kPa
  - Coeff. of consolidation = 3-4 m^2/year
- Problems that can arise
  - Air entering the model
    - Cavitation during unloading
    - Positive pour fluid head maintained

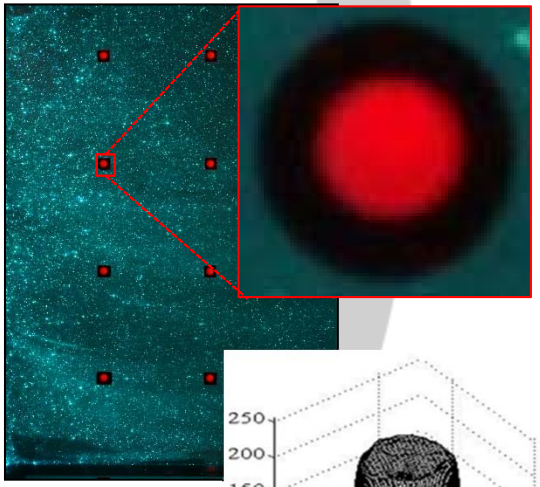


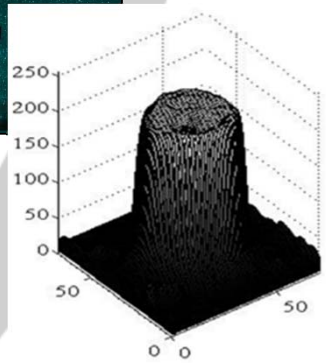


Modelling with Transparent Soil

Modelling advancements

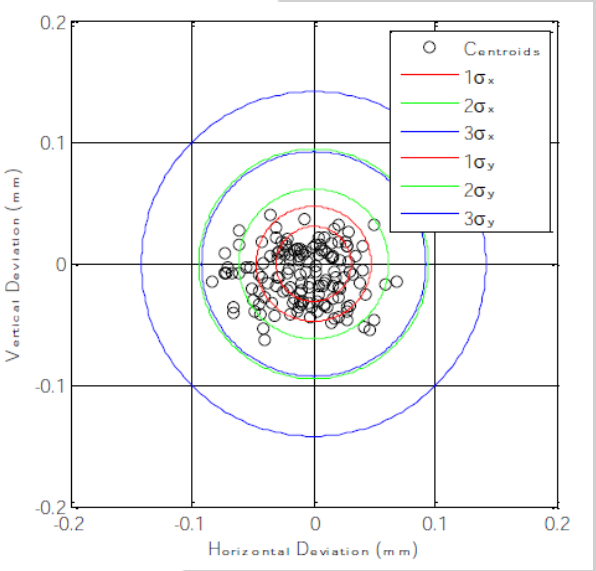
- New control target markers
  - Image contains Red: Green: Blue colour channels
  - Laser wavelength of 532nm (GREEN)
    - Red light channel used for the control markers
    - Soil displacement conducted on Blue & Green



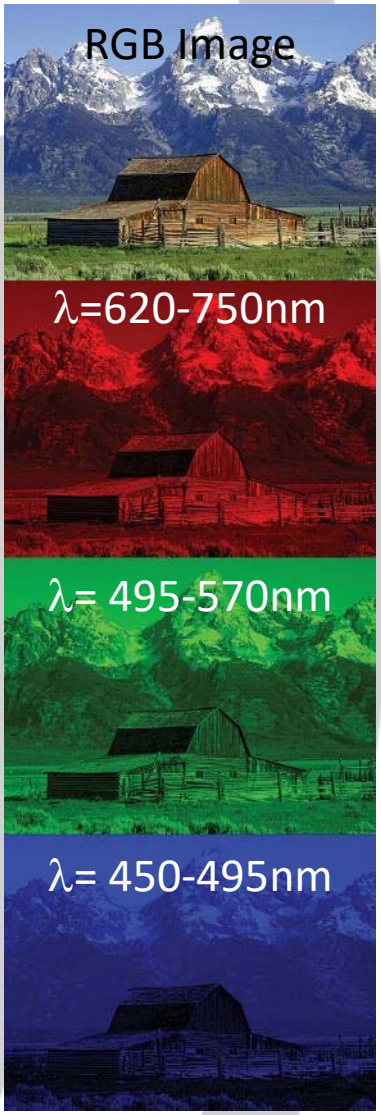


Control

Soil tracking



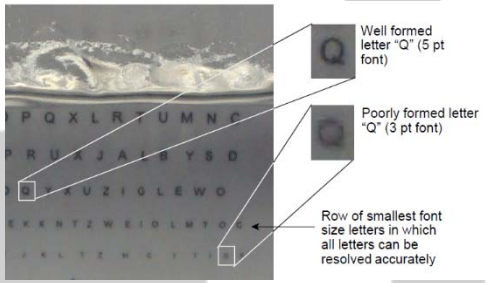
Factor of 3 reduction in control marker error

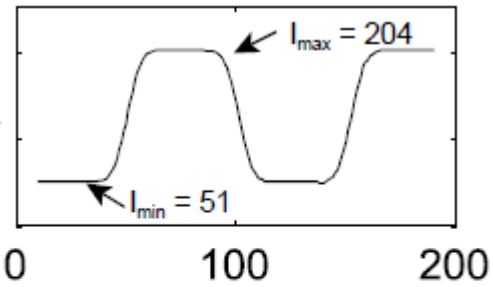


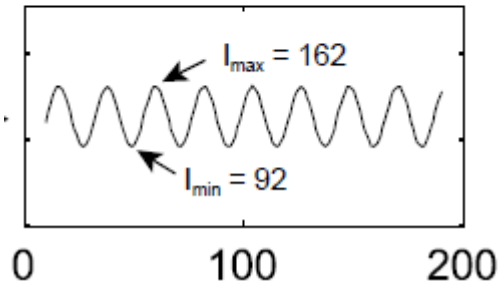
Modelling with Transparent Soil

Modelling advancements

- New framework for assessing transparency
  - Eye chart not sufficiently robust
- Modulation Transfer Function (MTF)
  - Standardised method of lens assessment
  - *'measures how faithfully the lens reproduces (or transfers) detail from the object to the image produced by the lens'*

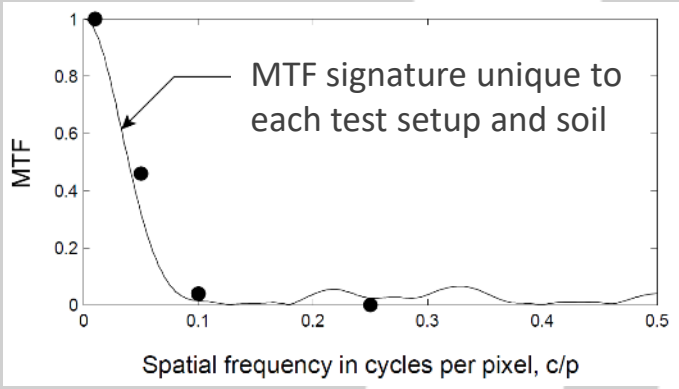


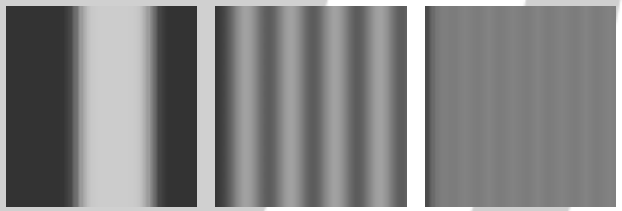




$$\frac{\text{Modulation of actual image}}{\text{Modulation of ideal image}} = \frac{(204-51)/(204+51)}{(204-51)/(204+51)} = 1$$

$$\frac{(162-92)/(162+92)}{(204-51)/(204+51)} = 0.46$$





Modelling with Transparent Soil

Example application – helical screw piles

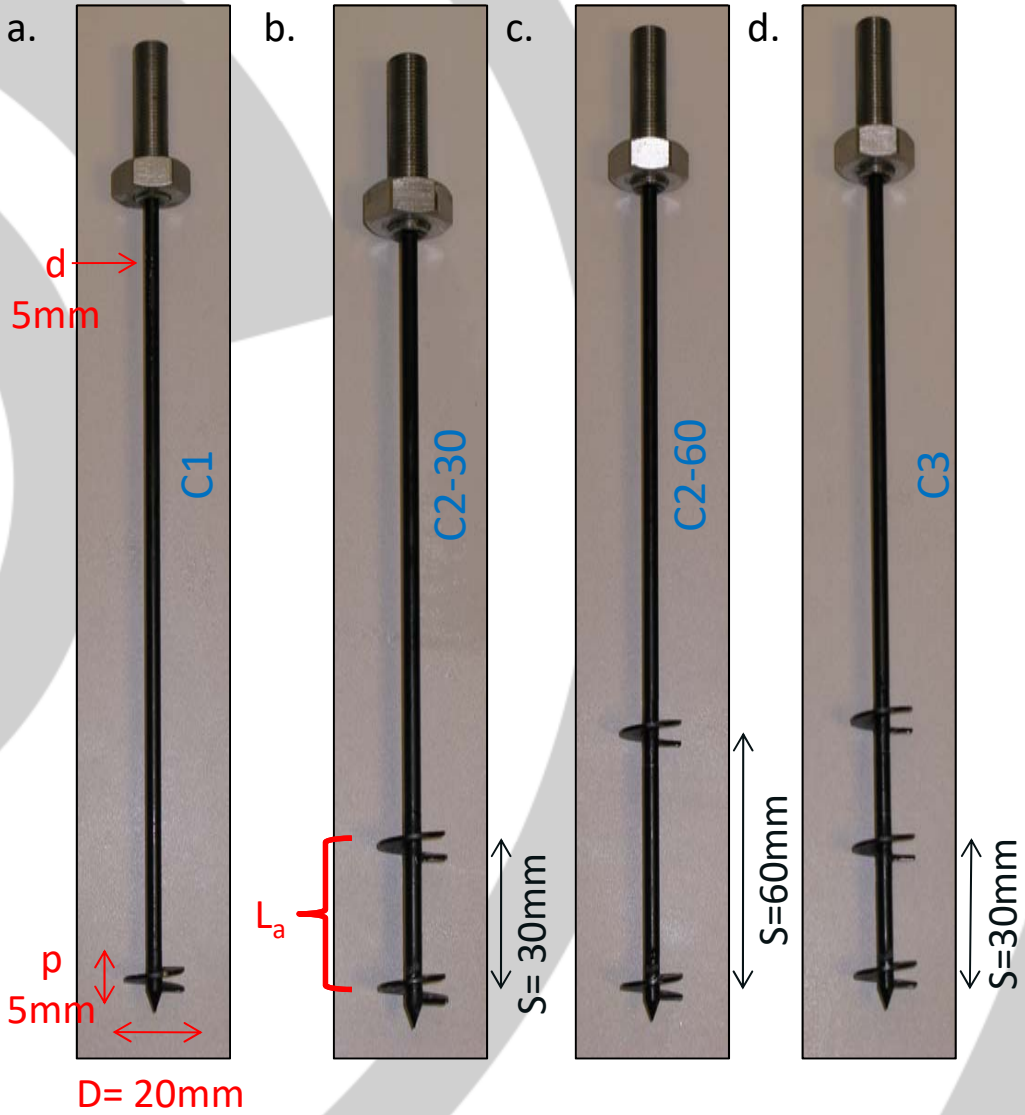
- Tubular or square shaft
- Single or regularly spaced helical plates
  - Typically 100-400mm diameter
- Minimal ground disturbance
- Recoverable/reusable

- Typical applications:
  - Marine anchors
  - Road and rail signage
  - Oil and gas pipelines
  - Temporary structures

Failure mechanics not definitively known

Modelling with Transparent Soil

Helical screw piles: model piles



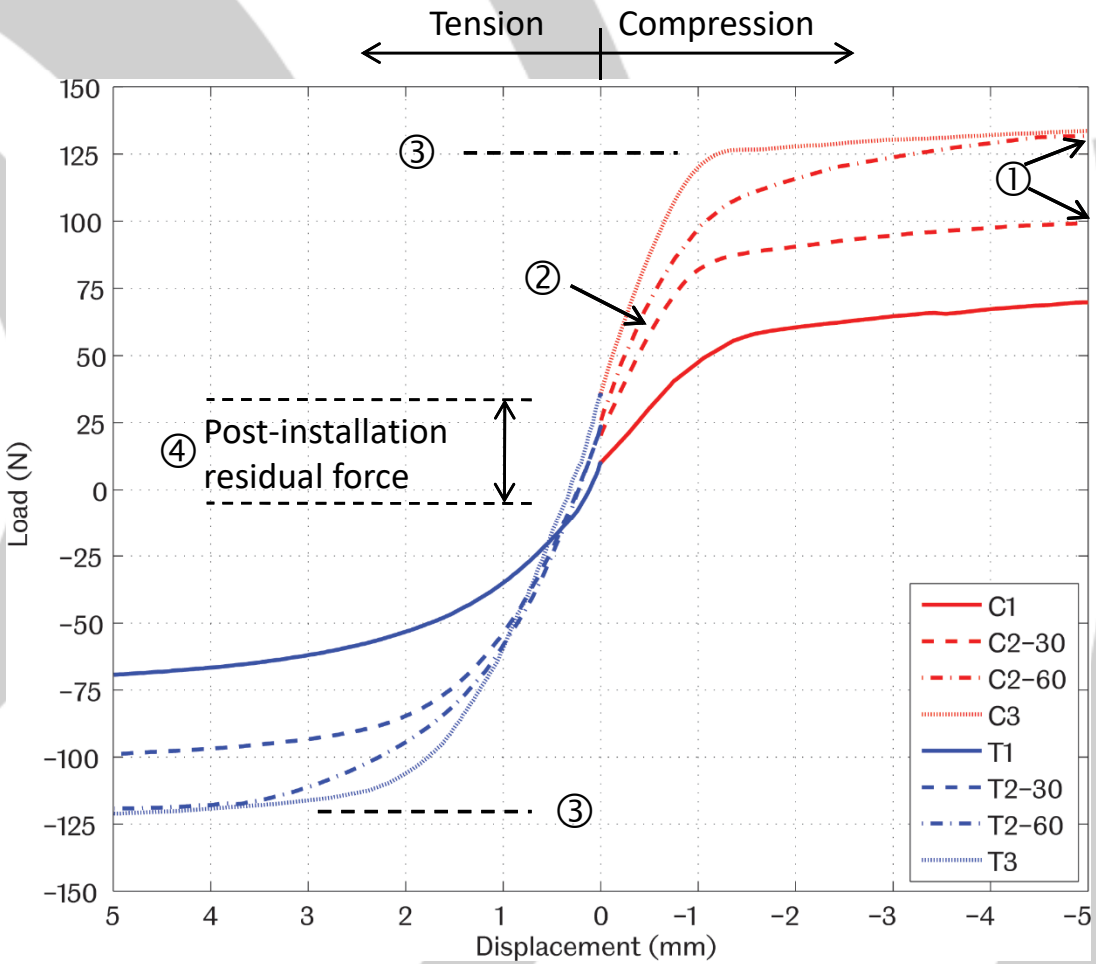
- Machined aluminum piles (1:10)
- Plate diameter (D) = 20mm
- Flight pitch (p) = 5mm
- Shaft diameter (d) = 5mm

- Configurations (spacing – s):
  a. Single helix pile
  b. Double helix pile: s = 30 mm
  c. Double helix pile: s = 60 mm
  d. Triple helix pile: s = 30 mm
- Active Length (L_a) between flights

- Screwed installation
- 0.2 mm/s loading (undrained rate)
- Deep embedment - H>4D
- 24 hour setup period allowed after installation prior to loading

Modelling with Transparent Soil

Helical screw piles: load-deflection performance



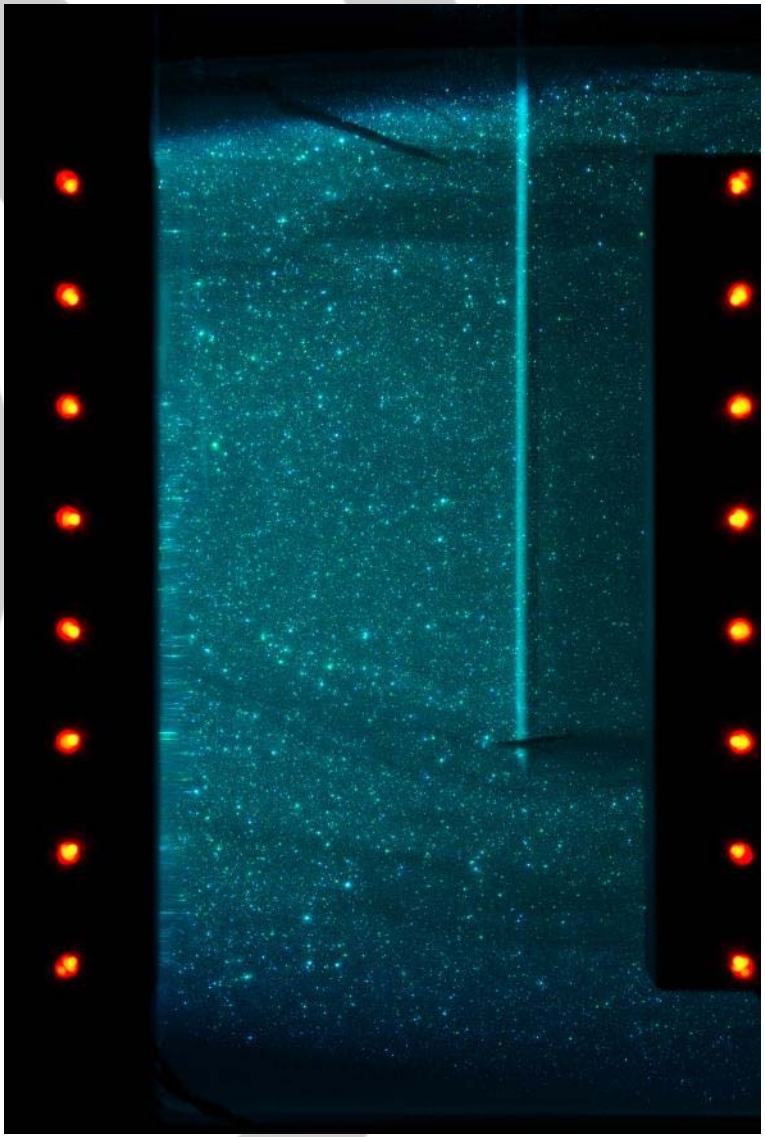
1. Ultimate capacity governed by L_a
   - C2-30 & C2-60
   - C2-60 & C3; L_a = 60mm
2. Development of capacity governed by No. of plates & s/D
   - C3 > C2-60 > C1
   - Increases with No. of plates
3. Compressive and tensile capacity very similar
4. Post-installation residual force proportional to model pile volume
   - i.e. number of helical plates

What are the failure mechanisms?

The University Of Sheffield.

Modelling with Transparent Soil

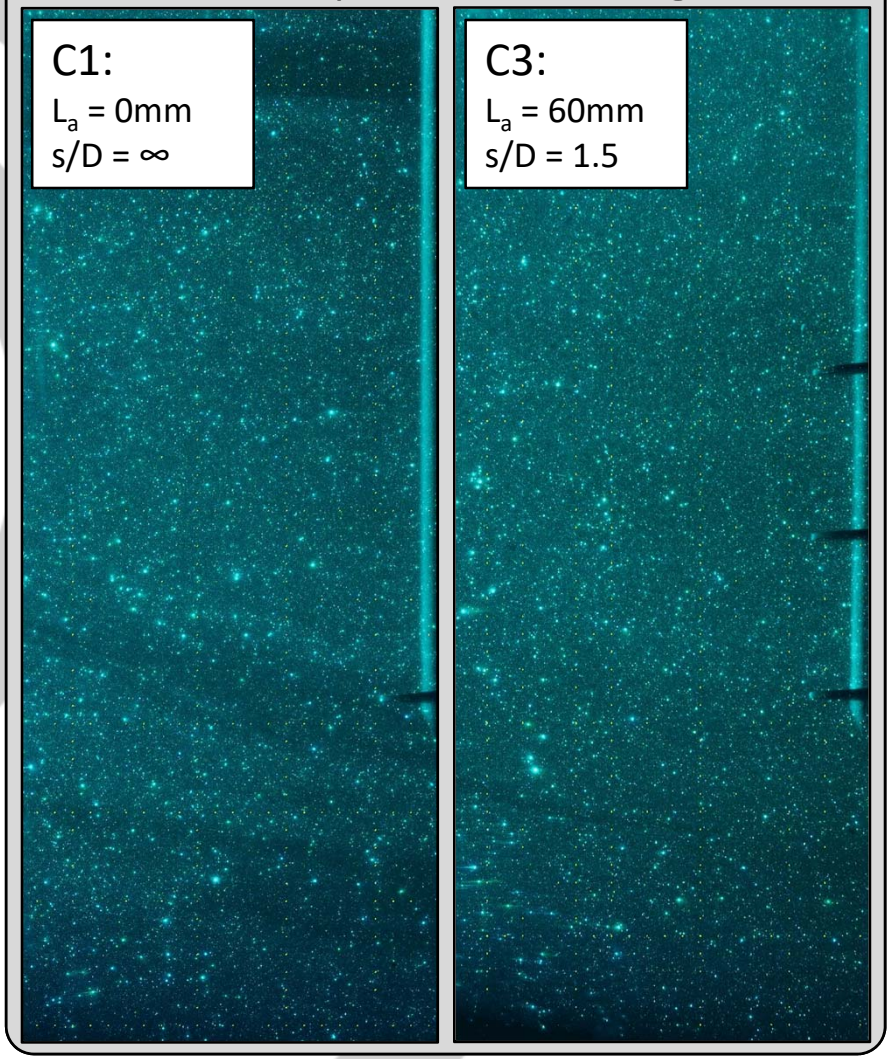
Helical screw piles: test video



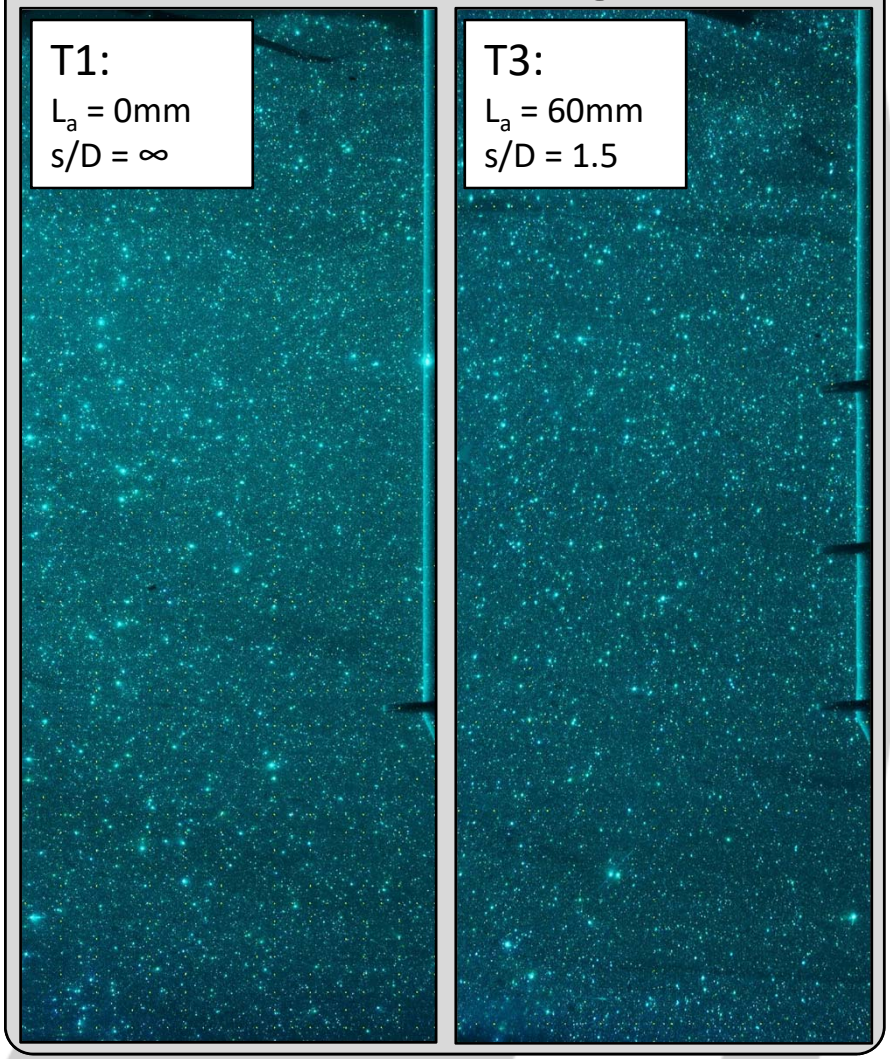
Modelling with Transparent Soil

Helical screw piles: test images

Compressive Loading



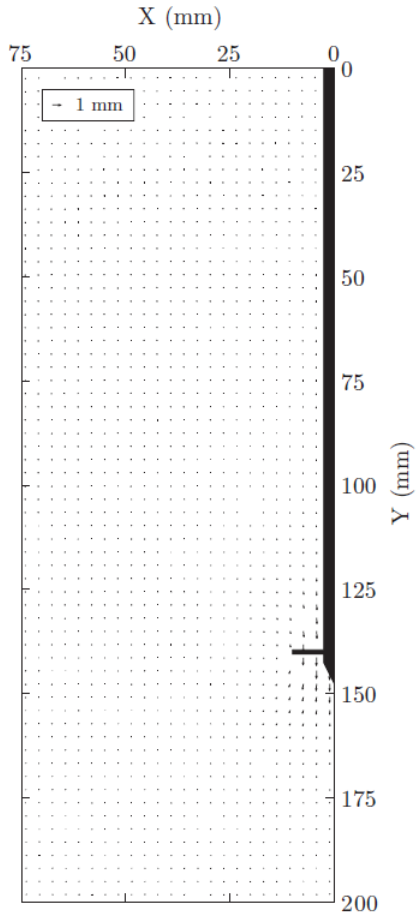
Tensile Loading



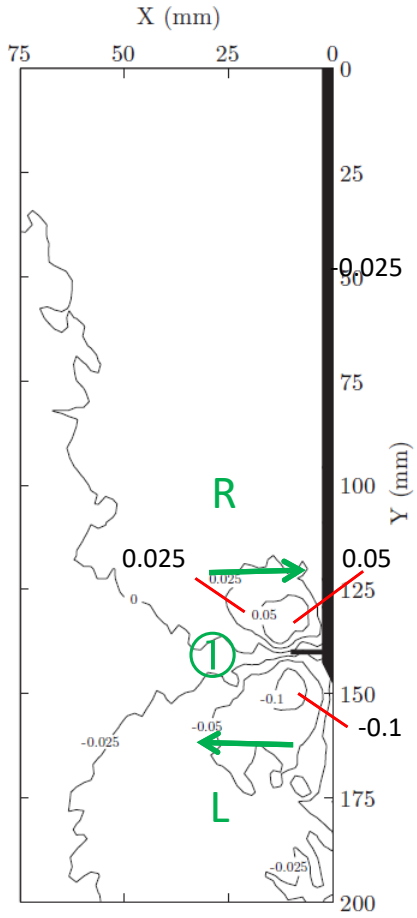
Modelling with Transparent Soil

Test C1 – cumulative behaviour: 0 – 1 mm

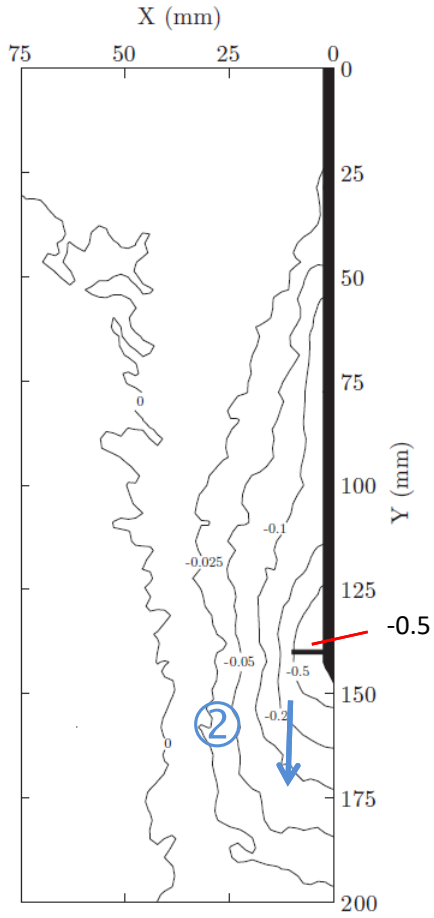
Vector



Horizontal disp



Vertical disp



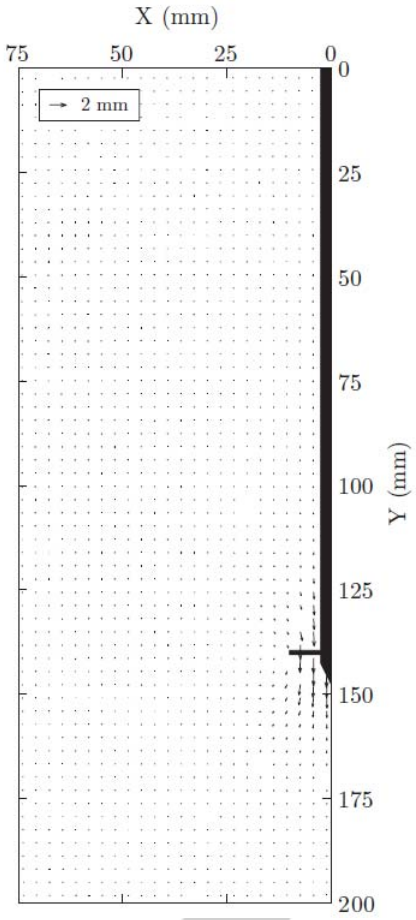
① Soil flow (rotation) around the plate

② Soil downward movement

Modelling with Transparent Soil

Test C1 – cumulative behaviour: 0 – 2 mm

Vector



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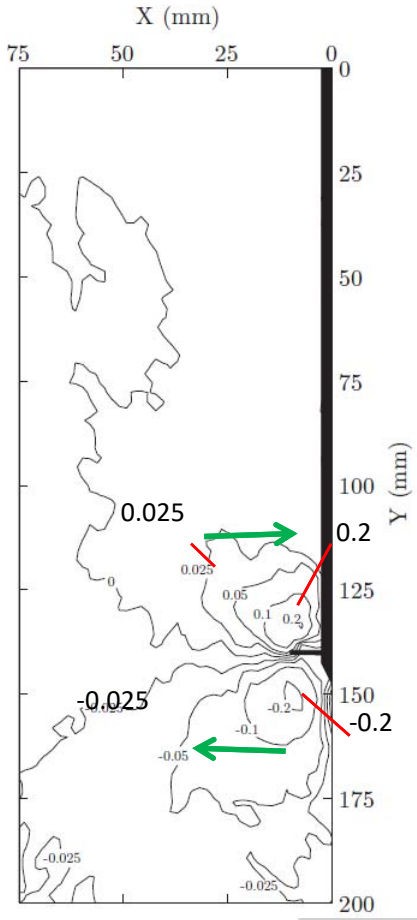
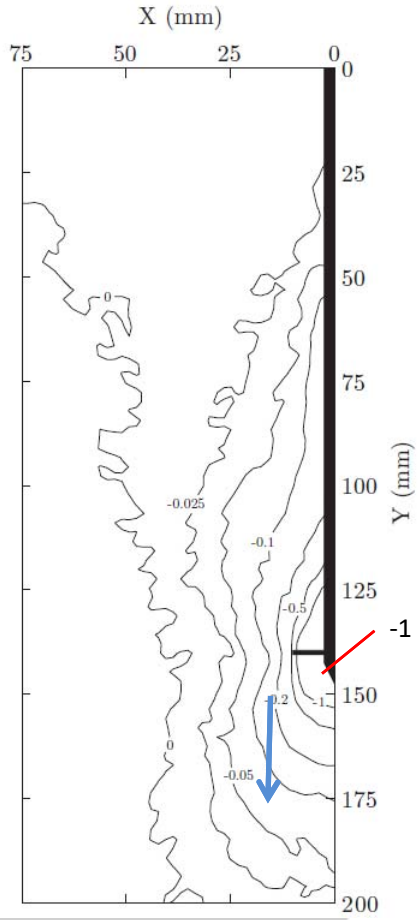


Vertical disp



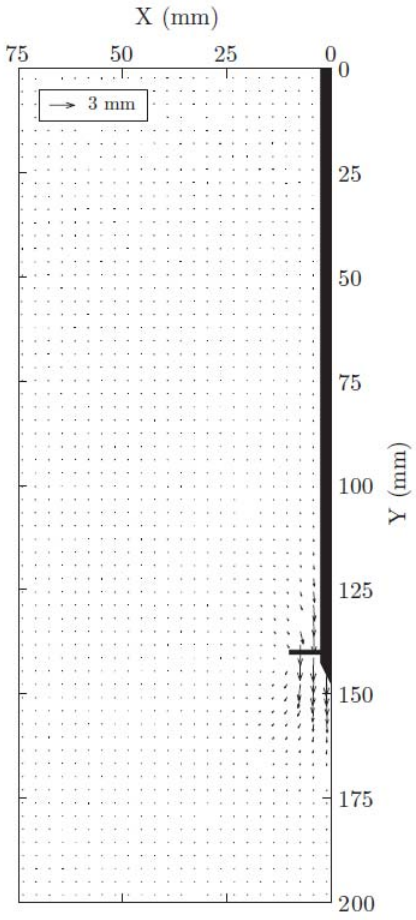
① Soil flow (rotation) around the plate

② Soil downward movement

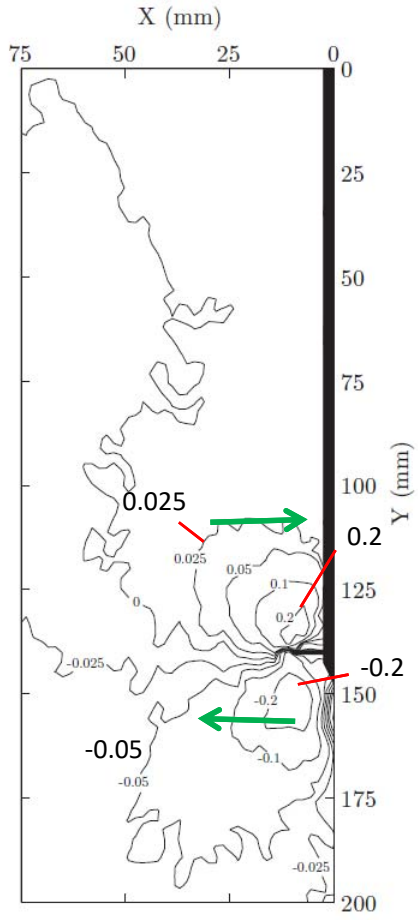
Modelling with Transparent Soil

Test C1 – cumulative behaviour: 0 – 3 mm

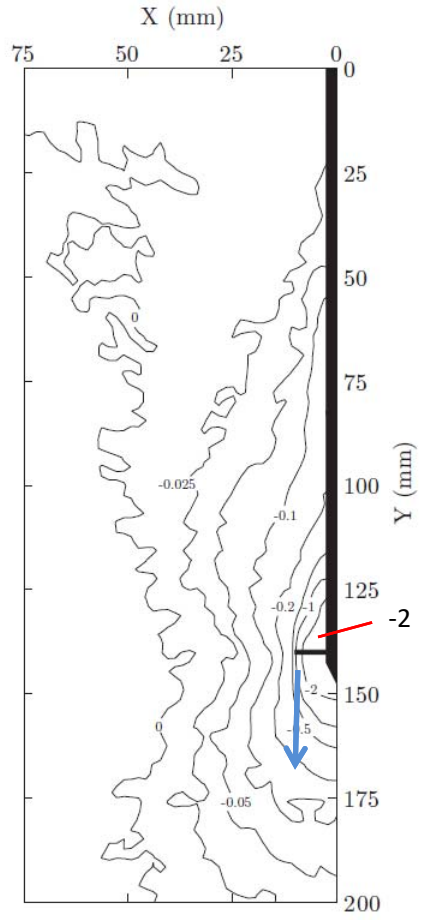
Vector



Horizontal disp



Vertical disp



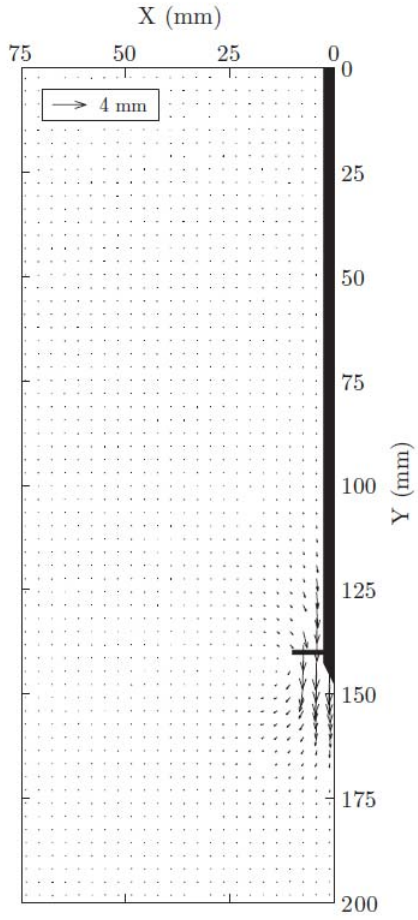
① Soil flow (rotation) around the plate

② Soil downward movement

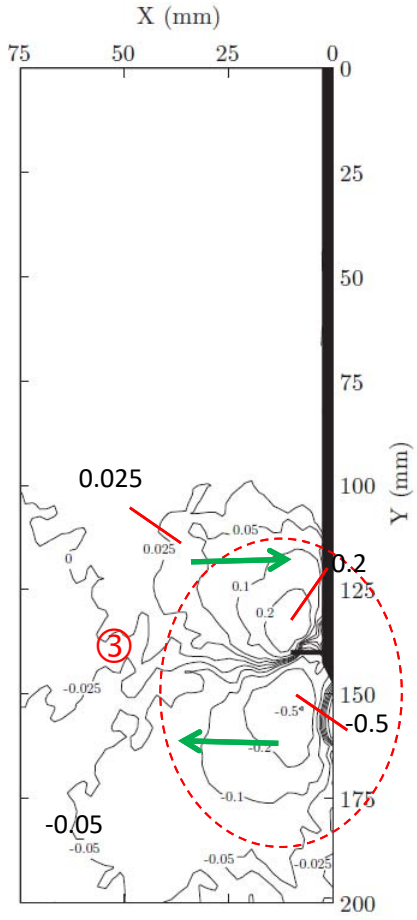
Modelling with Transparent Soil

Test C1 – cumulative behaviour: 0 – 4 mm

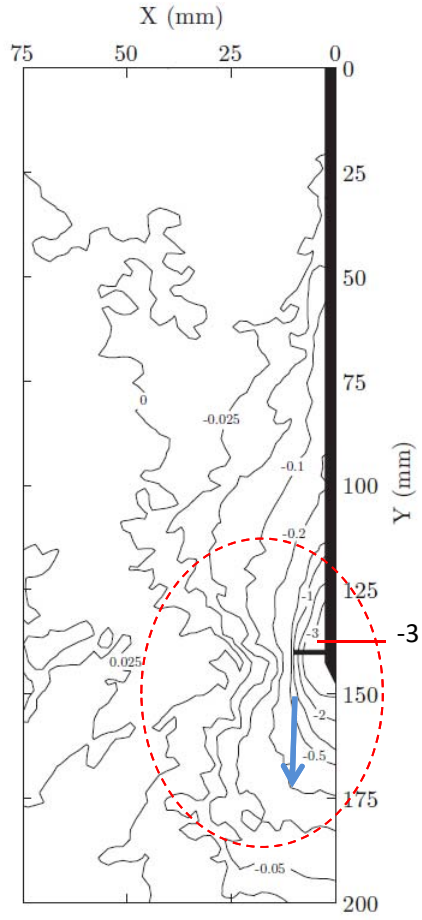
Vector



Horizontal disp



Vertical disp



① Soil flow (rotation) around the plate

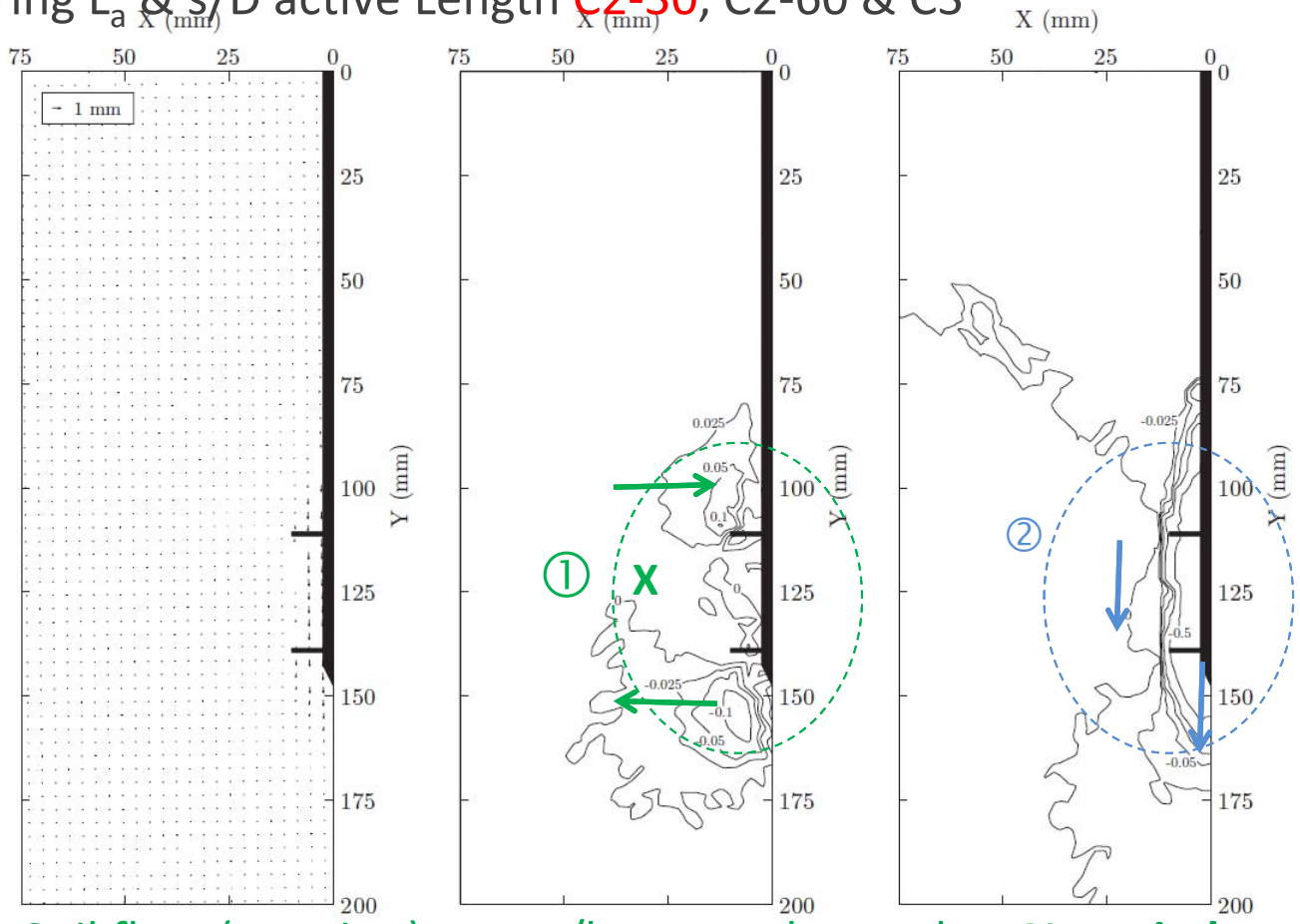
② Soil downward movement

③ Increased magnitudes of displacement

Modelling with Transparent Soil

Test C2-30 – incremental behaviour: 2 – 3 mm

- Comparing L_a & s/D active Length C2-30, C2-60 & C3



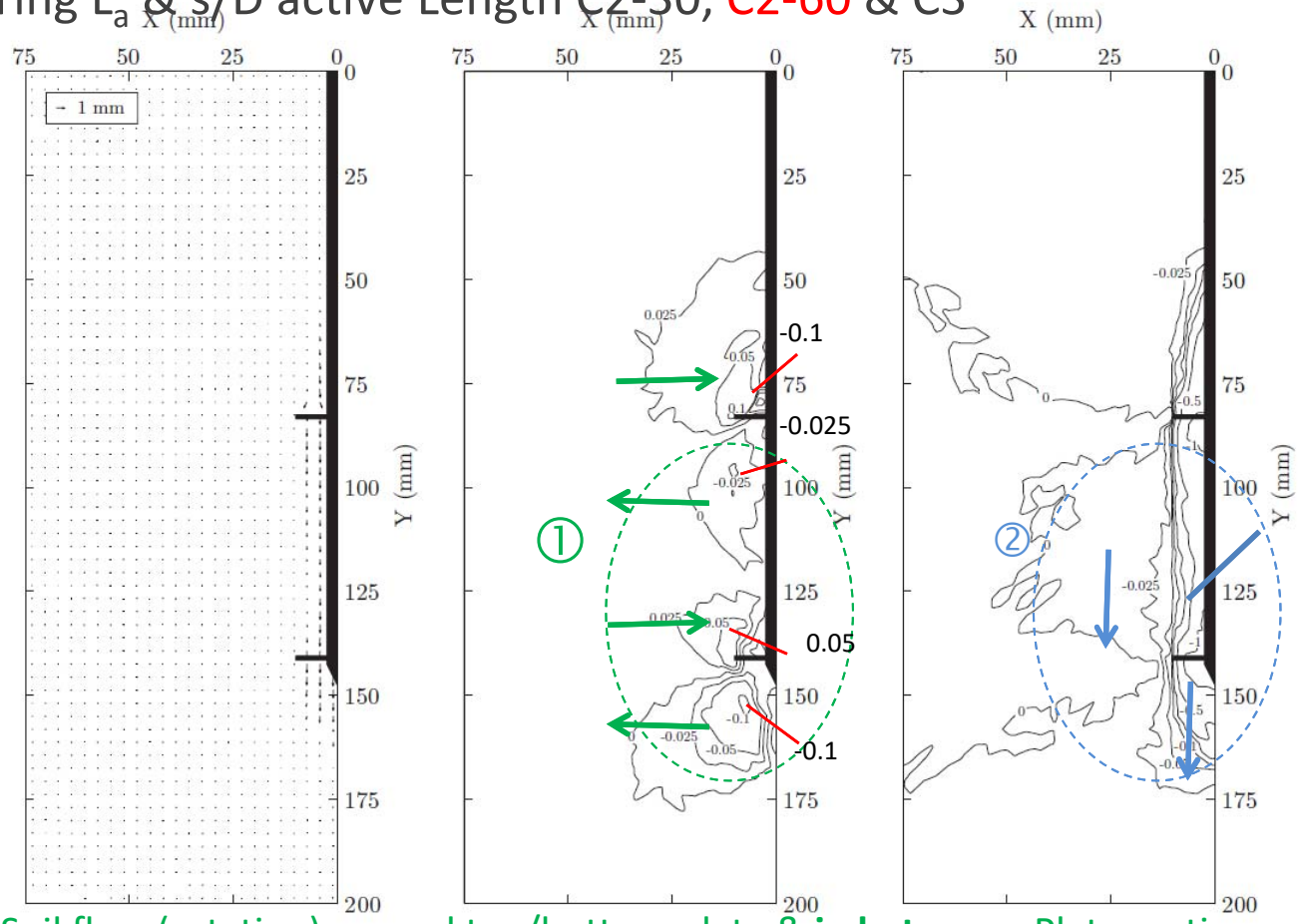
① Soil flow (rotation) at top/bottom plate only – **None in between the plates**

② Soil downward movement beneath – ALONG side of plates

Modelling with Transparent Soil

Test C2-60 – incremental behaviour: 2 – 3 mm

- Comparing L_a & s/D active Length C2-30, C2-60 & C3



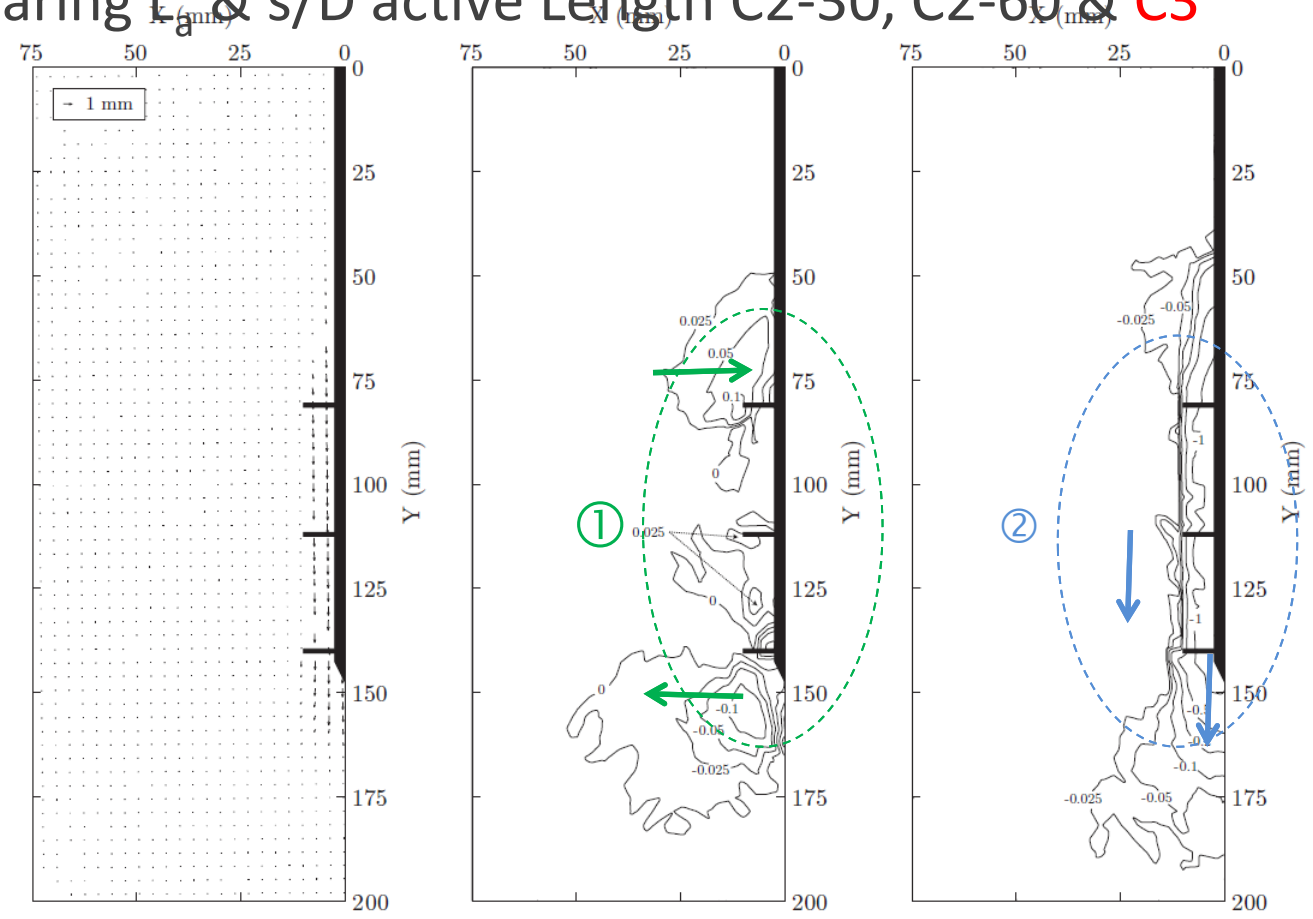
① Soil flow (rotation) around top/bottom plate & **in between**: Plates acting independently as spacing ratio high

② Soil downward movement beneath – ALONG side of plates but not as concentrated at higher s/D

Modelling with Transparent Soil

Test C3 – incremental behaviour: 2 – 3 mm

- Comparing L_a & s/D active Length C2-30, C2-60 & C3

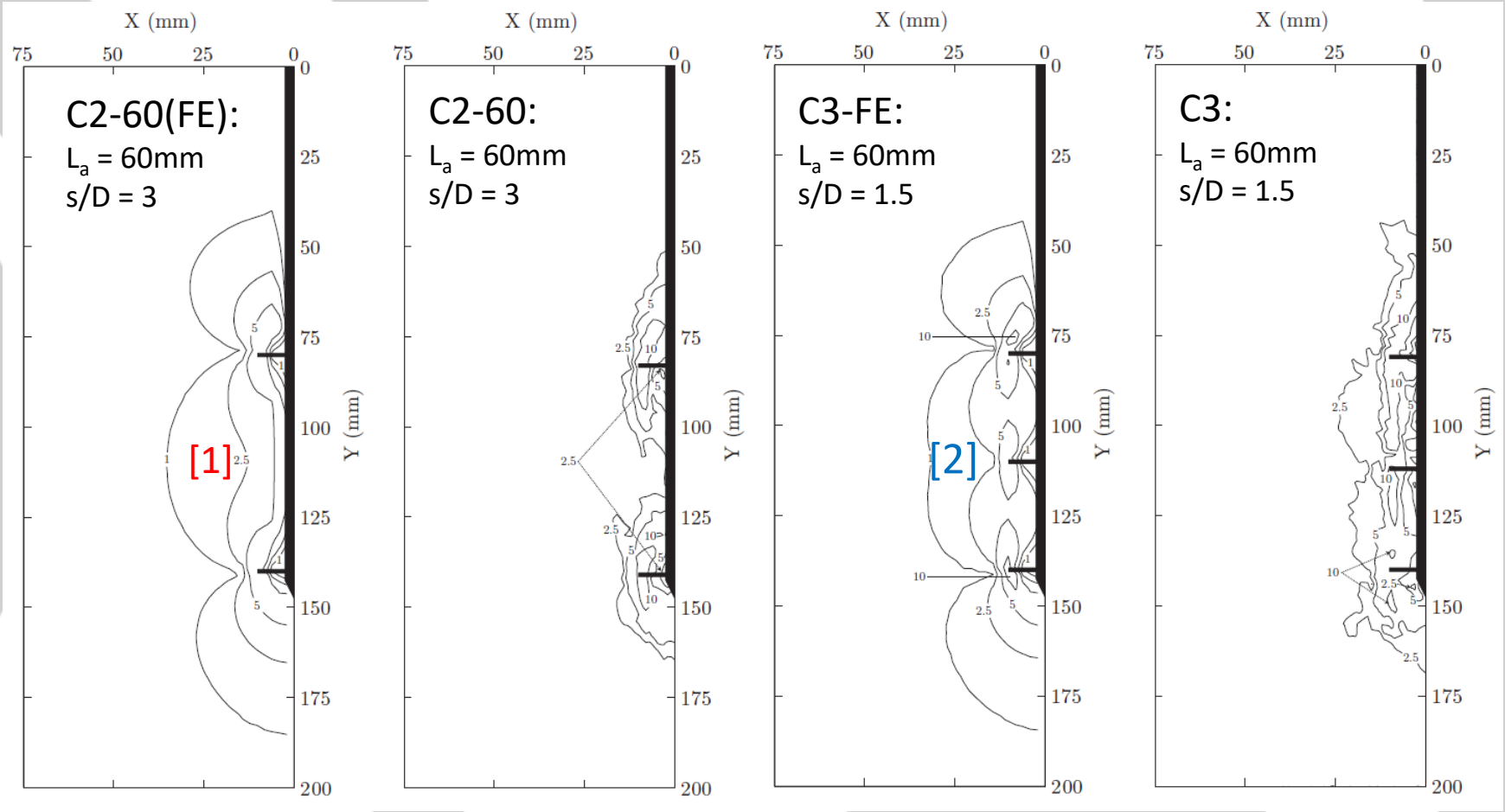


① Soil flow (rotation) around top/bottom plate & not significantly between: soil cylinder formed

② Soil downward movement beneath – ALONG side of plates

Modelling with Transparent Soil

Mode of failure: compressive loading



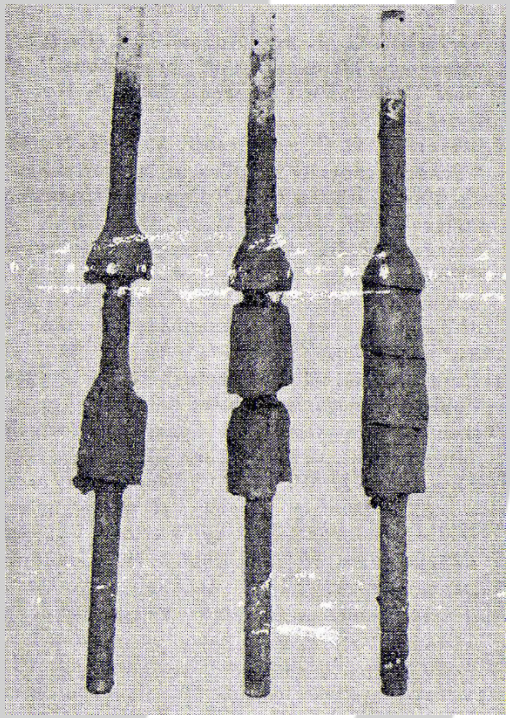
- Shear strain observations similar
  - Isolated plates [1], shear band joining along edge [2]

Modelling with Transparent Soil

Helix screw piles: summary

1. Failure mechanics:
   - Cylindrical failure surface evident for screw piles as hypothesized by Rao et al. 1991.
   - Distinct shear band seen at outer radii of helical plates
   - Individual plate bearing vs cylindrical failure dependent on s/D ratio

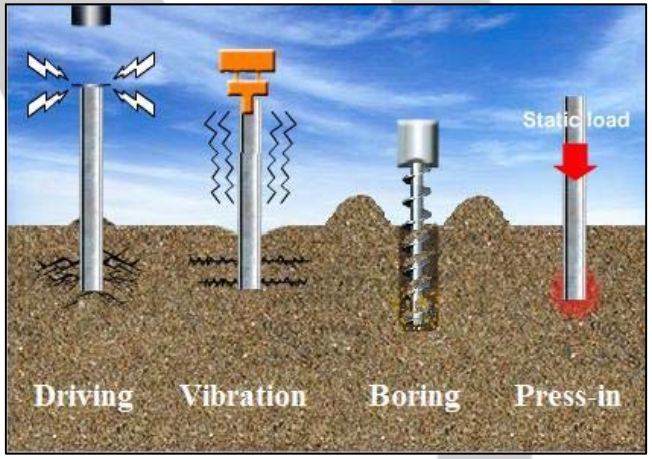
2. Design implications:
   - Correct selection of failure mode
   - ULS capacity governed by L_a
   - Rate of capacity gain governed by s/D ratio



Modelling with Transparent Soil

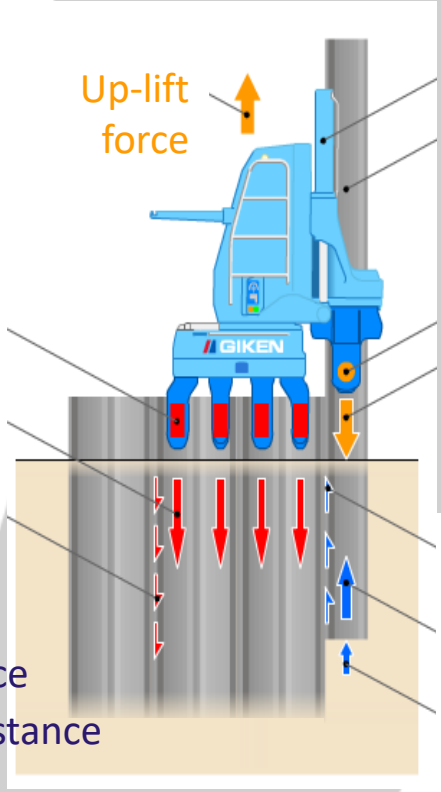
Example application: press-in piling

- Classical Piling methods (driving, vibration, boring)
  - vibrations and soil disturbance



- Reduce installation force
- Ground disturbance

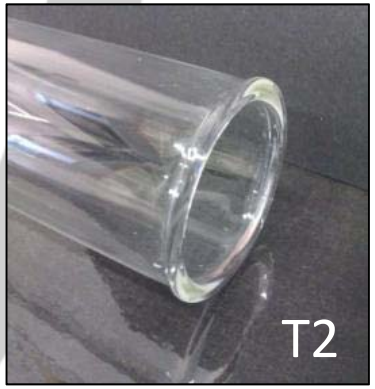
GIKEN

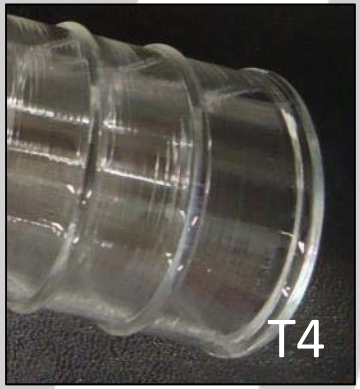


Modelling with Transparent Soil

Press-in piling: model piles

Test	Pile configuration						
	Material	Length (mm)	Straight	Shoe	Rib	Spacing (s:mm)	D_{outer} (mm)
T1	Glass	400	X	-	-	-	46
T2	Glass	400	-	X	-	-	49
T3	Glass	400	-	X	X	30	49
T4	Glass	400	-	X	X	15	49



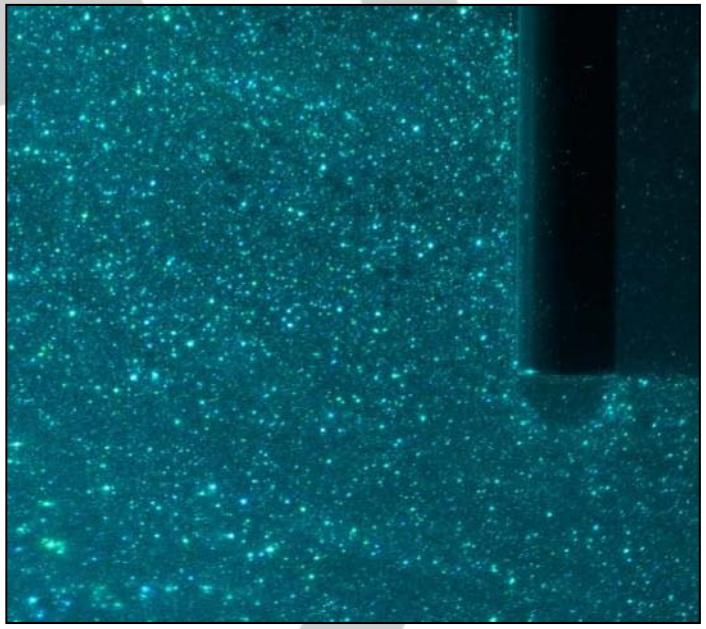


Piles made from glass to allow internal visualisation.

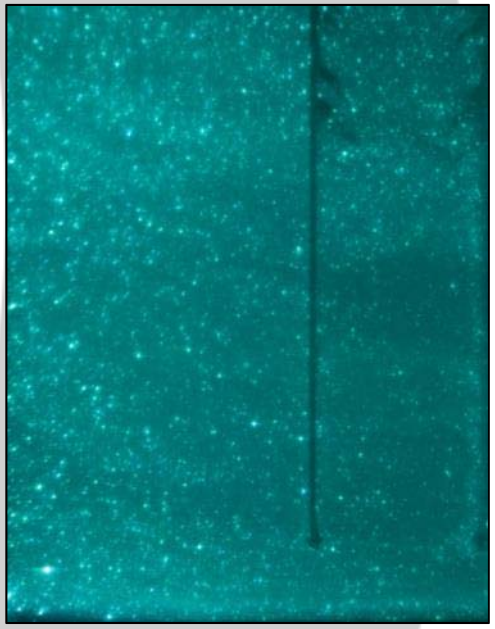
Modelling with Transparent Soil

Press-in piling: internal observations

- Internal visualisation possible



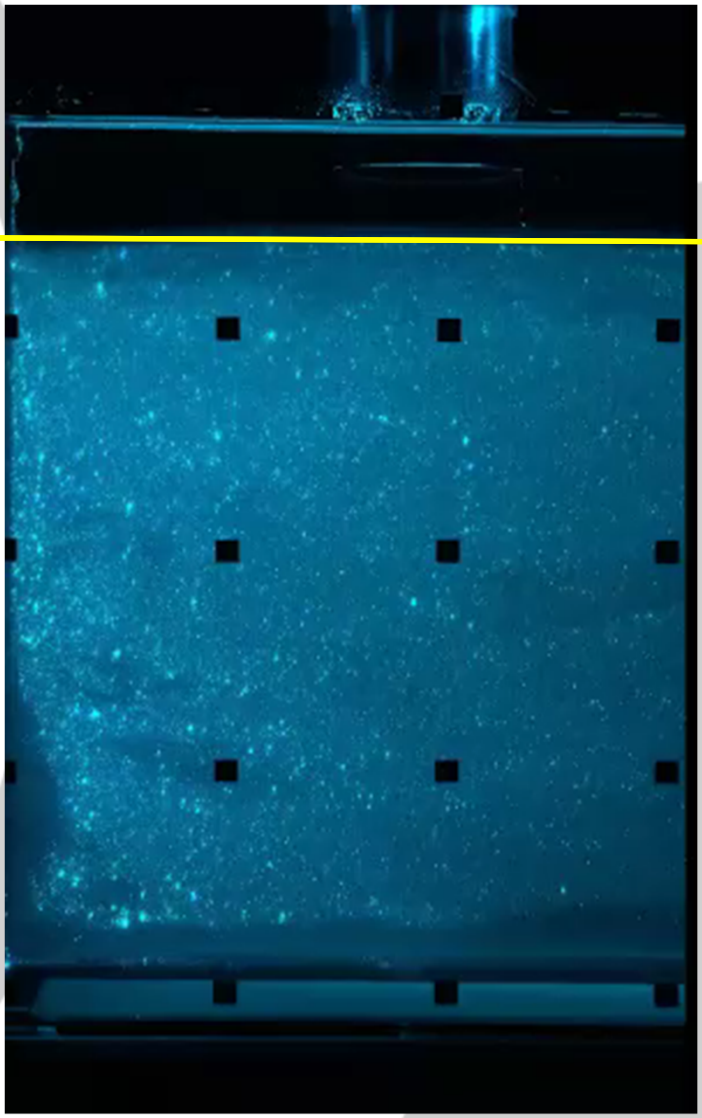
Shadow



No Shadow

Modelling with Transparent Soil

Press-in piling: internal observations



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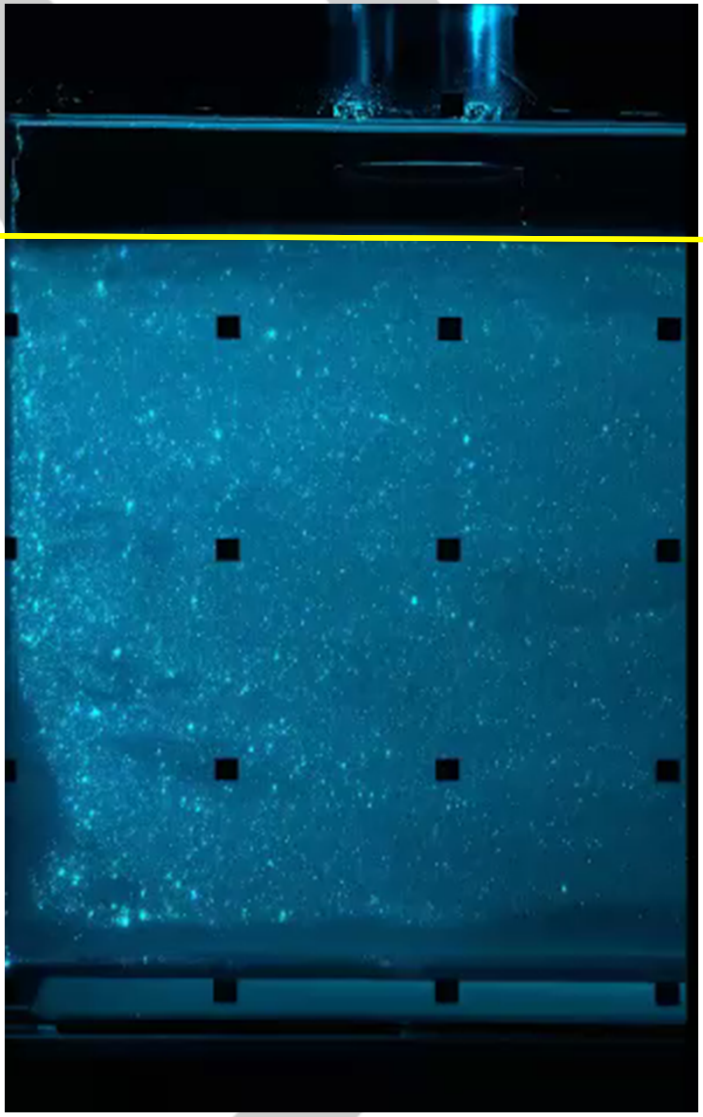
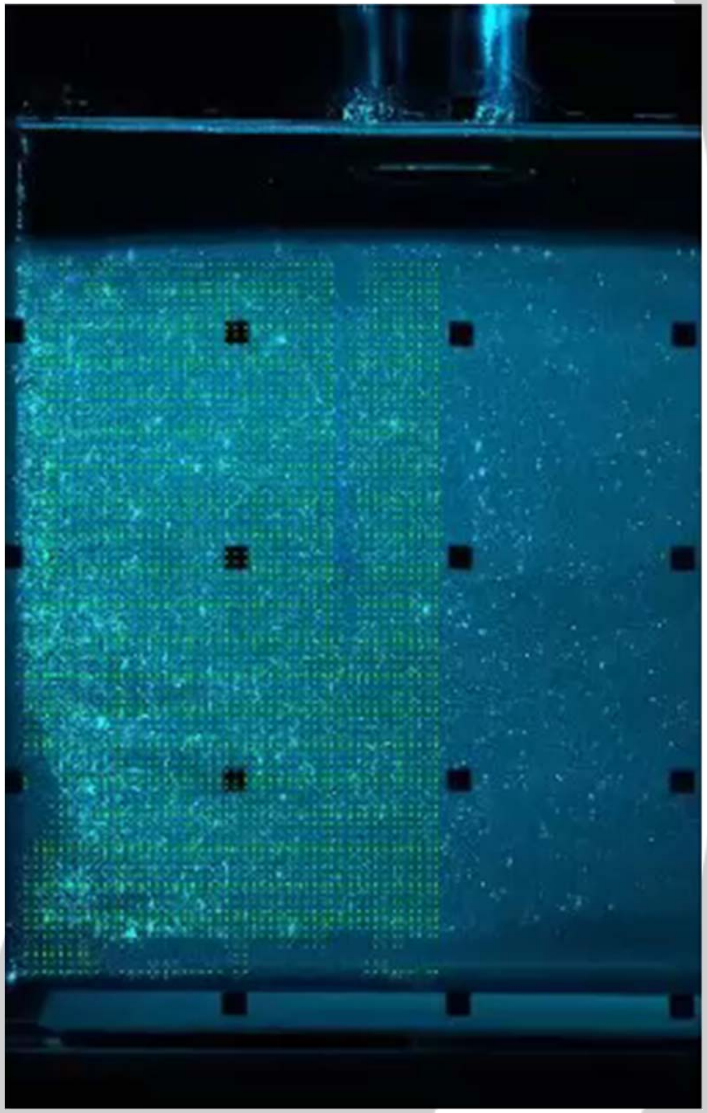
Modelling with Transparent Soil

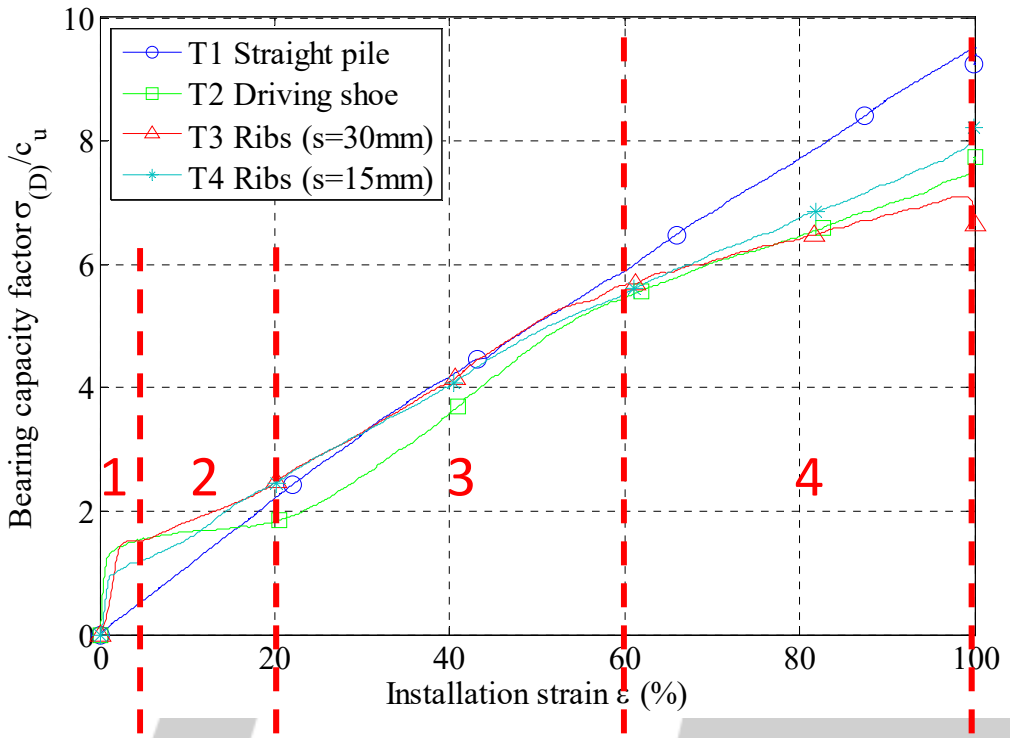
Press-in piling: internal observations





Modelling with Transparent Soil

Press-in piling: load-deflection performance

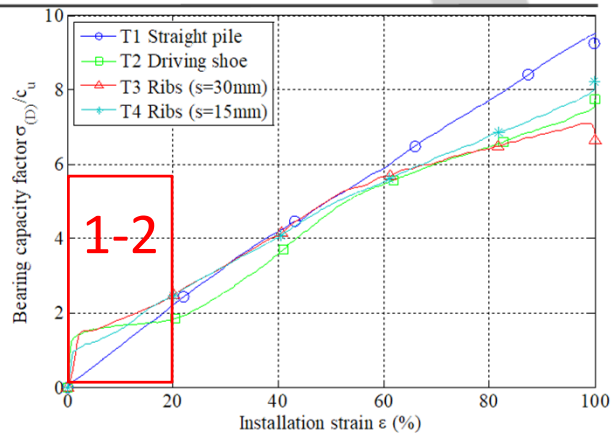


1. Base resistance increased and influenced by the driving shoe
2. Horizontal movement away from the pile
3. Flow around condition and full contact at side
4. Ribs impact and soil plug

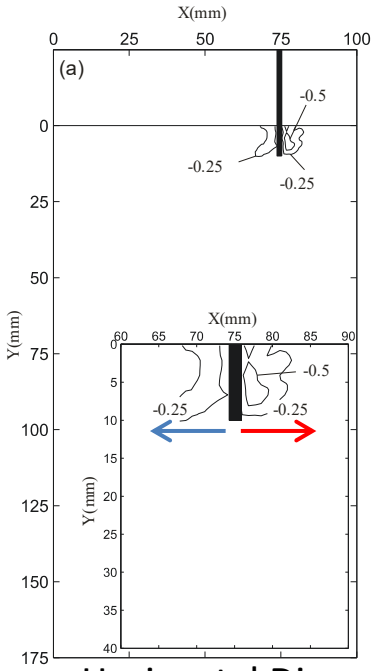
Modelling with Transparent Soil

Soil displacement: initial penetration in Zone 1 - 2

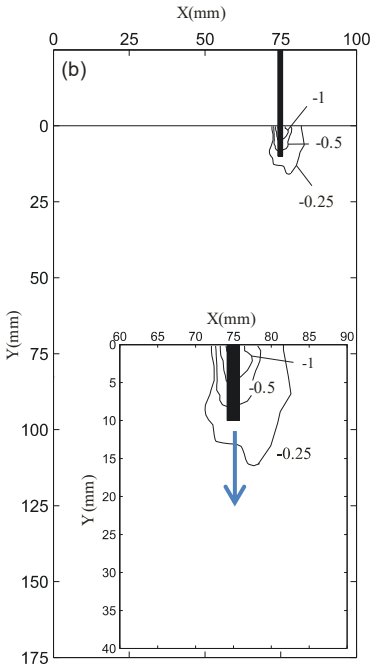
- T1: [1] resistance genereted through the shaft friction
  [2] no initial increase in bearing resistance
- T2, T3, T4:
  [1] increase of initial resistance
  [2] more soil moved due to the driving shoe



Straight Pile

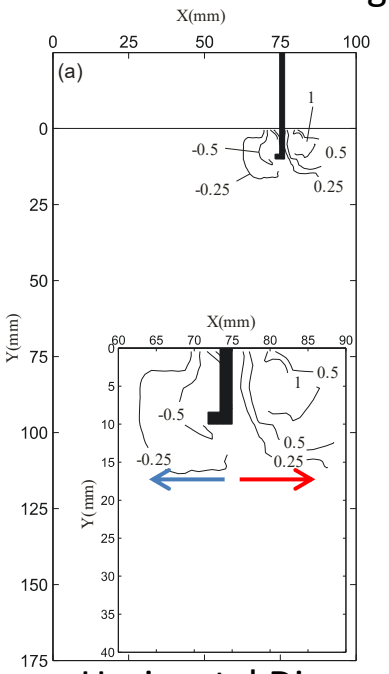


Horizontal Disp.

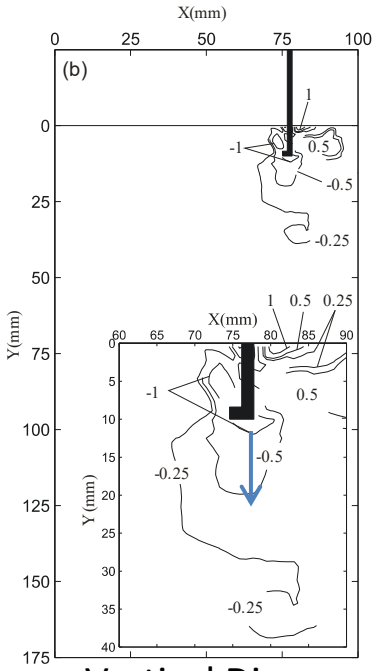


Vertical Disp.

Driving Shoe - Pile



Horizontal Disp.



Vertical Disp.

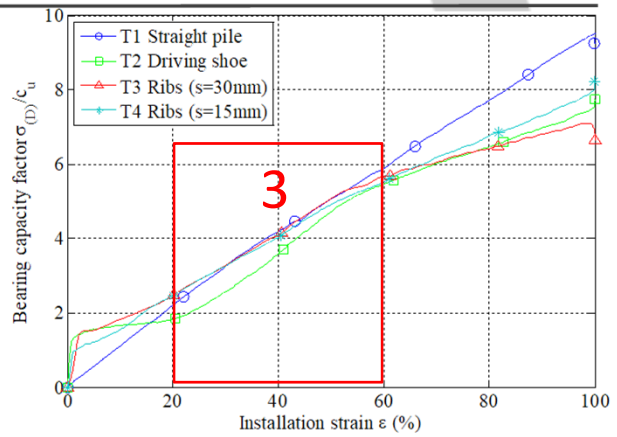
Modelling with Transparent Soil

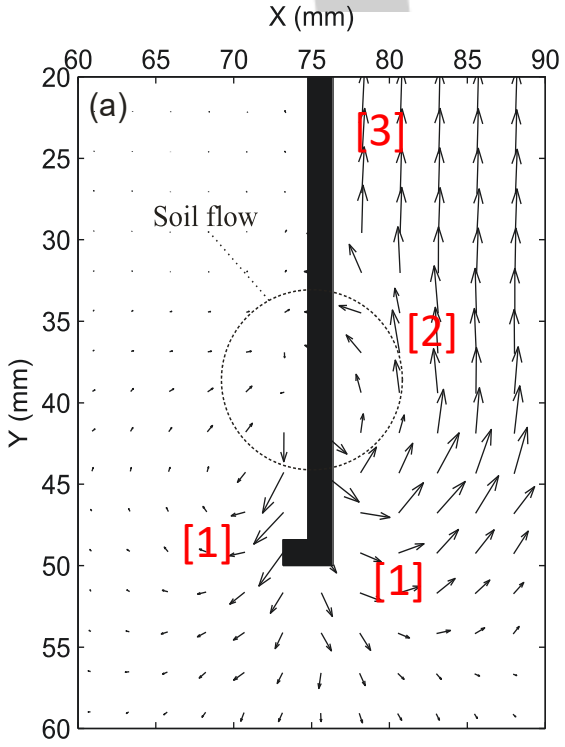
Soil displacement: flow around & shaft re-engagement in Zone 3

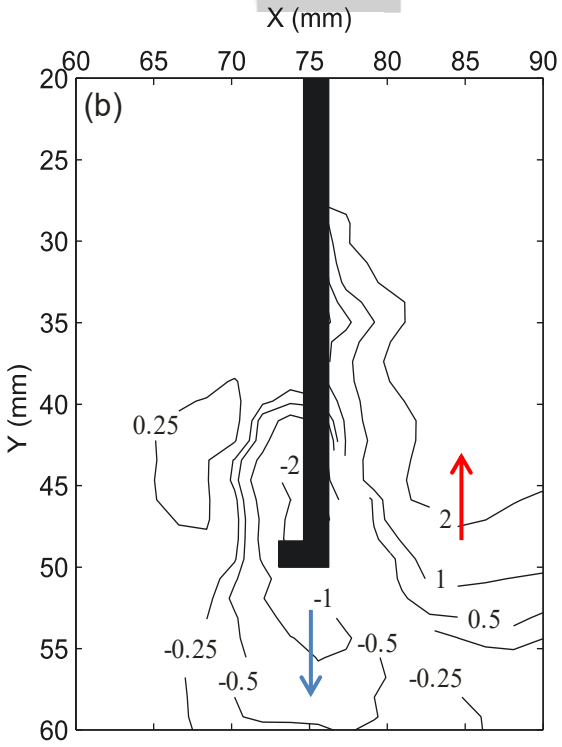
[1] Soil movement away from the outer and inner sides of the shoe

[2] Soil rotation back towards the side increasing confinement & the internal stress

[3] Re-engagement of the shaft frictional resistance on load plot



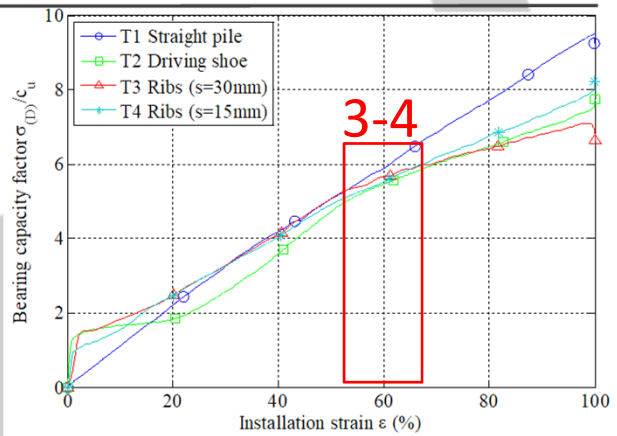


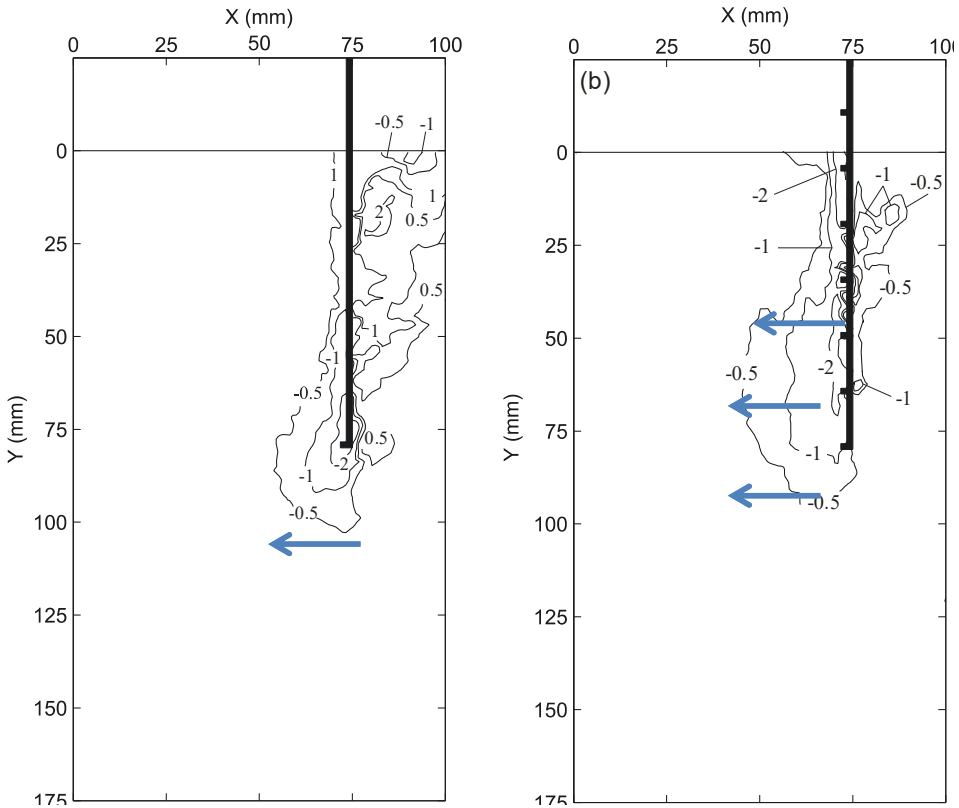


Modelling with Transparent Soil

Soil displacement: impact of surface body ribs

- Increased horizontal movement away from pile side along the length





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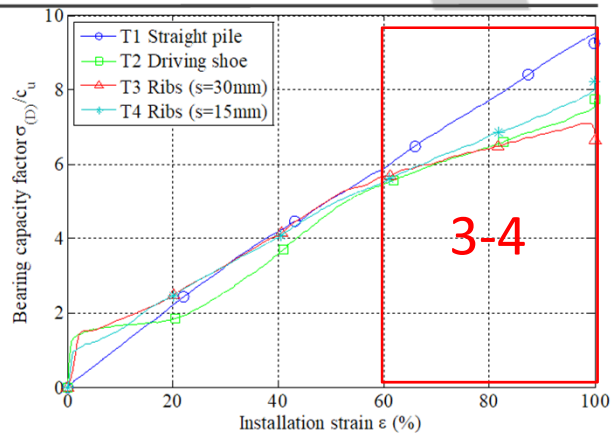
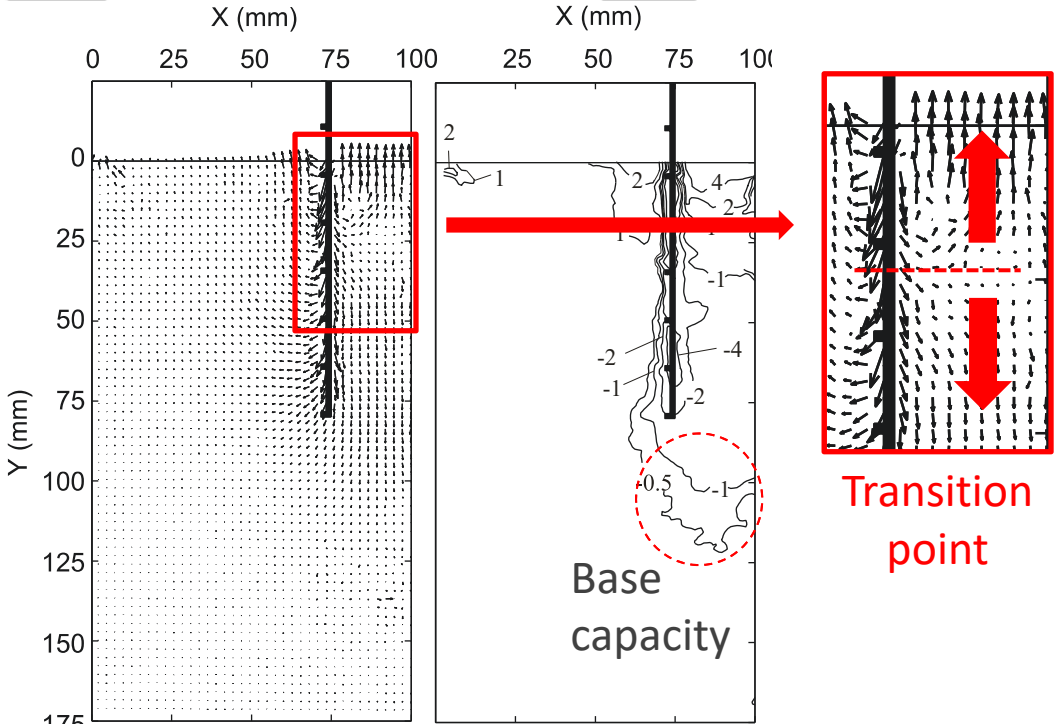
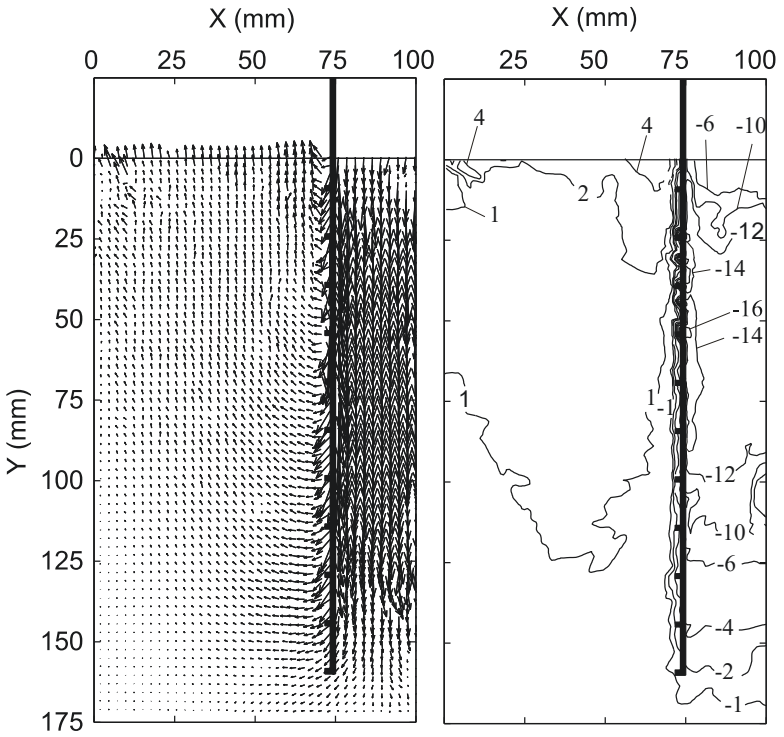
Modelling with Transparent Soil

Soil displacement: soil plugging in Zone 4

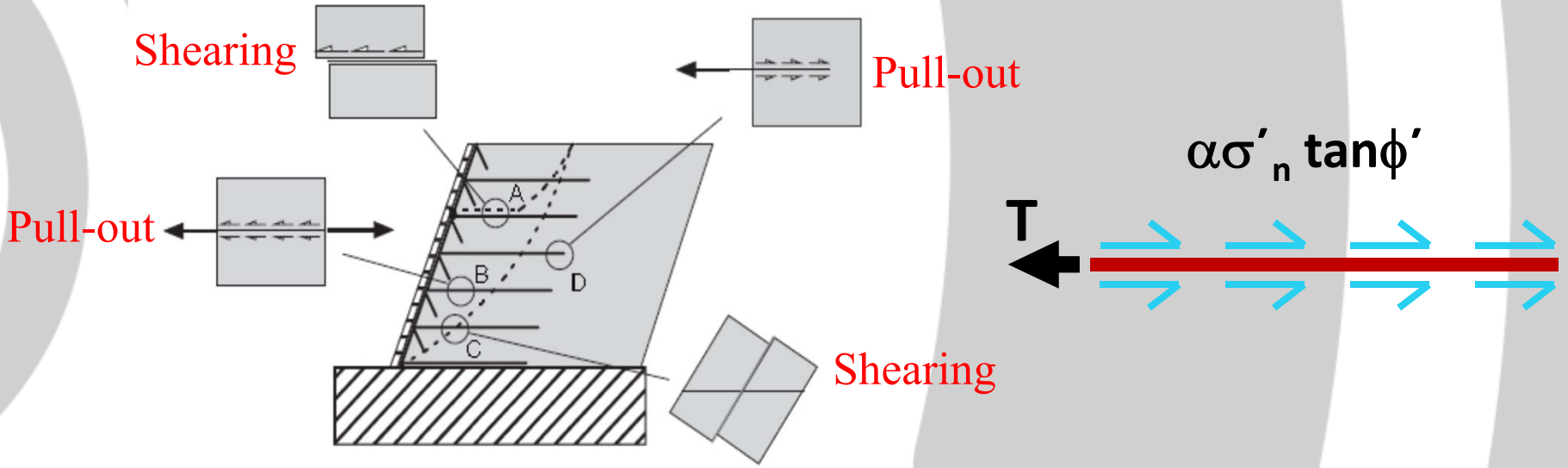
- Soil plugging
  - change in soil direction inside the pile;
  - onset of soil plugging inside the pile where a lost in shaft friction occurs
  - 'Switch on' of base resistance







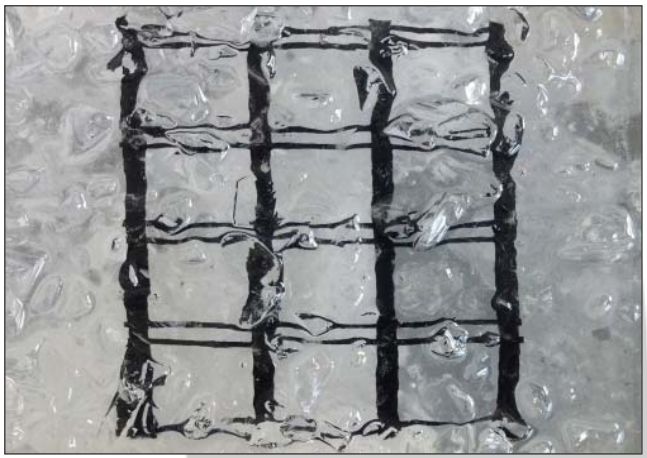
Interaction in geo-reinforcement presents a major challenge in design



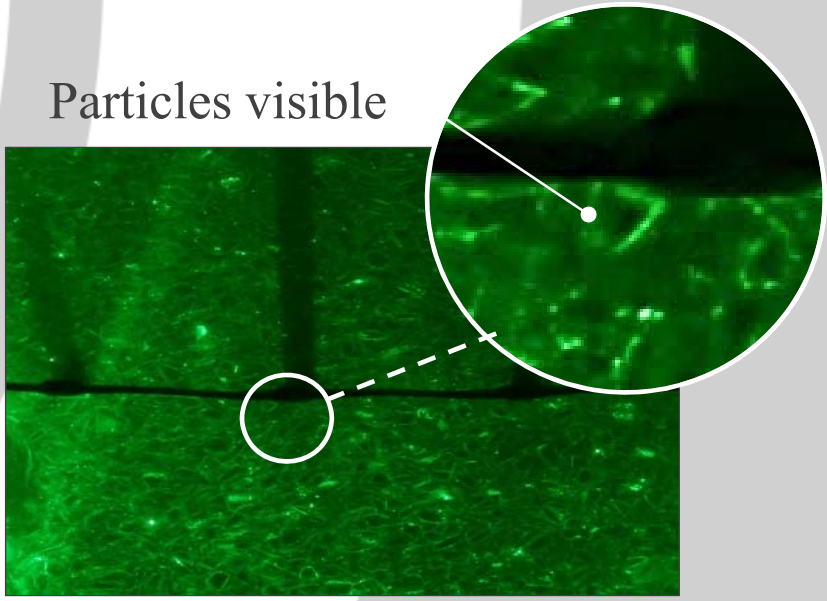
- Interface coefficient (α) not well understood and defined in a broad range in design [α = 0.6 to 0.8]
- Need for greater understanding of interaction mechanics

Modelling with Transparent Soil

Soil Reinforcement

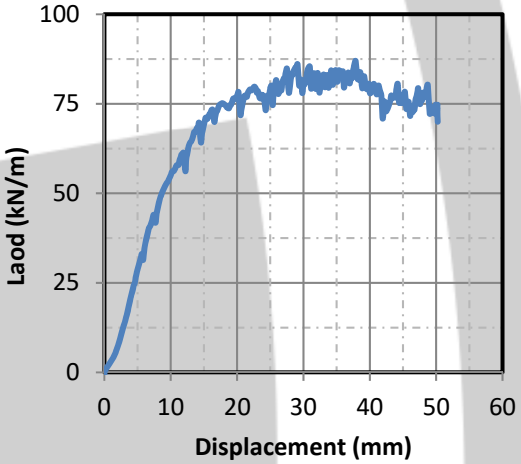


Particles visible

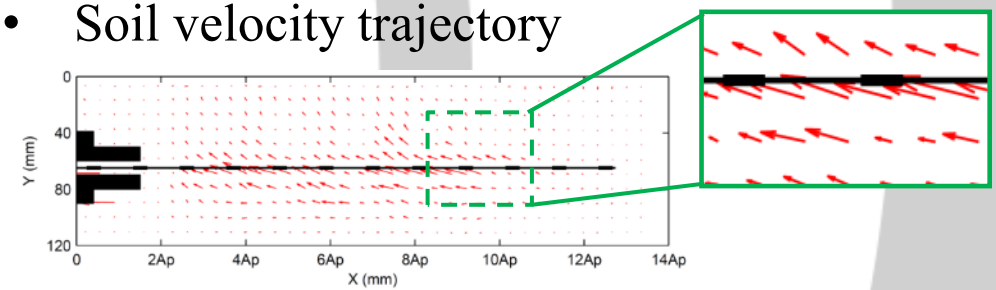


Data output and appraisal

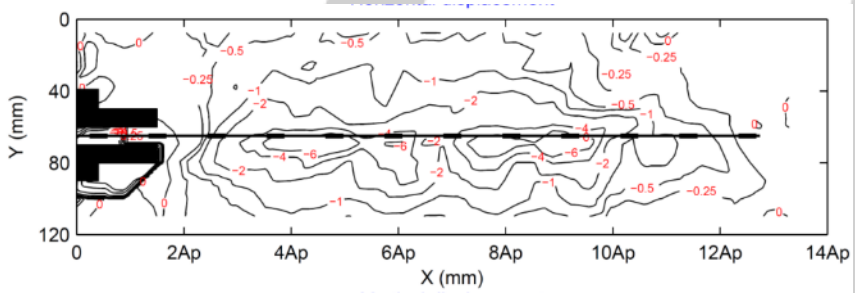
- External – Load / Disp. behaviour



- Internal – Soil interaction behaviour [DIC]
  - Soil velocity trajectory



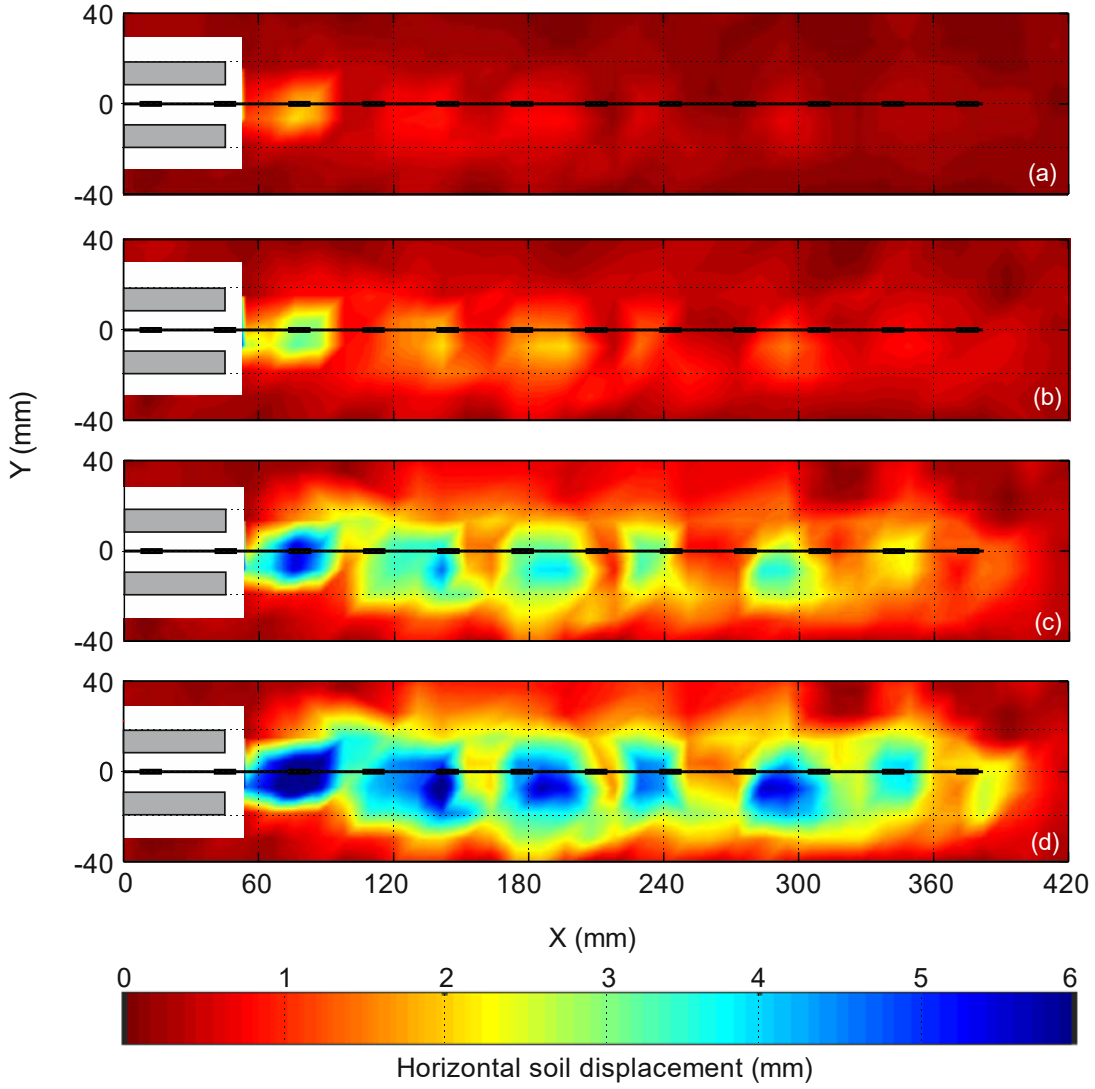
  - Vertical & Horizontal Contours of displacement



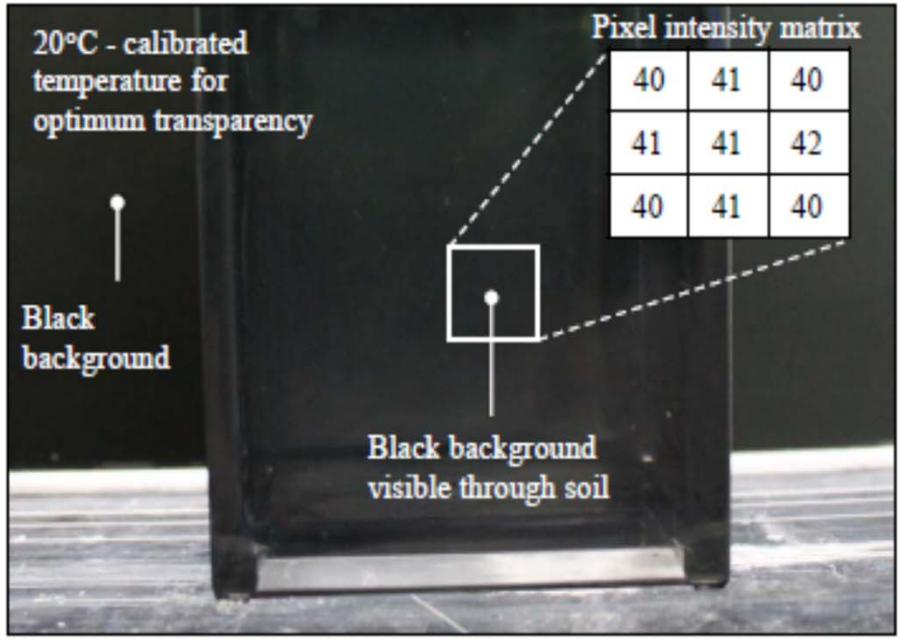
- Region of soil movement
- Zone of influence
- Local & global response (cumulatively & incrementally)

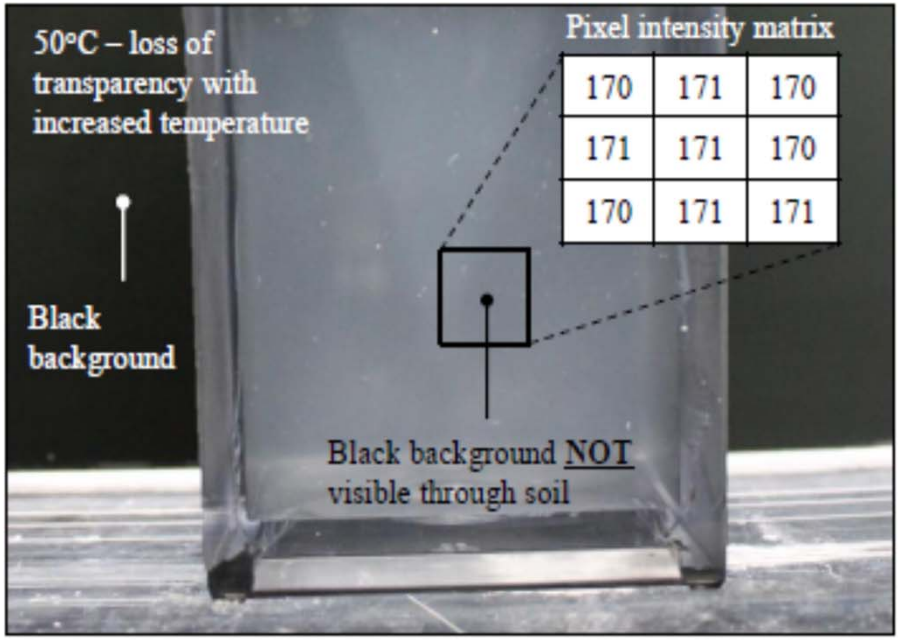
Interaction behaviour of soil and geo-grid reinforcement

Reinforced soils



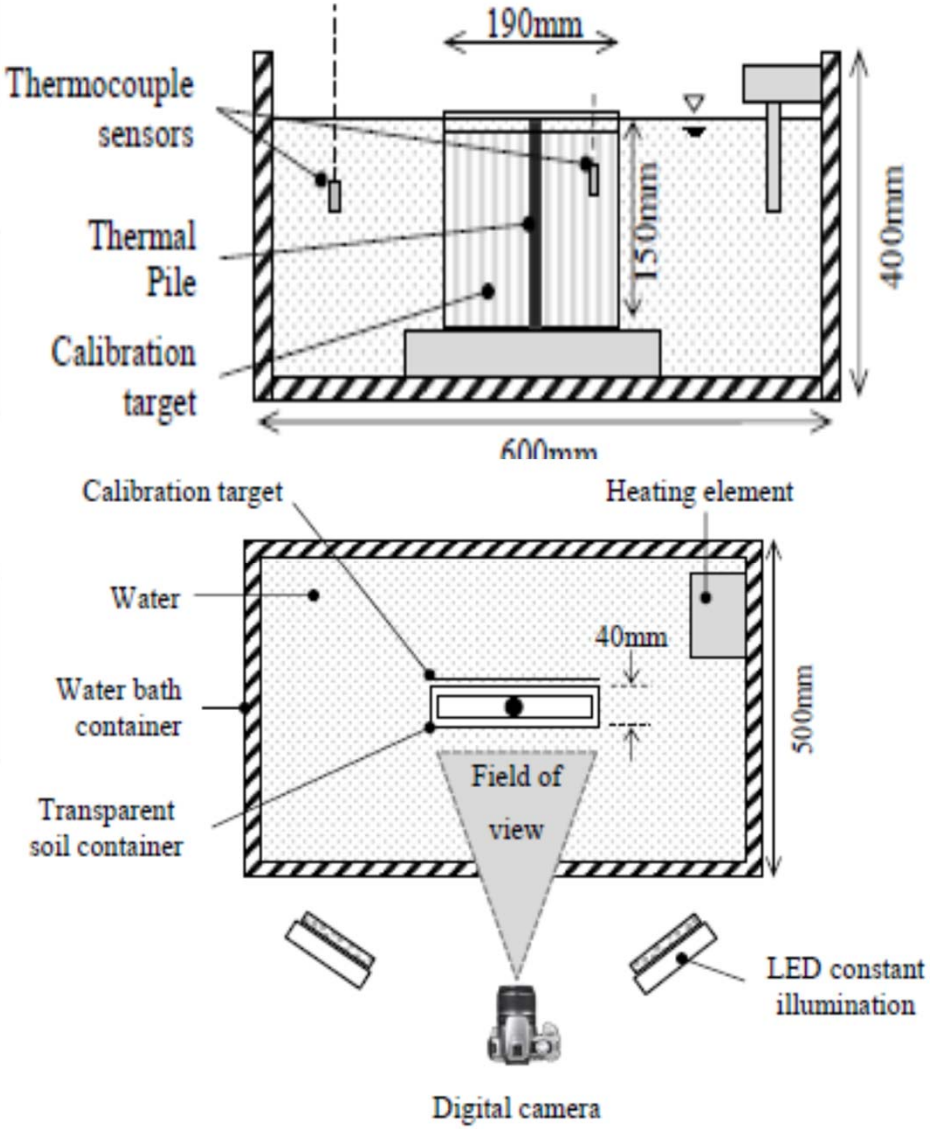
Energy Piles

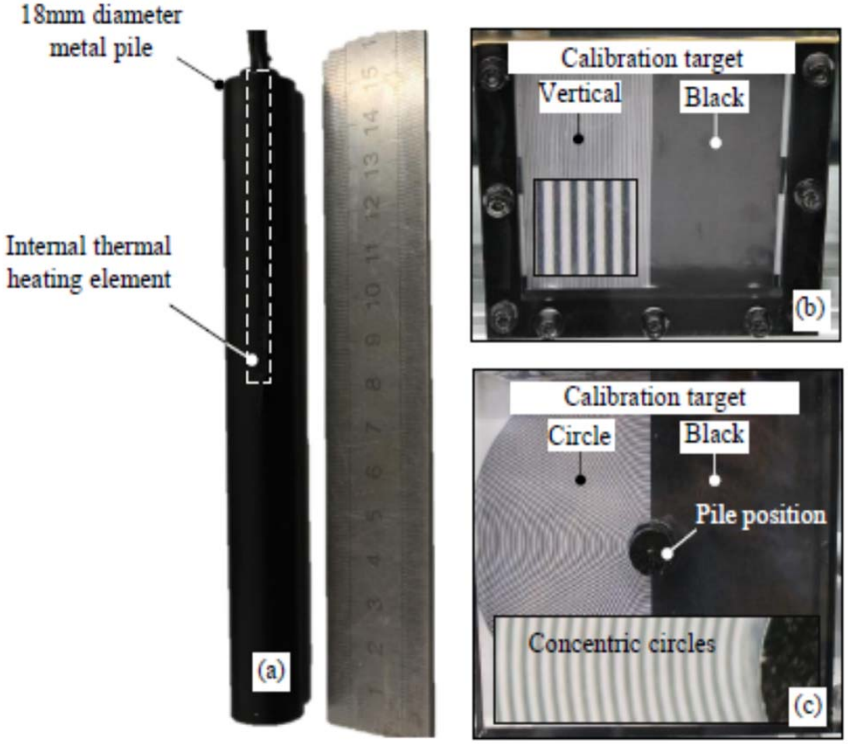




Modelling with Transparent Soil

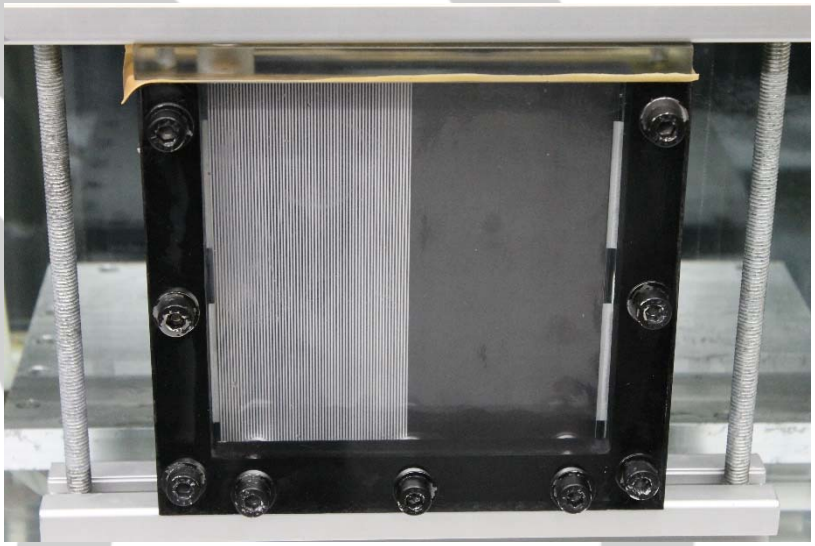
Thermal Modelling

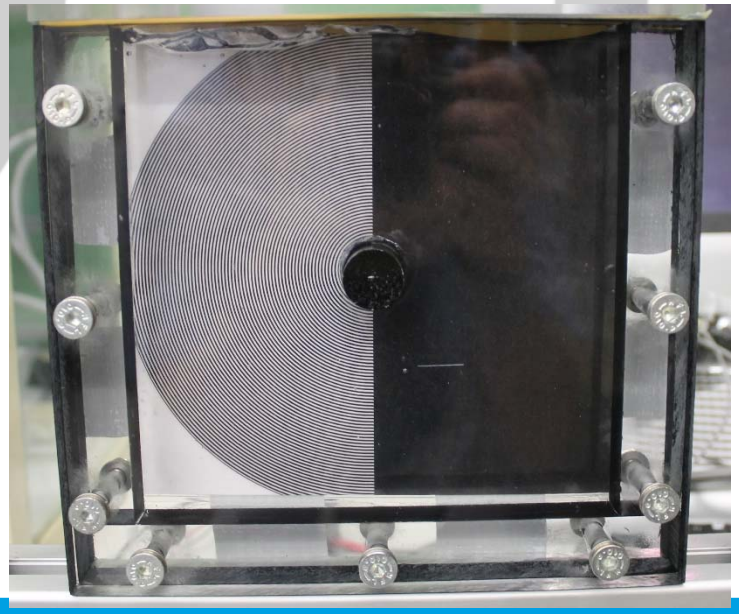


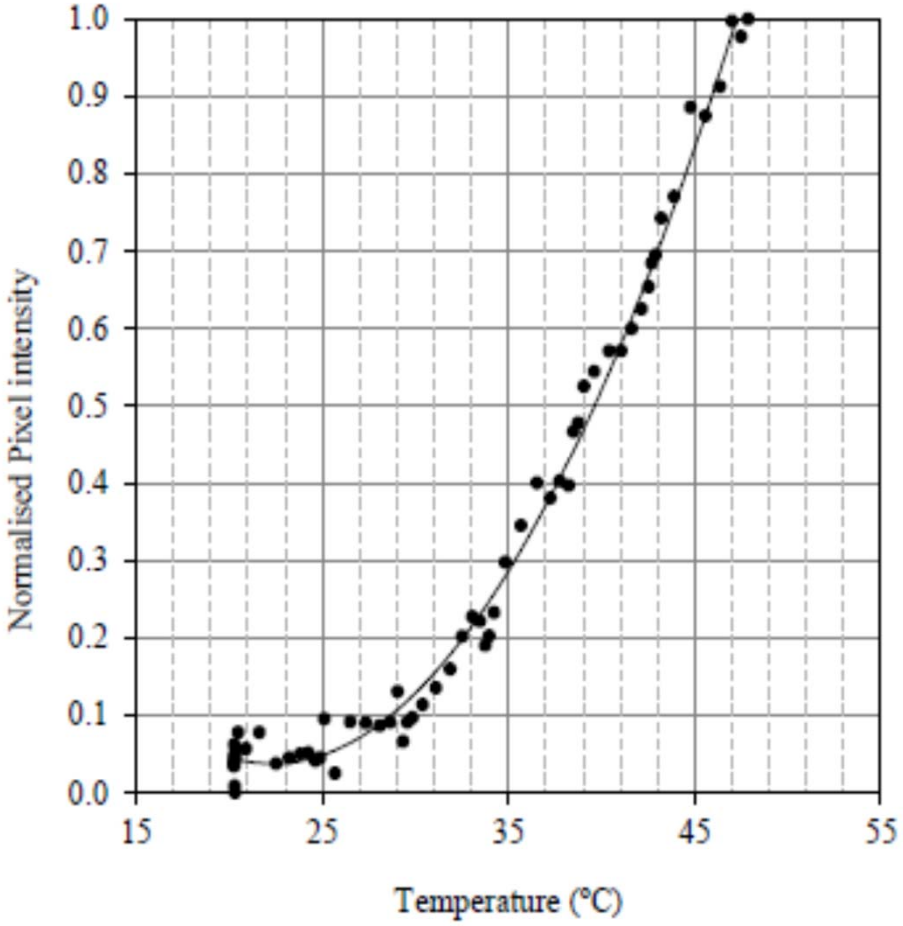


Modelling with Transparent Soil

Thermal Modelling

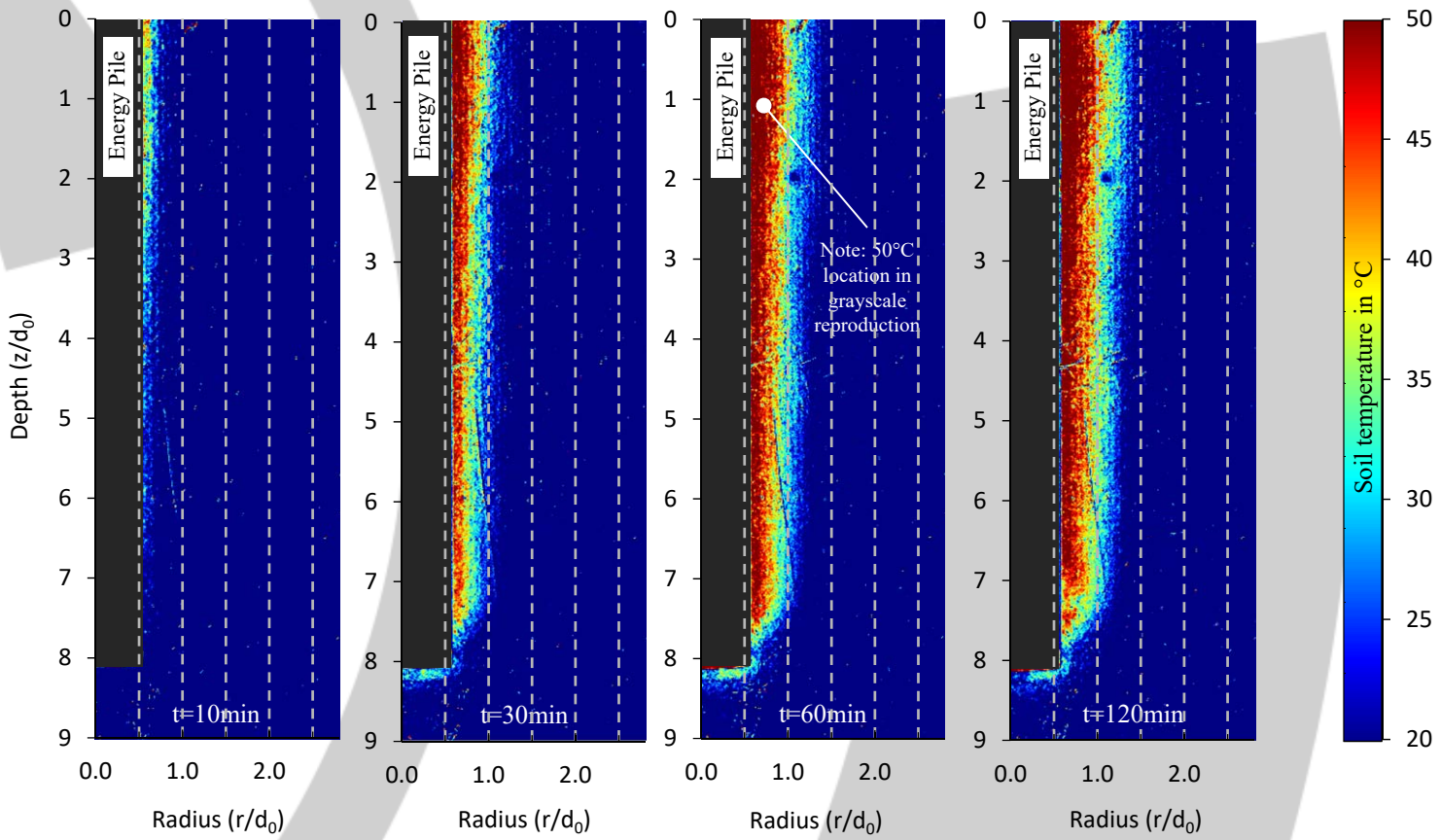






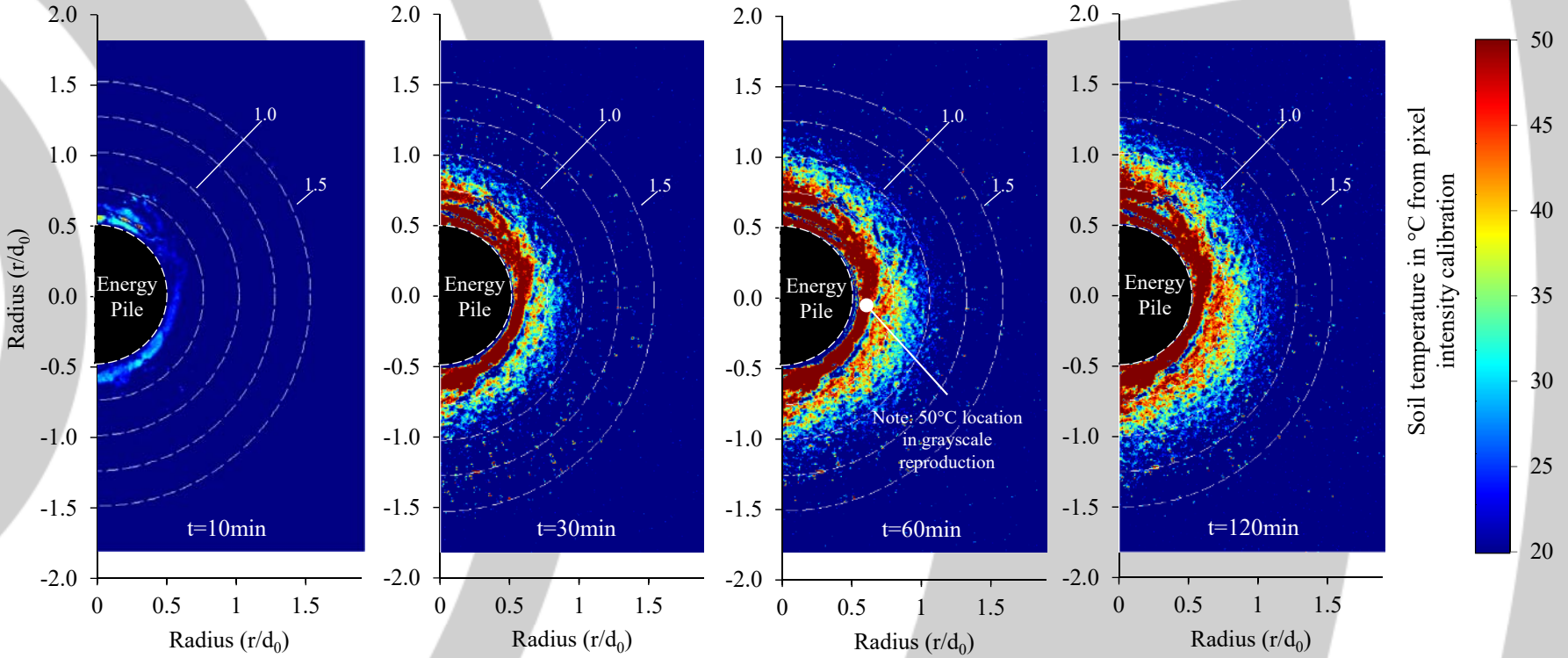
Modelling with Transparent Soil

Thermal Modelling



Modelling with Transparent Soil

Thermal Modelling



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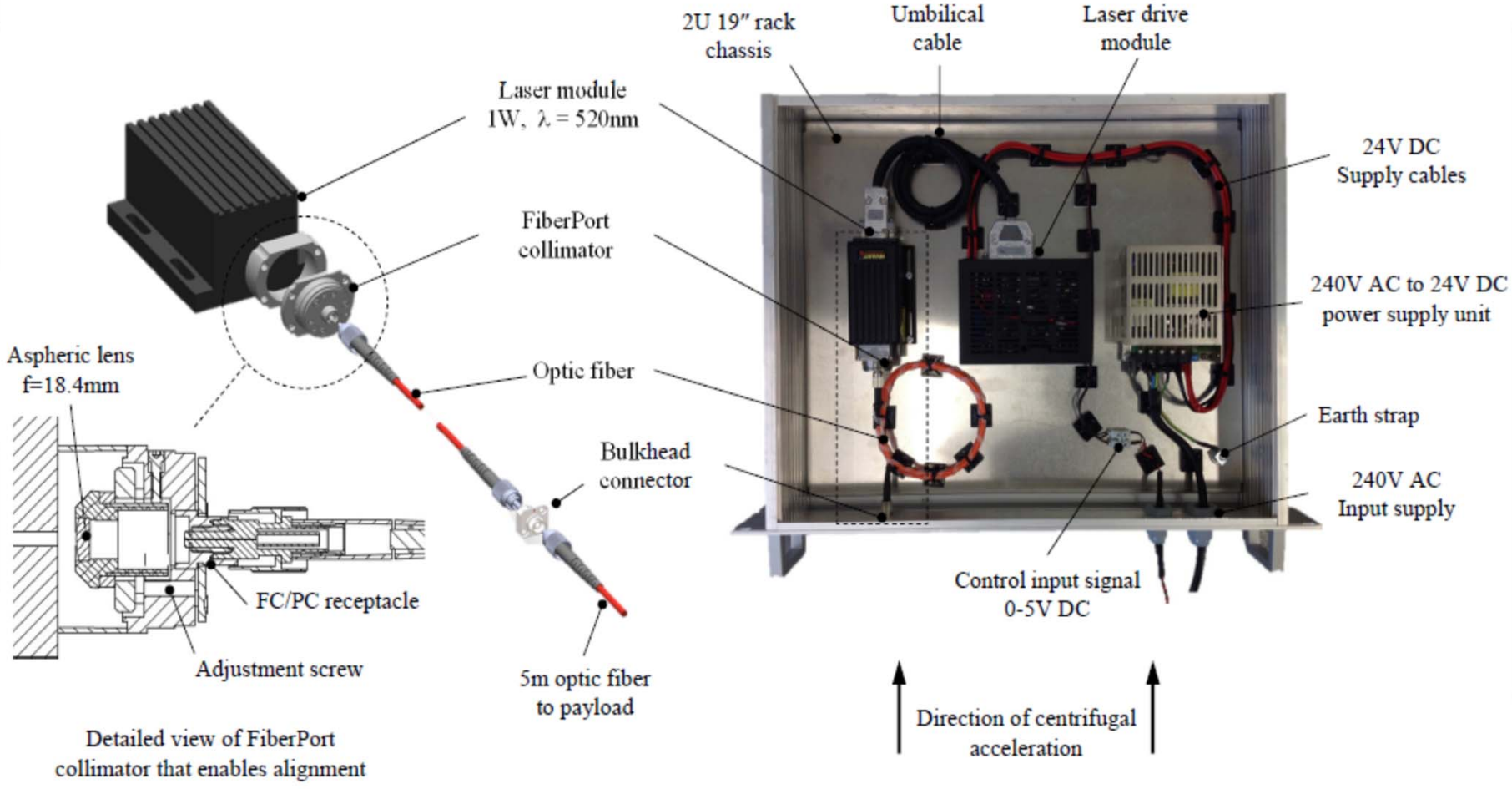
Modelling with Transparent Soil

Centrifuge tests

Modelling with Transparent Soil

Centrifuge tests



Detailed view of FiberPort collimator that enables alignment

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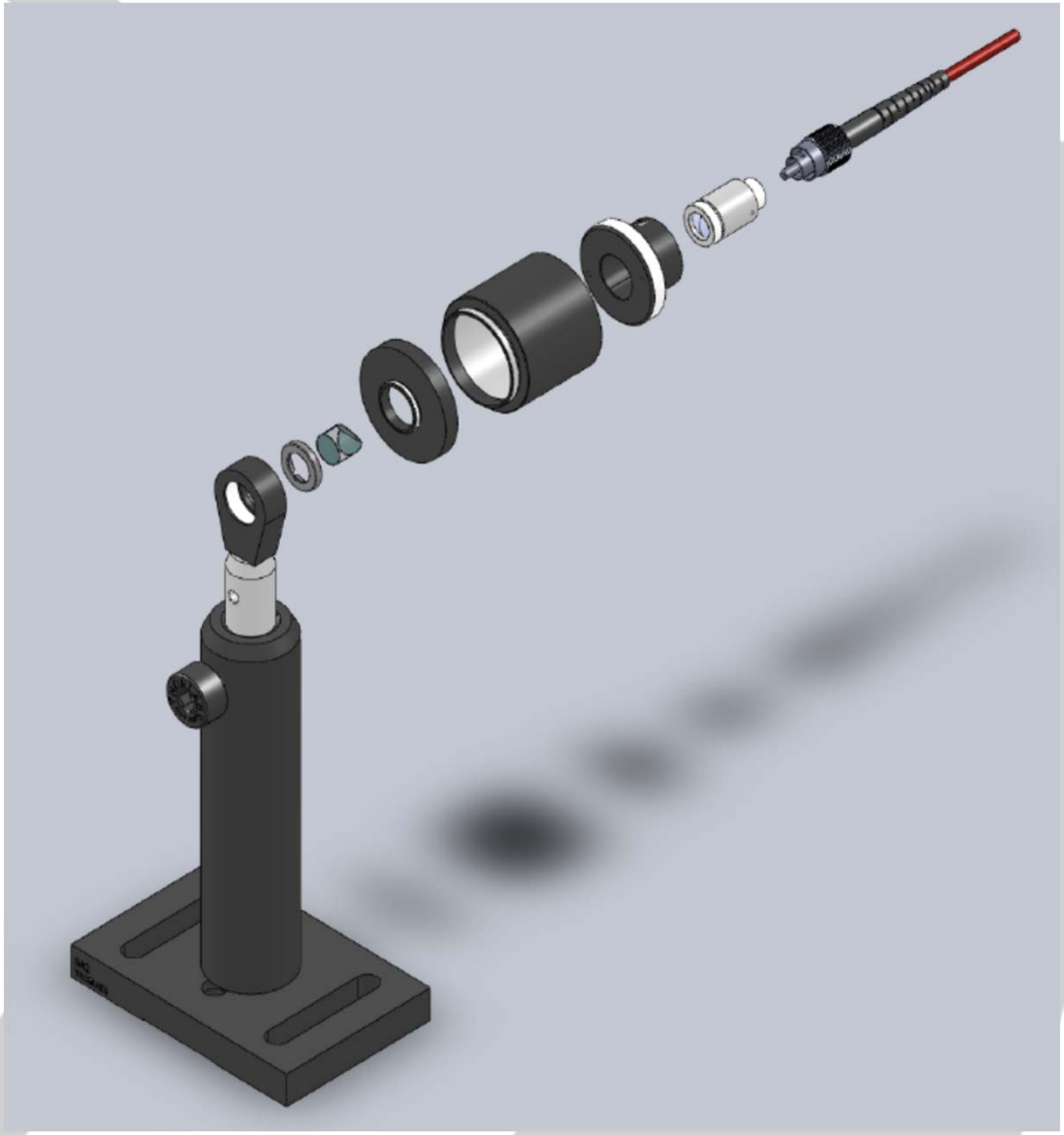
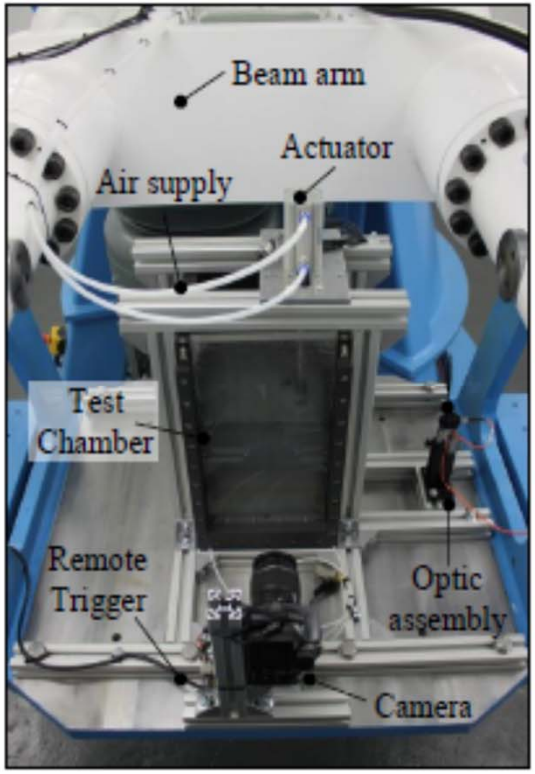
Modelling with Transparent Soil

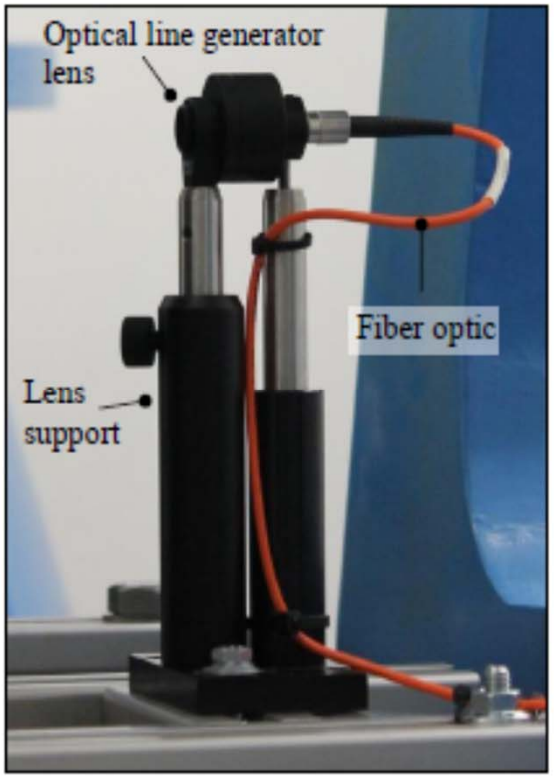
Centrifuge tests



Modelling with Transparent Soil

Centrifuge tests





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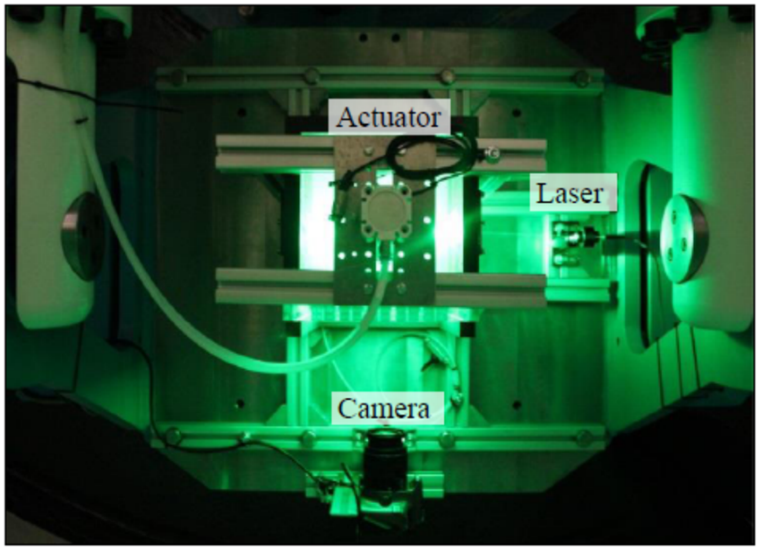
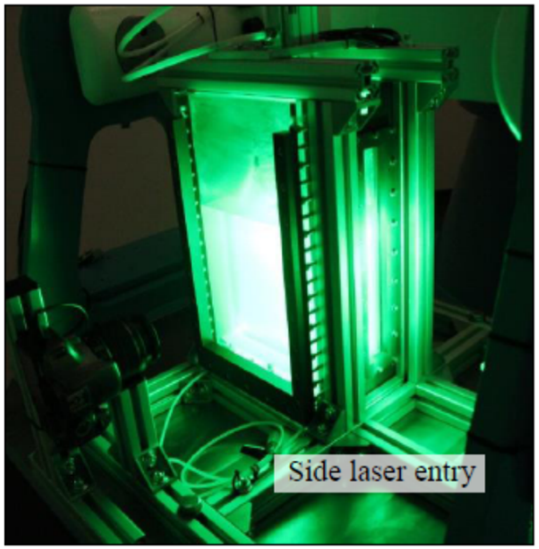
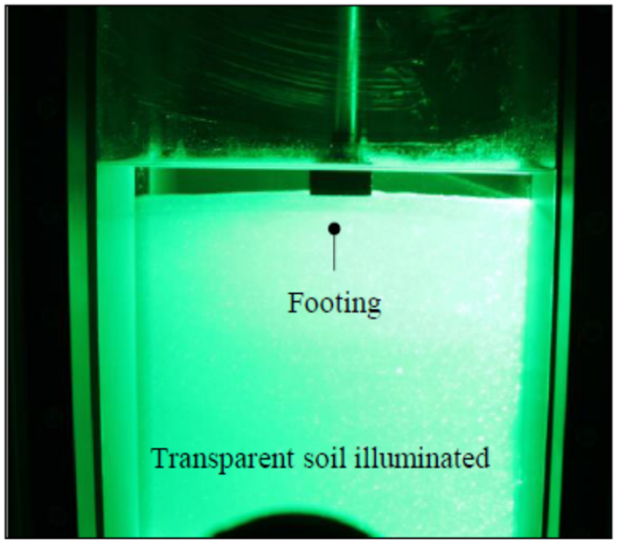
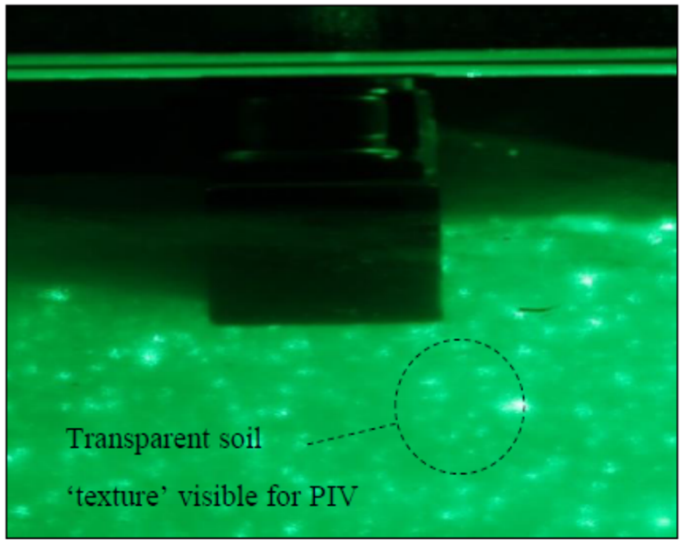
Modelling with Transparent Soil

Centrifuge tests



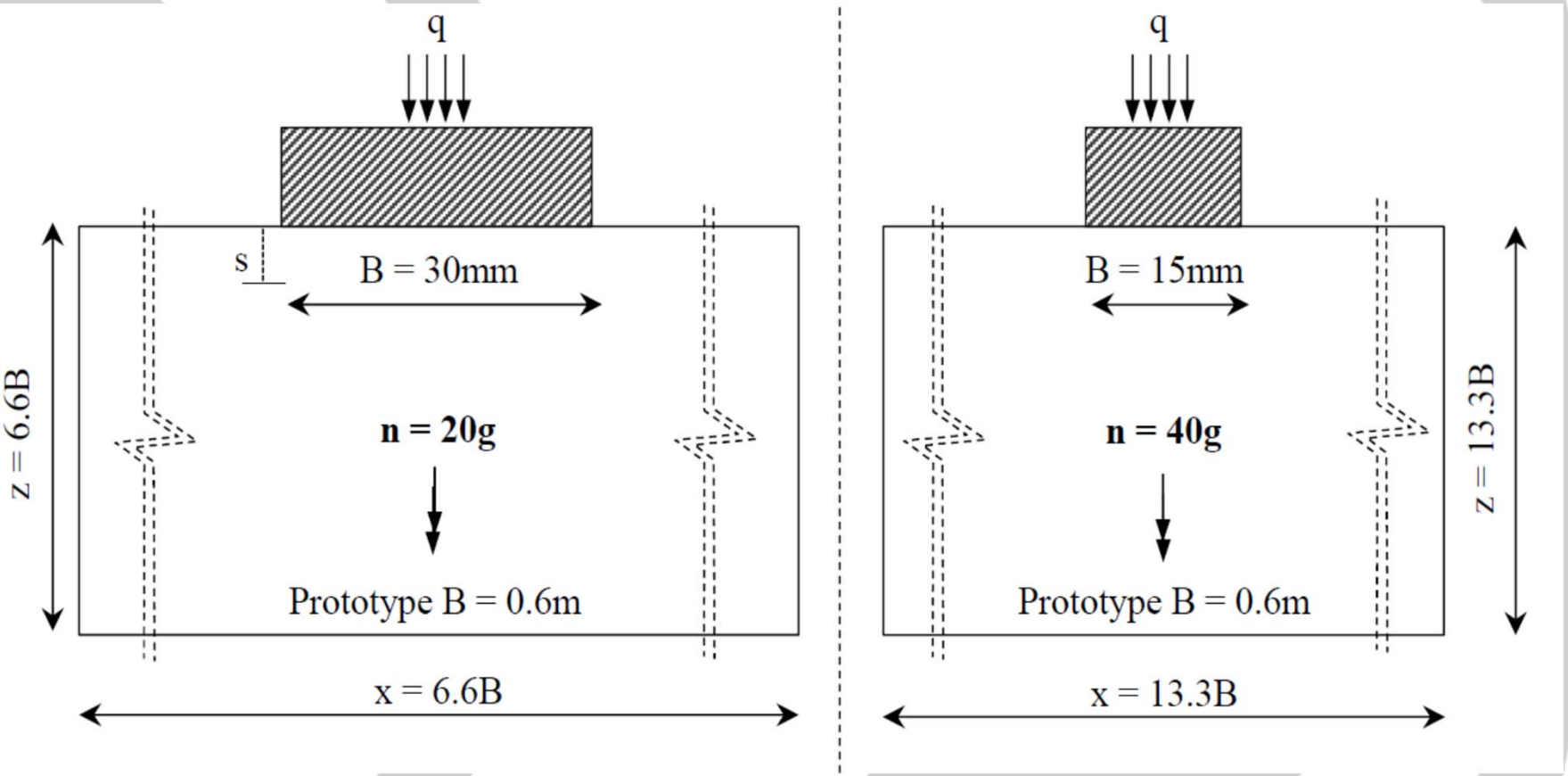






Modelling with Transparent Soil

Centrifuge tests



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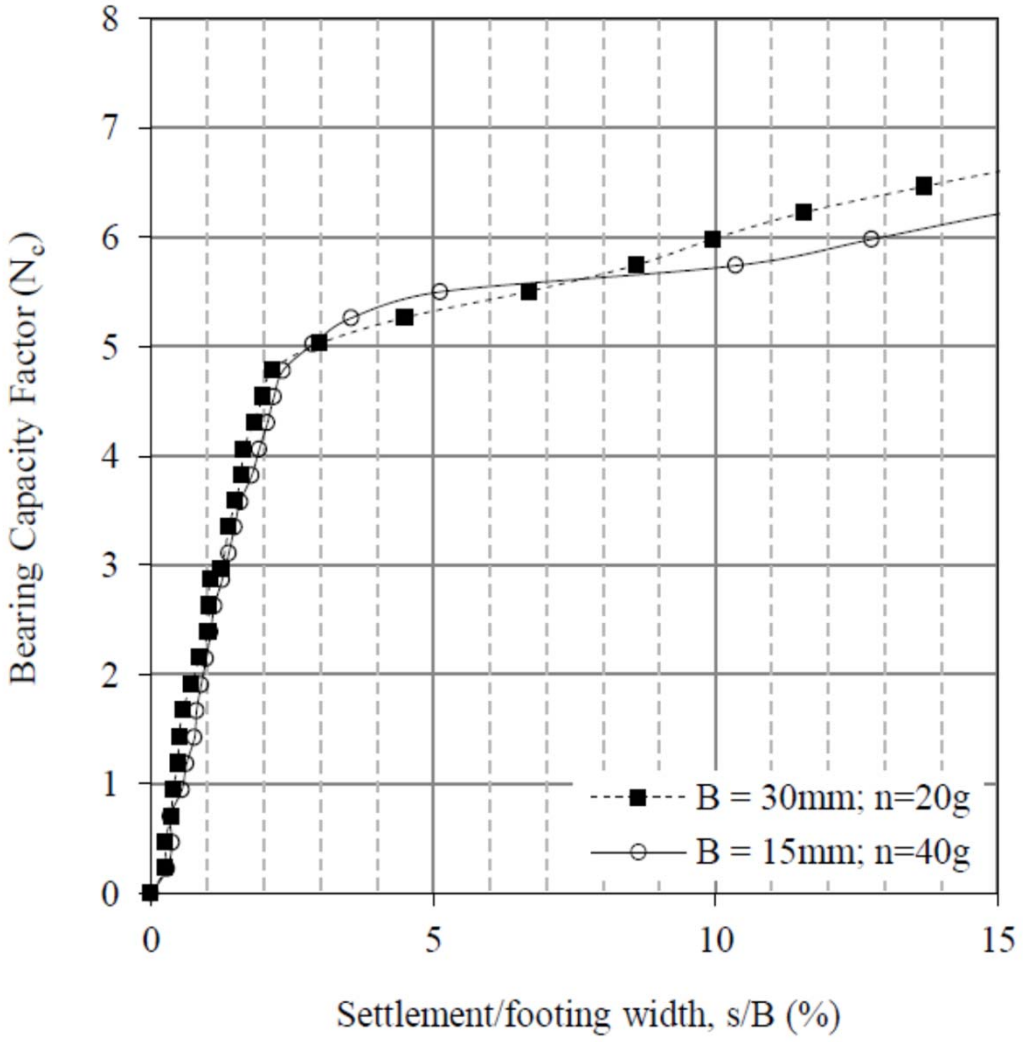

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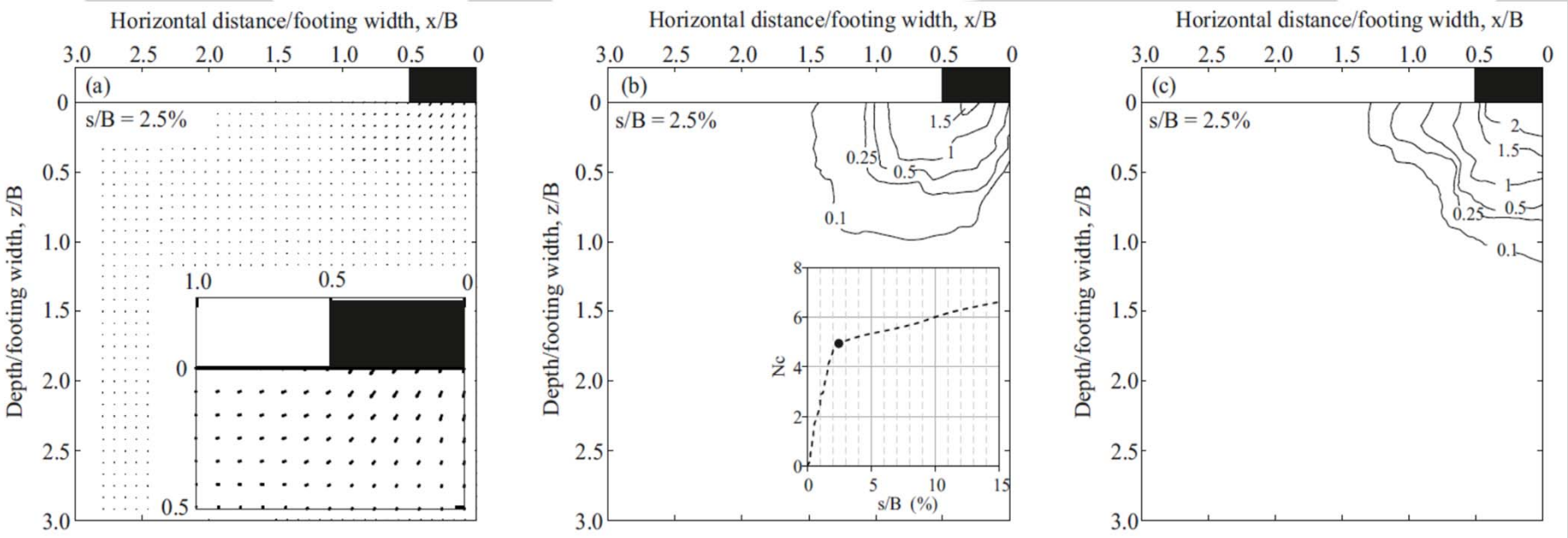
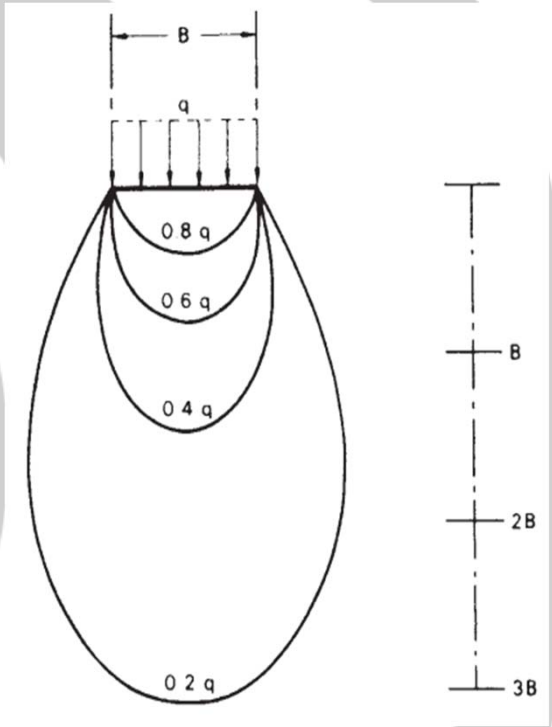
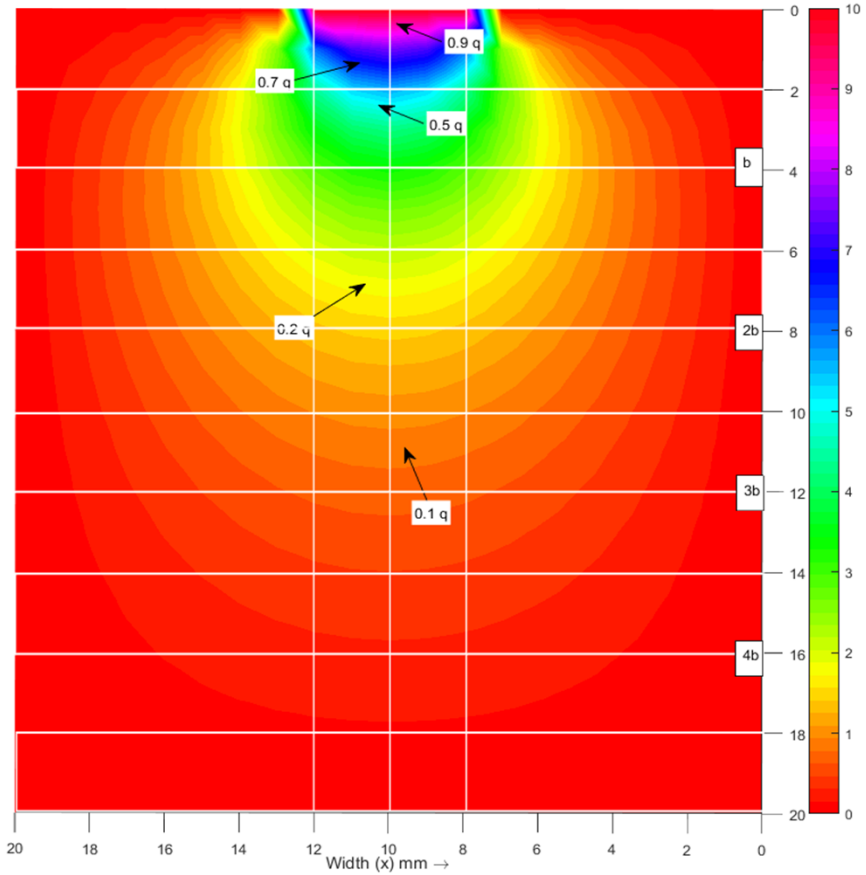


Modelling with Transparent Soil

Stress-strain





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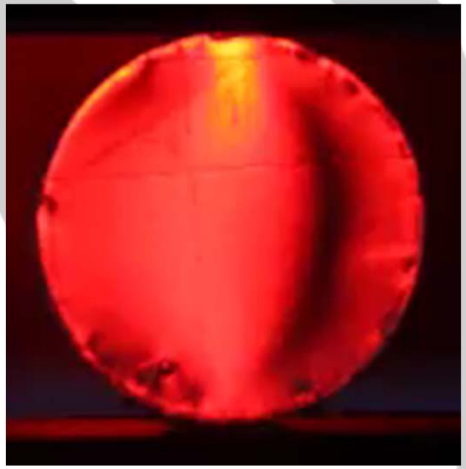

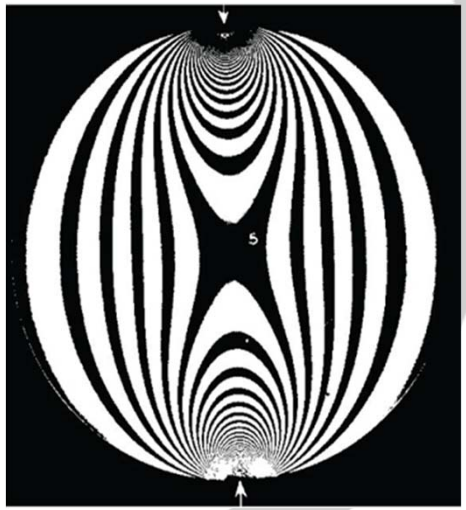

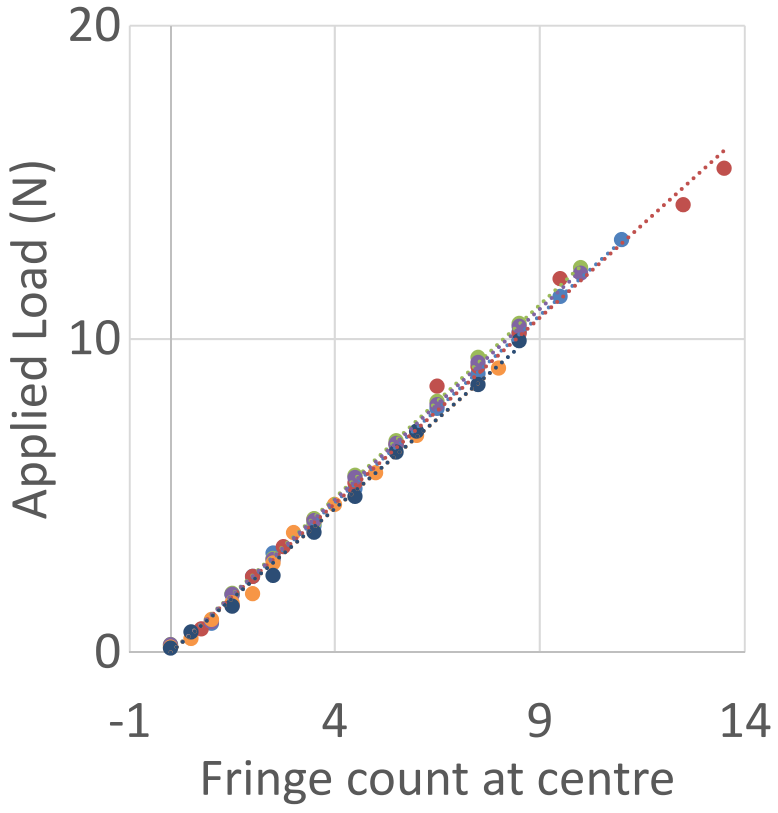

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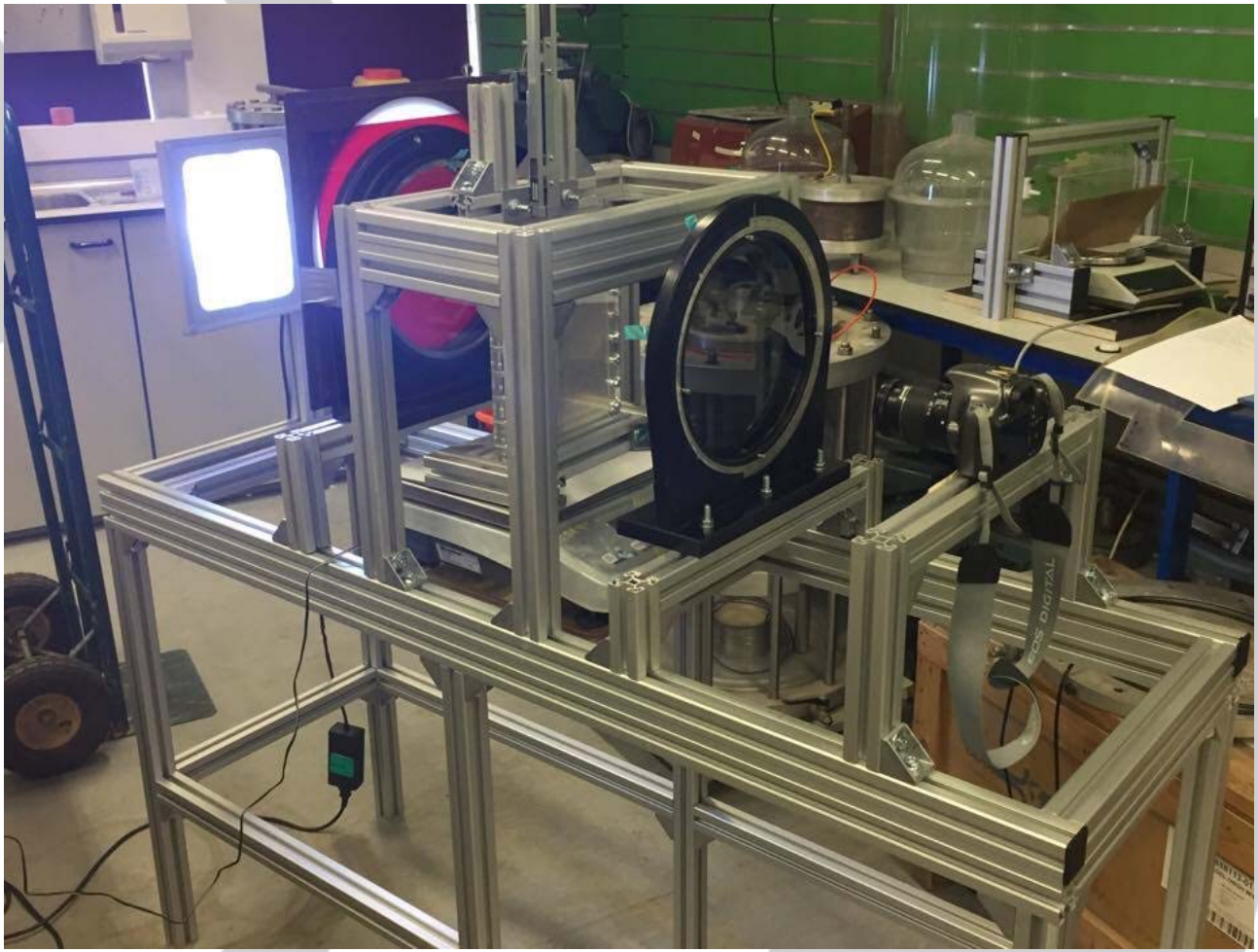
Modelling with Transparent Soil

Stress-strain



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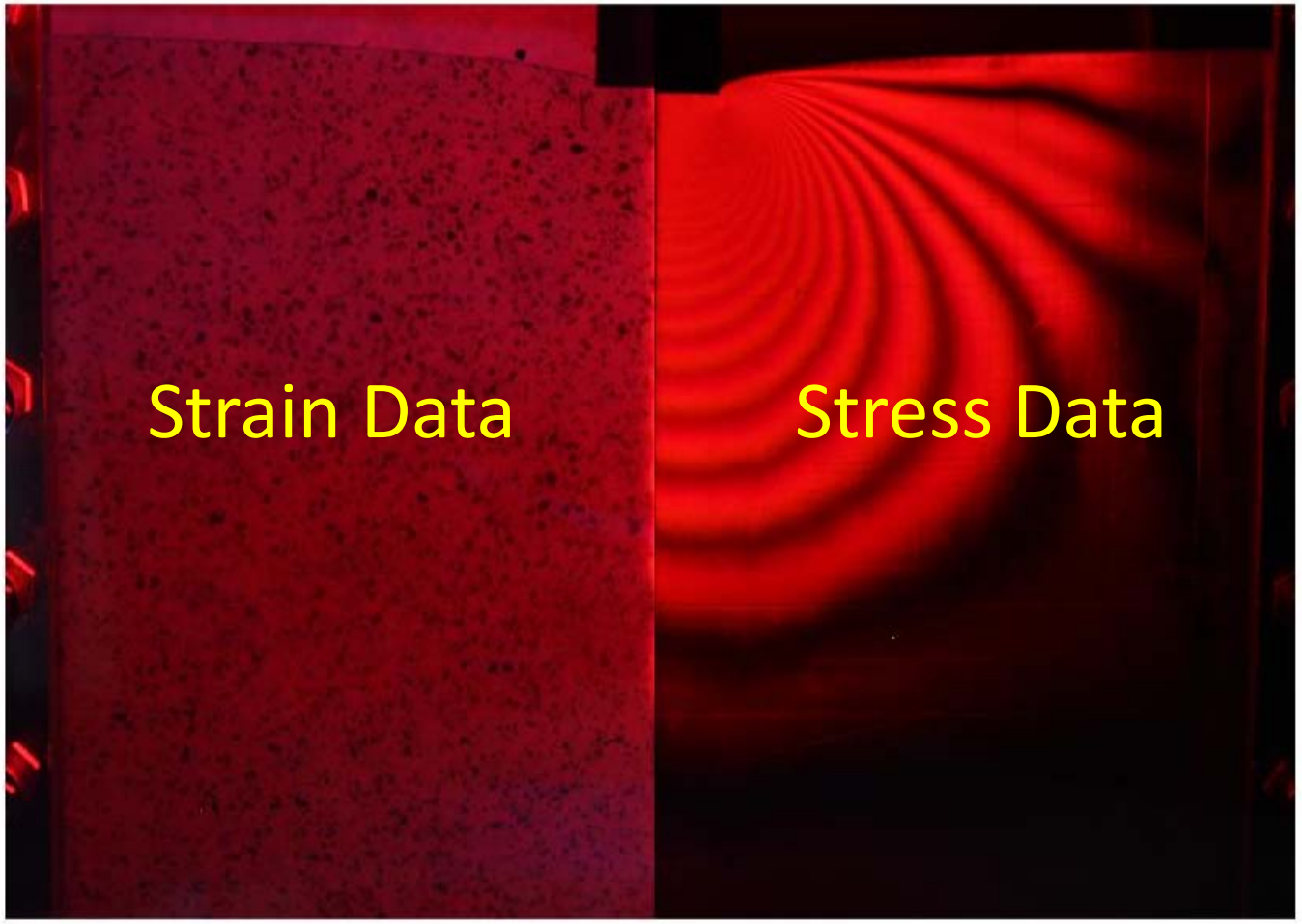
Stress-strain



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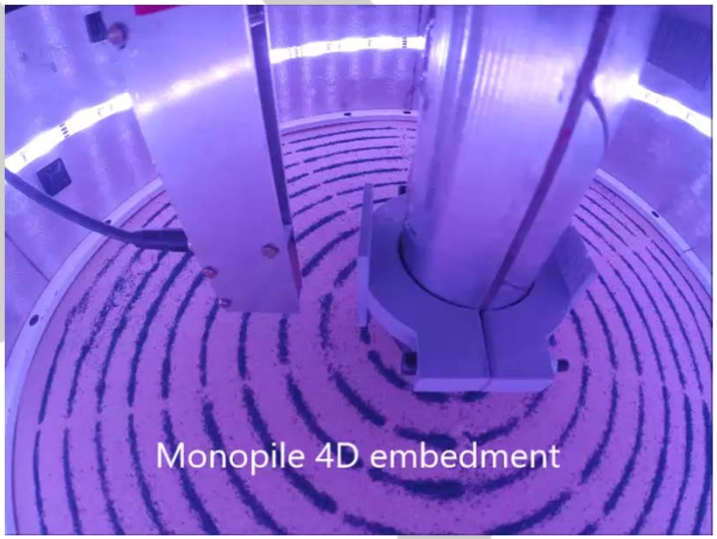
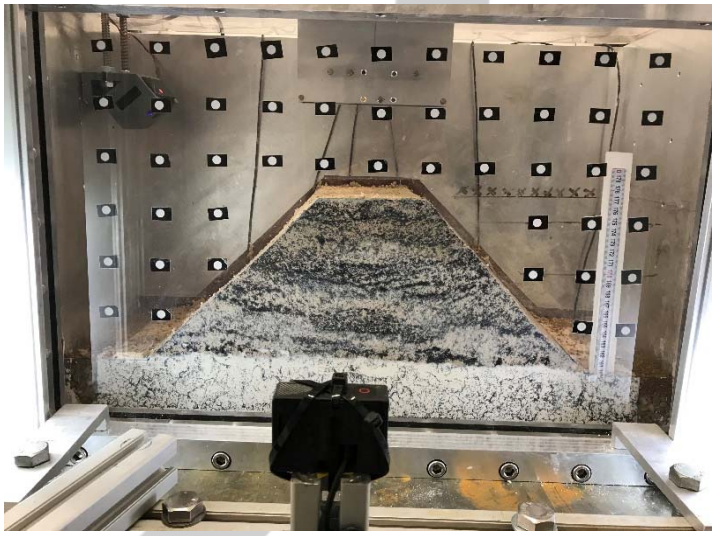
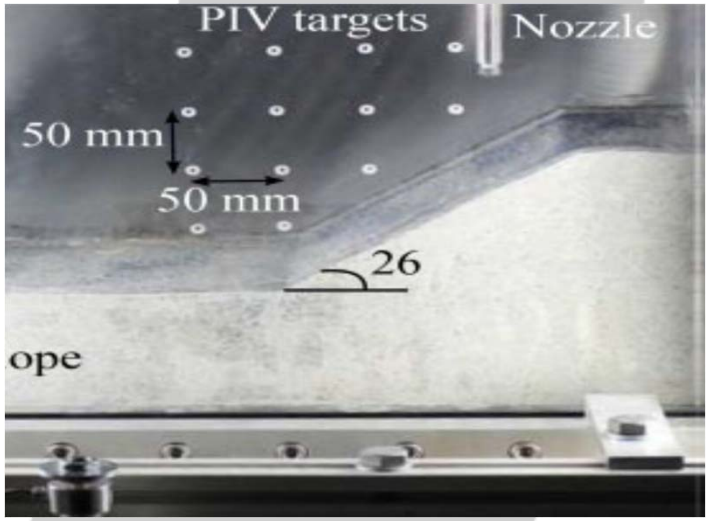
Current & Future Studies

Resilience







Conclusions

Summary

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- Technology continually evolving – new opportunities
- Keep it simple!
- Advanced visual methods are unlocking new insight and understanding
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