University of Nottingham
UK | CHINA | MALAYSIA

The challenges associated with laboratory scale physical modelling of high-plasticity spoil materials

Charles Heron

Co-authors: Thejesh Garala, Ge Cui, Naman Kantesaria, Nat-Phi Doan, Koushik Halder, Alec Marshall

Faculty of Engineering, University of Nottingham, UK

Introduction

- Overburden soil (or spoil) is excavated first and dumped to a location near the mine site
- Most post exploitation open pit voids are turned into water reservoirs.
- Effective utilisation of post mine dump sites, especially for renewable energy generation.

For both RAFF & SUMAD projects, it is essential to:

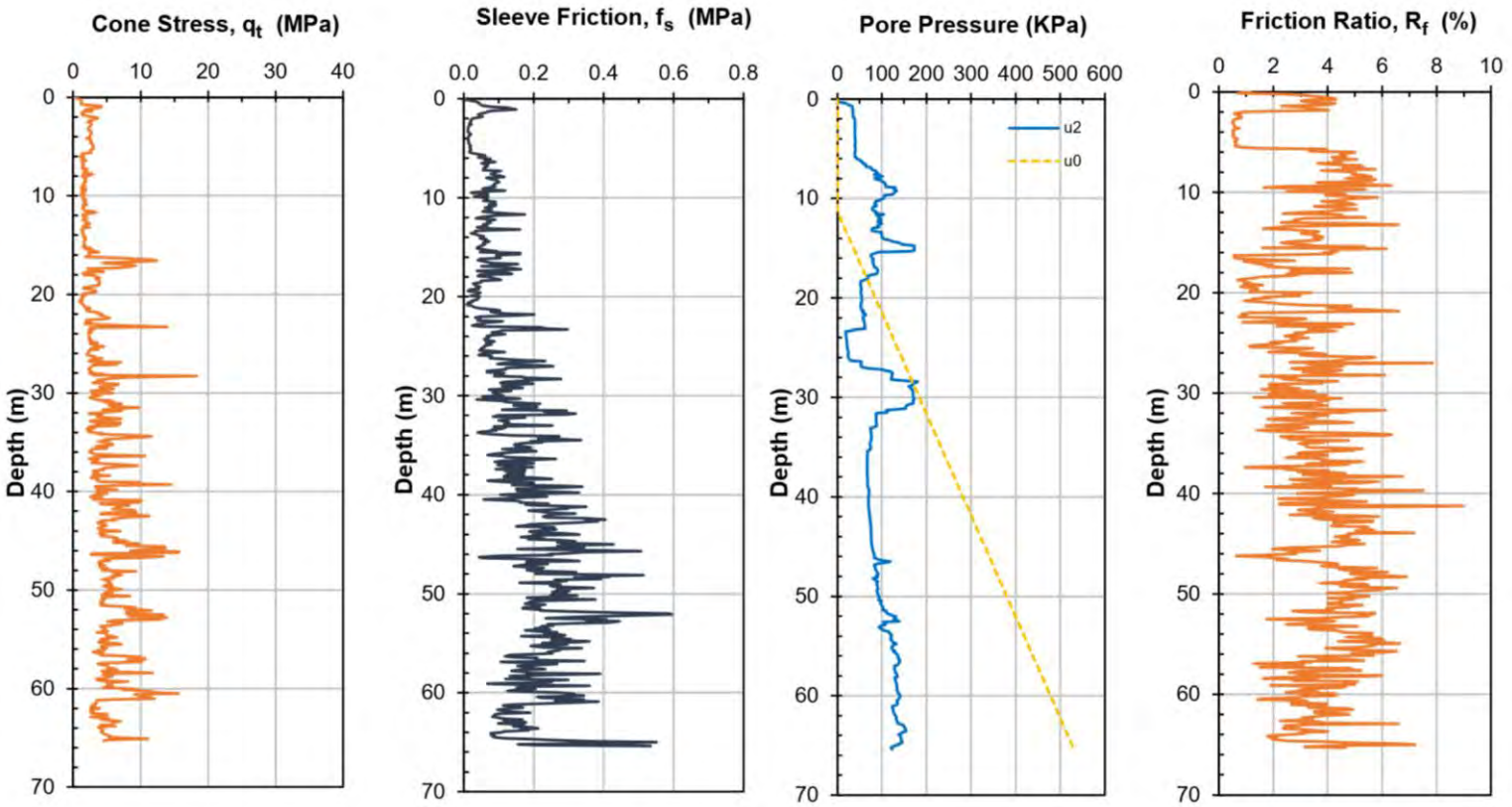
- Evaluate the engineering behaviour of spoil
- Develop an equivalent spoil for physical modelling (centrifuge) experiments

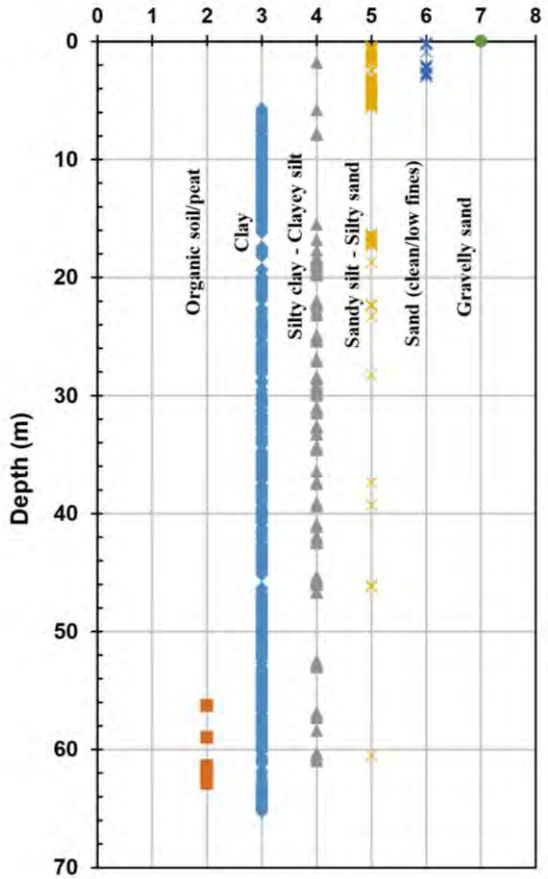
Image source: imagelinkglobal.com

Image source: photocase.com

Engineering Behaviour of Spoil

- Extensive programme of field and laboratory tests were performed to characterize the spoil material from two sites in the Czech Republic.
- Collaborative partners worked on other sites based in Europe (e.g., Poland).
- 21 Field CPTs were performed along Lake Most, in the Czech Republic.





Classification of spoil from CPT data using Jefferies and Davies (1993)

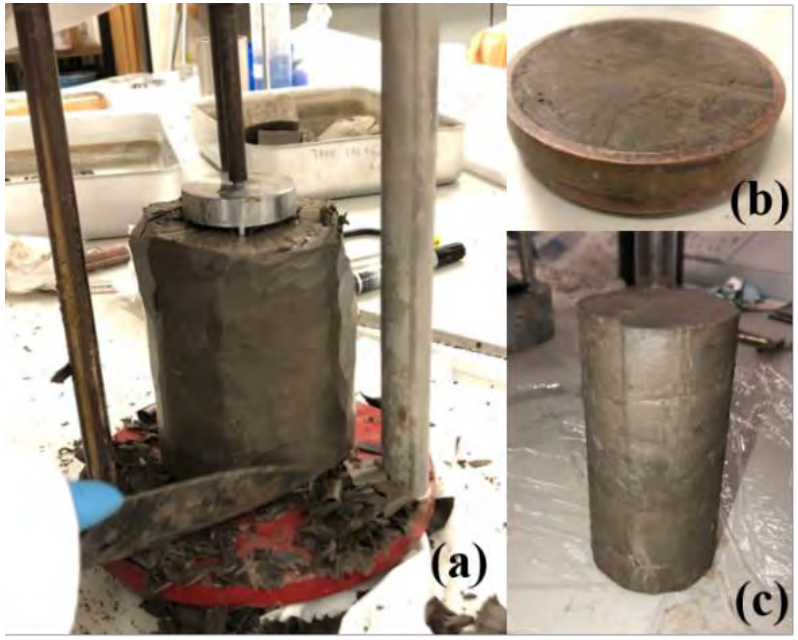
Engineering Behaviour of Spoil

- Sample cores were collected from ČSA open pit mine, in the Czech Republic.
- Extensive soil characterisation tests were performed to evaluate the index (Atterberg limits, particle size distribution analyses, specific gravity tests) and engineering properties (oedometer tests, triaxial tests, simple shear tests and SWCC) of the spoil samples received from the field.

Field sample cores

Details of sample cores collected from ČSA open pit mine

Sample	Depth (m)
CSA01	6.2 - 6.6
CSA02	14.5 - 15.0
CSA03	28.2 - 28.6
CSA04	51.3 - 51.6
CSA05	71.0 - 71.4
CSA06	91.0 - 91.3
CSA07	131.2 - 131.7



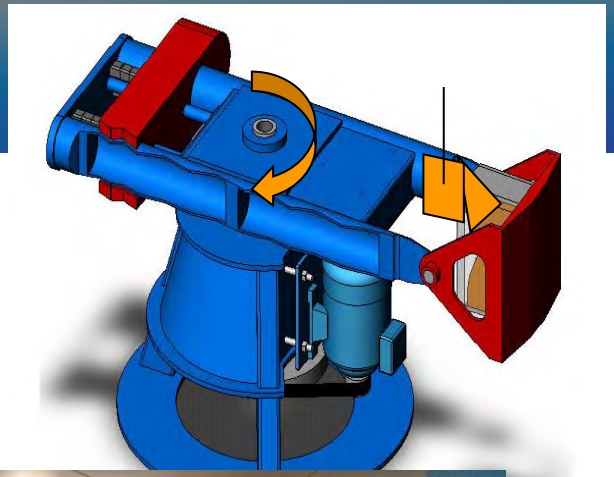
(a) Sample trimming, (b) specimen for oedometer test, and (c) specimen for triaxial test.

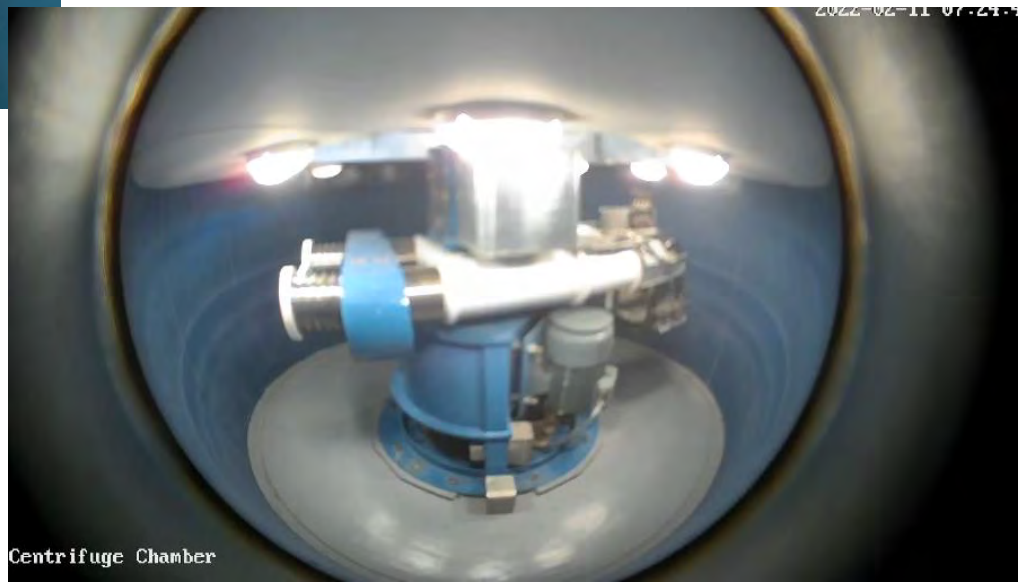
University of Nottingham
UK | CHINA | MALAYSIA

Centrifuge Testing

Nottingham Centre for Geomechanics

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





Equivalent Spoil for Centrifuge Experiments

- It is essential to use the same type of soil in centrifuge experiments for a reasonable comparison of results from different centrifuge tests.
- Field spoil is highly heterogeneous both between sites or even locally within a single location.
- Many mine pits within the UK and EU regions are composed of fine-grained material (silty clay).
- Kaolin is widely used to model fine-grained soils, but kaolin alone may not simulate the behaviour of field spoil.

Spoil material

Equivalent spoil material

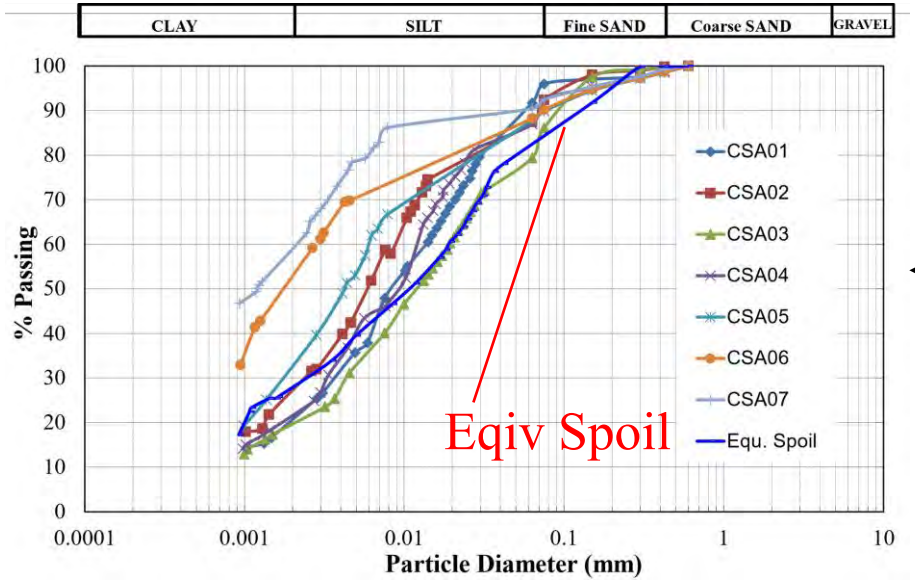
Equivalent Spoil for Centrifuge Experiments

Geotechnical characteristics of mixtures of sandy silt and kaolin clay

Test Number		1	2	3	4	5	6
Percentage	Sandy silt	77	71	67	50	30	0
	Kaolin clay	23	29	33	50	70	100
Plasticity index (%)		13.8	15.3	17.5	23.4	26	33.4
Specific gravity, G_s		2.60	2.64	2.61	2.60	2.60	2.60
Compression index, C_c		0.18	0.19	0.21	0.31	0.38	0.55
Recompression index, C_r		0.019	0.019	0.025	0.045	0.068	0.111
Secondary compression index, C_α		0.0027	0.0028	0.0026	0.004	0.004	0.004

- Obtaining natural silt by sieving was overly laborious and time consuming.
- A commercially available crushed quartz sand (A50 silica flour) in silt particle size range was used.
- After extensive trial tests, it was found that a mixture of 50% silt (A50 silica flour), 30% bentonite, and 20% kaolin could represent the behaviour of ČSA open-pit mine spoil.

Equivalent Spoil for Centrifuge Experiments



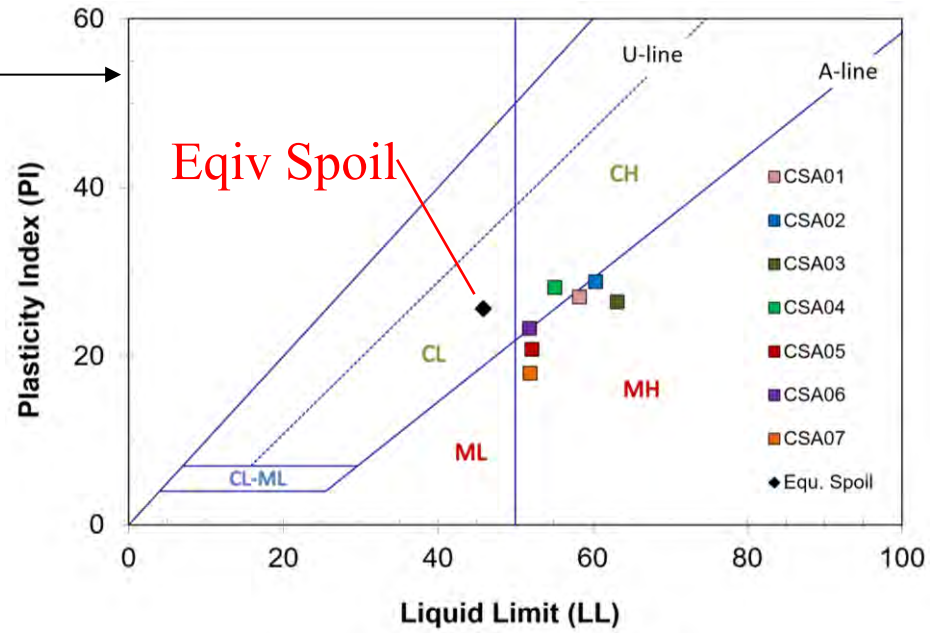
Particle size distribution

Permeability

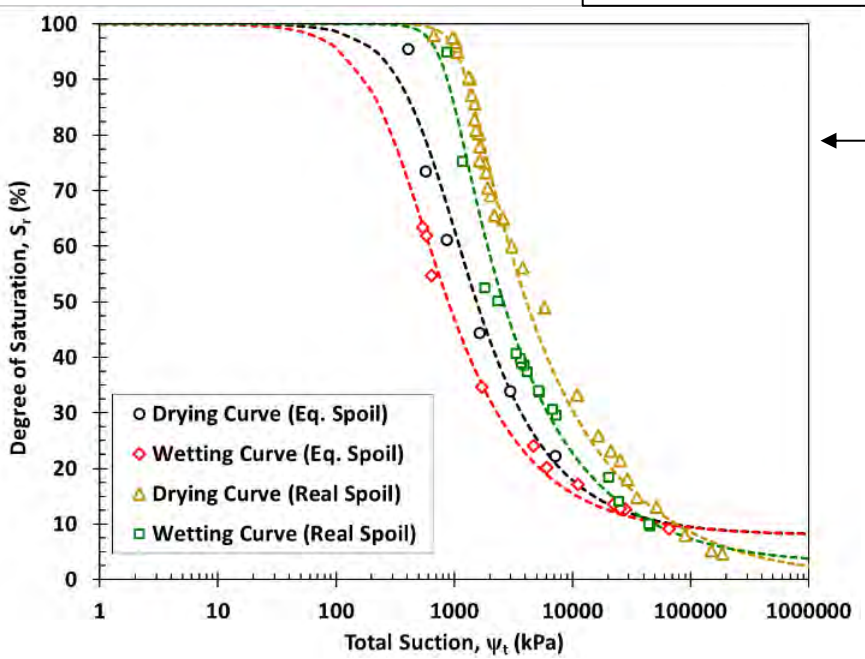
Field spoil = 0.9×10^{-11} m/s

Equivalent spoil = 1.3×10^{-11} m/s

Plasticity chart



Soil Water Characteristics Curve



Challenges with the Physical Modelling of Spoil Material

Time for slurry consolidation (by mixing oven-dry soil with de-aired water at a water content equivalent to twice the liquid limit):

Time for consolidating 330 mm deep spoil slurry:

$$T_v = \frac{c_v t}{h^2}$$

$$t_{90} = \frac{T_{90} \times h^2}{c_v}$$

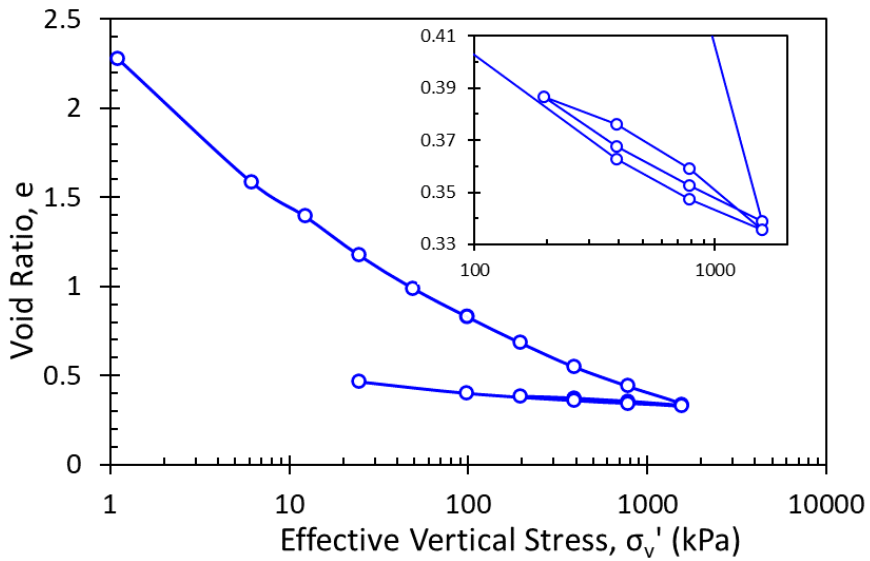
$$t_{90} = \frac{0.848 \times 165^2}{0.00457} = 58.5 \text{ days}$$

Time for consolidating 330 mm deep kaolin slurry:

$$t_{90} = \frac{0.848 \times 165^2}{0.27} = \sim 1 \text{ day}$$

Centrifuge model preparation: slurry height was ~700mm – needed ~265 days for consolidation!

Consolidation characteristics of equivalent spoil



Compression index, c_c = 0.545

Swell index, c_s = 0.051 - 0.08

Recompression index, c_r = 0.068

Coefficient of consolidation, c_v = 0.0046 mm^2/s

Permeability, k = 1.30 × 10^{-11} m/s

- For pure speswhite kaolin:

  c_v = 0.27 mm^2/s ; k = 3 × 10^{-8} m/s

  (Springman, 1989)

Challenges with the Physical Modelling of Spoil Material

In addition to preparing consolidated soil samples, an alternative approach was sought to speed up the process.

- Compaction is a viable alternative to consolidation for preparing centrifuge models with fine-grained soils.
    - Difficult to ensure uniform compaction throughout the entire soil body and possible formation of air pockets.
- Effect of climatic conditions on the Slope behaviour:

Study	Take & Bolton (2004)	Hudacsek et al. (2009)
Model preparation	Consolidated kaolin model	Compacted kaolin model
Cycles of wetting and drying	Embankments were observed to swell and shrink significantly	No significant shrinkage and swelling movements
Mode of failure	Progressive failure started to be generated after several years	Additional hydraulic cycles provoked decreasing cyclic soil movement

Proposed Model Preparation with Spoil Material

A new model preparation technique was developed:

Compacted Model

- Same dry density as consolidated model.
- Moisture content corresponding to chosen dry density from the compaction curve.

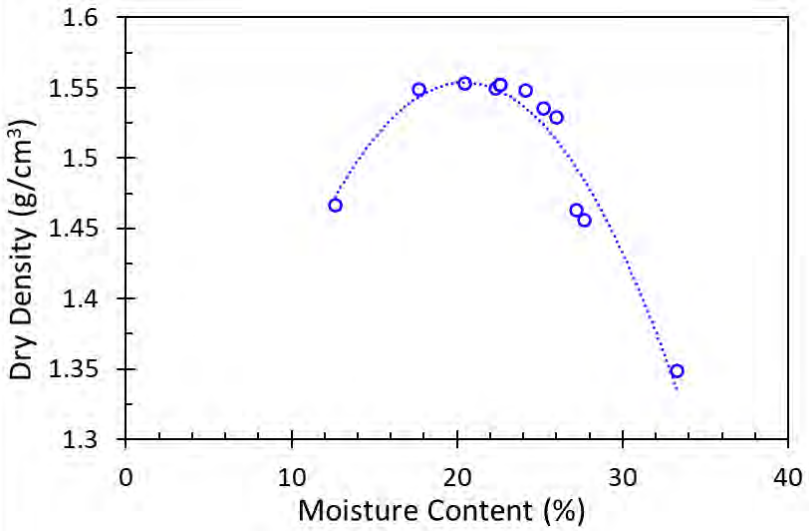
Saturation

- With deaired water under vacuum conditions.

Consolidation

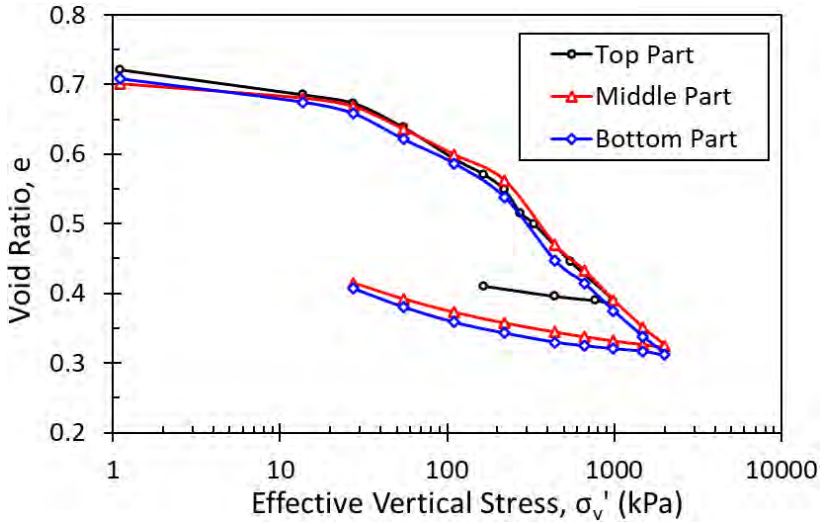
- Under a vertical stress slightly larger than the effective pre-consolidation stress of the compacted spoil.
- This will ensure that the whole soil model is subjected to same vertical stress and minimizes any air pockets.

Proposed Model Preparation with Spoil Material



Compaction curve of the equivalent spoil

- To maintain a certain soil stress history or over-consolidation ratio (OCR) profile, slurry models needed to be consolidated under 180 kPa vertical stress.
- The spoil slurry at the end of 180 kPa consolidation stress will have a moisture content of 29% and a dry density of 1.48 g/cm^3.
- Same dry density was maintained between the compacted and consolidated models.
- For the moisture content of the compacted models, the moisture content corresponding to the dry density of 1.48 g/cm^3 on the wet side of the compaction curve (around 27%) was chosen.

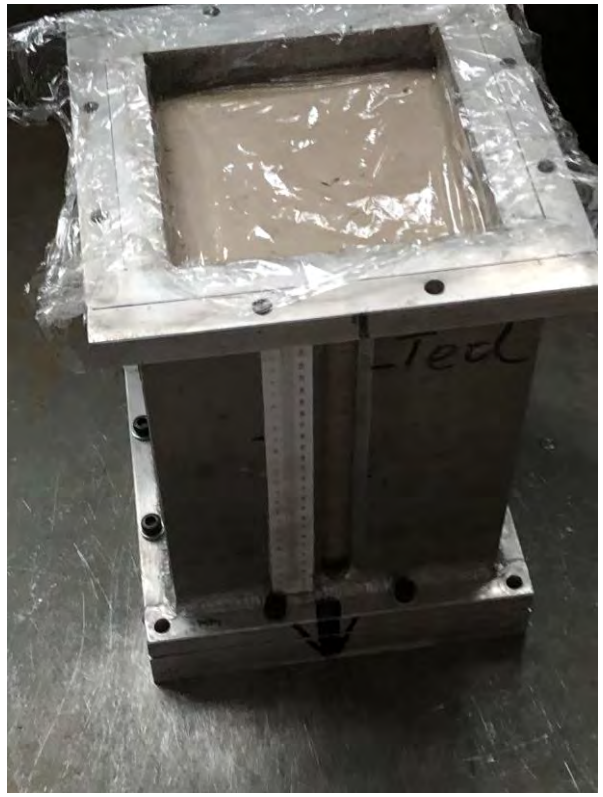


- A sample was prepared in a Proctor mould by compacting equivalent spoil.
- Three specimens were extracted from the compacted sample at different depths.
- All three specimens had a pre-consolidation stress (σ_c') of approximately 175 kPa.

Consolidation curves of the compacted equivalent spoil

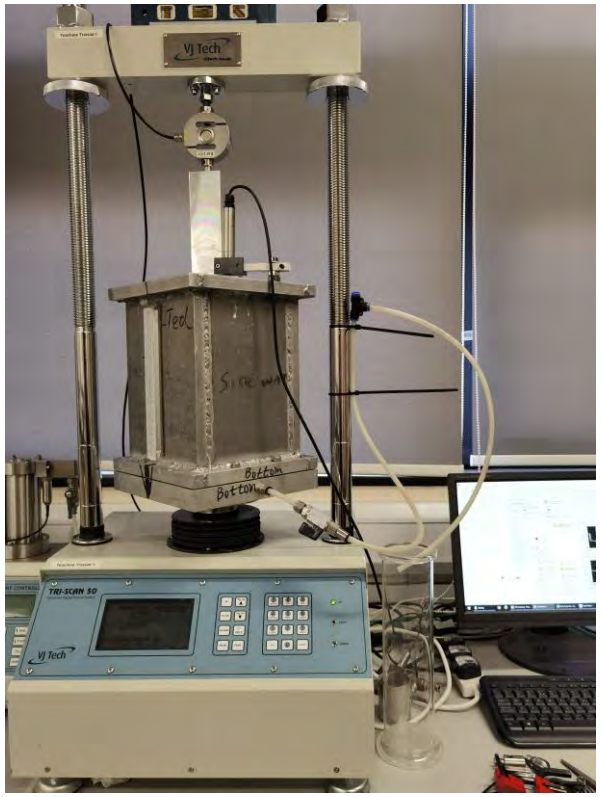
Consistency of Proposed Model Preparation Methodology

- To verify the proposed method, trial tests were performed on a container with dimensions 160 mm × 160 mm × 277 mm (L × W × H).



Compaction of spoil

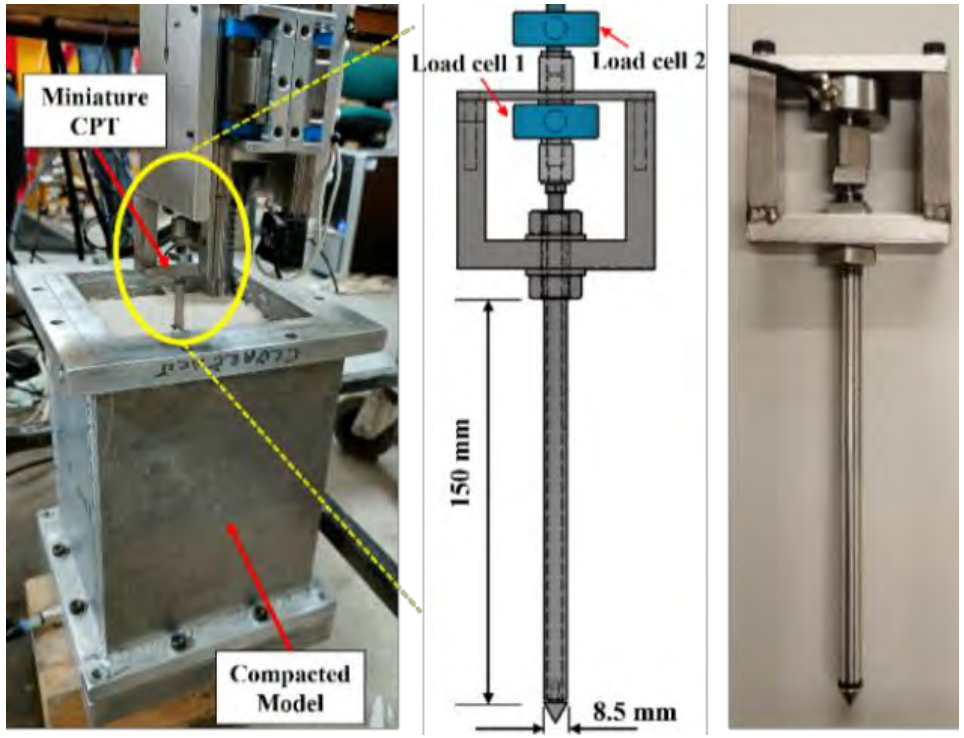
Saturation of spoil model

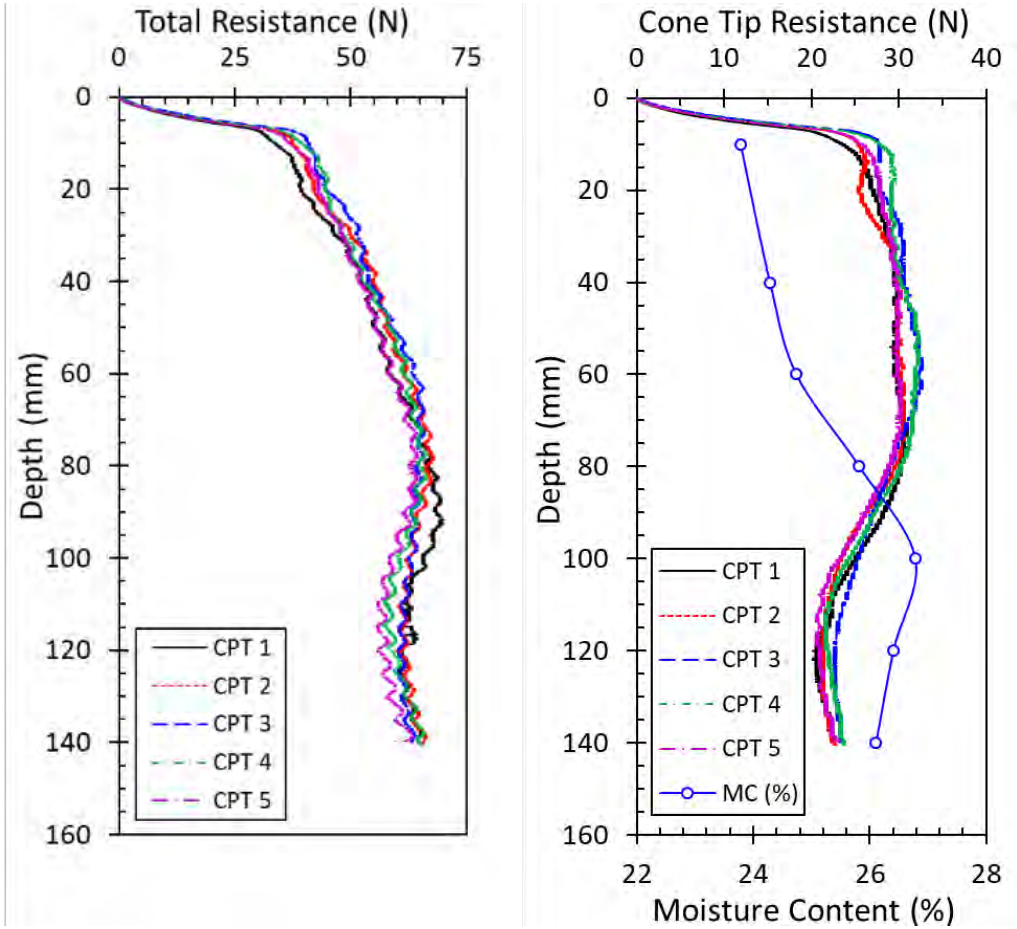


Consolidation of spoil model

Consistency of Proposed Model Preparation Methodology

- Miniature CPT tests were performed at different locations in the model.
- The miniature CPT is 150 mm long with a cone tip of 60° and a diameter of 8.5 mm.
- Based on the coefficient of consolidation of the equivalent spoil, the rate of cone penetration was determined as 0.2 mm/sec to ensure undrained conditions and avoiding rapid straining.

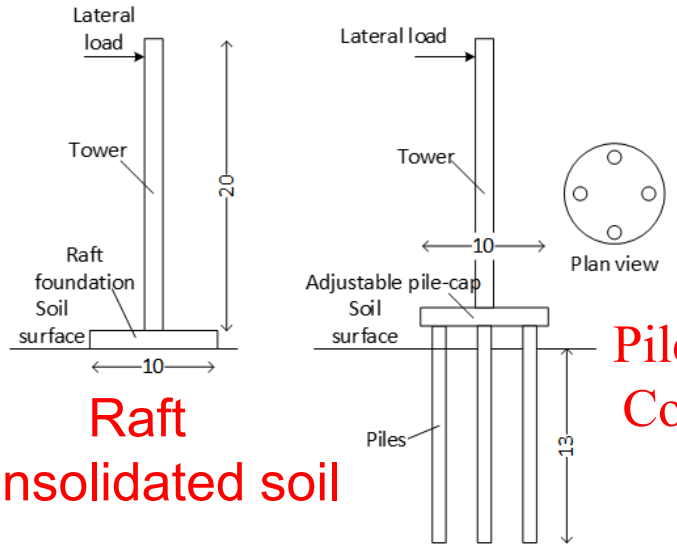




Use of compacted spoil models - SUMAD

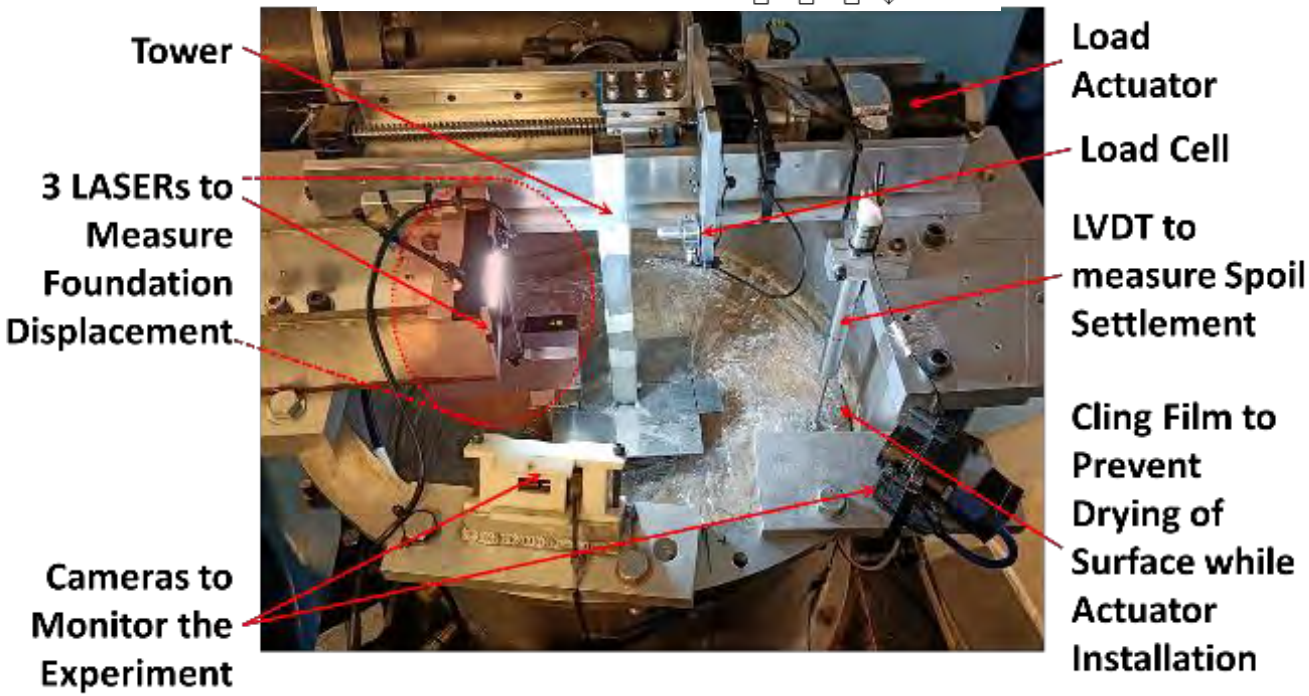
Consolidated and compacted models used on SUMAD project:

- ~9 months to prepare consolidated sample for raft foundation test
- ~3 months to prepare compacted sample for pile foundation test.



Raft
Consolidated soil

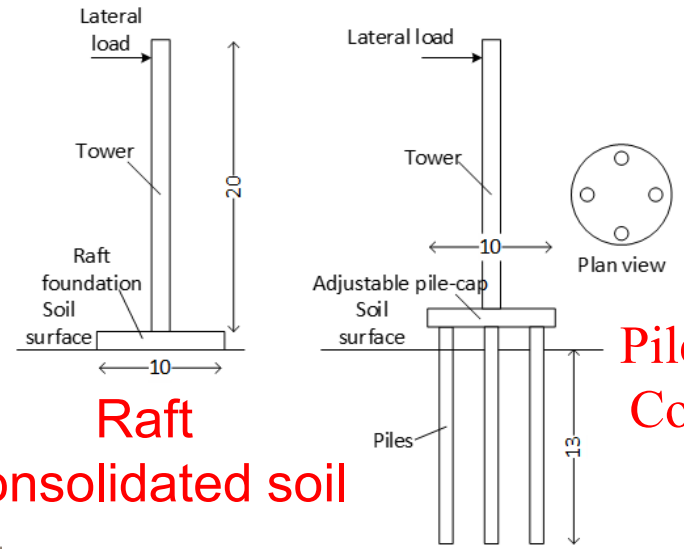
Pile-foundations
Compacted soil



Use of compacted spoil models - SUMAD

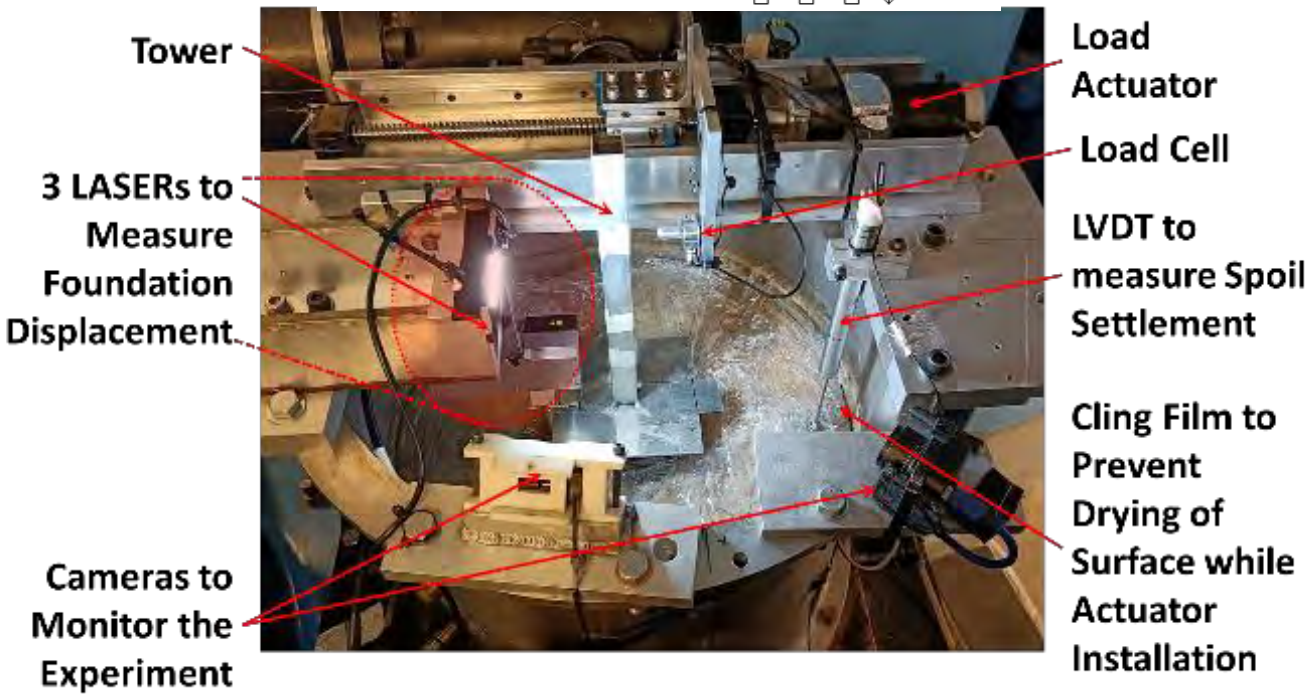
Consolidated and compacted models used on SUMAD project:

- Worth mentioning that, for both consolidated and compacted soil models, the models needed to be run continuously in the centrifuge for up to 2 weeks to achieve all stages of tests:
  - Consolidation to centrifuge stress equilibrium state
  - Cyclic loading
  - Change of water table level and re-establish equilibrium state
  - Spin down/up to install miniature CPT
  - Re-establish equilibrium stress state



Raft
Consolidated soil

Pile-foundations
Compacted soil



Conclusions

- Results and literature sources suggest that many mine pit spoil materials are composed of silty clay material.
- Difficult to simulate complex fine-grained spoil behaviour in physical modelling (centrifuge) experiments
  - Excessive and impractical time-scales for model soil preparation
- A new method for preparing compacted models whilst ensuring soil body consistency was proposed
  - Soil compaction, saturation, and consolidation under stresses beyond the pre-consolidation stress of the compacted soil.
  - Requires ~25-30% of time for preparation of consolidated sample – saved ~ 6 months of preparation time for centrifuge models
- Centrifuge tests still required up to 2 weeks of continuous run time to achieve tests – this represents a significant operational challenge!
- Further consolidation of models in the centrifuge should further improve the consistency of the soil model.

Thank you

Funding:

EU's Research Fund for Coal and Steel under the projects:

- "RAFF – Risk Assessment of Final Pits during Flooding" Grant No. 847299
- "SUMAD - Sustainable Use of Mining Waste Dumps" Grant No. 847227.