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Large Scale Testing Facilities – Use of high gravity Centrifuge Tests to investigate Soil Liquefaction Phenomena

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Introduction

- Liquefaction by definition is reduction of effective stress in soil to near zero magnitude due to rise in excess pore water pressure
- Soil looses its shear stiffness causing it to flow, and any structures it supports to sink/rotate
- Observation of sand boils, mud flows, sand blows are often considered as confirmation of liquefaction in post earthquake period

Sand boils near Nantou Taiwan (1999)

Haiti earthquake

Liquefaction induced Building settlement/rotation

Bhuj Earthquake (2001)

Christchurch New Zealand Earthquake (2011)

Liquefaction induced lateral spreading

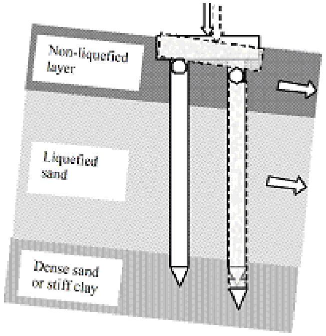
Christchurch New Zealand Earthquake (2011)

Muisine Ecuador Earthquake (2016)

Liquefaction induced pile damage

Haiti Earthquake (2010)

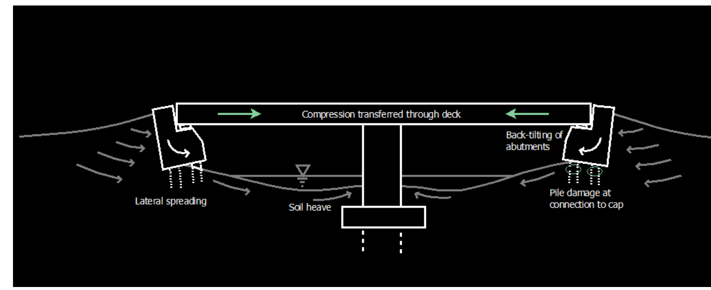
Muisine Ecuador Earthquake (2016)



**Design of Pile Foundations in Liquefiable Soils*, Madabhushi, Knappett & Haigh (2009), Imperial College Press

Liquefaction induced bridge damage – Abutment Rotation failure mode

Muisine Ecuador Earthquake (2016)



Haskell, J.J.M., Madabhushi, S.P.G., Cubrinovski, M. and Winkley, A., (2013), Lateral spreading-induced abutment rotation in the 2011 Christchurch earthquake: observations and analysis, Geotechnique, Vol. 63, No. 15, pp 1310-1327.

Christchurch New Zealand Earthquake (2011)

Liquefaction induced uplift

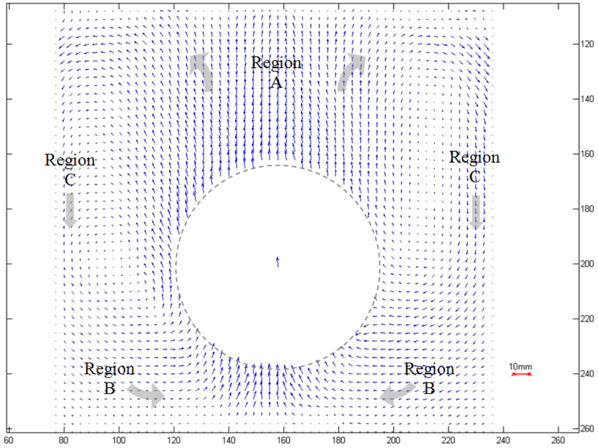
Tohoku Japan Earthquake (2014)

Muisine Ecuador Earthquake (2016)

Liquefaction induced uplift

Muisine Ecuador Earthquake (2016)

Chūetsu Japan Earthquake (2004)



PIV Imaging from Centrifuge Tests*

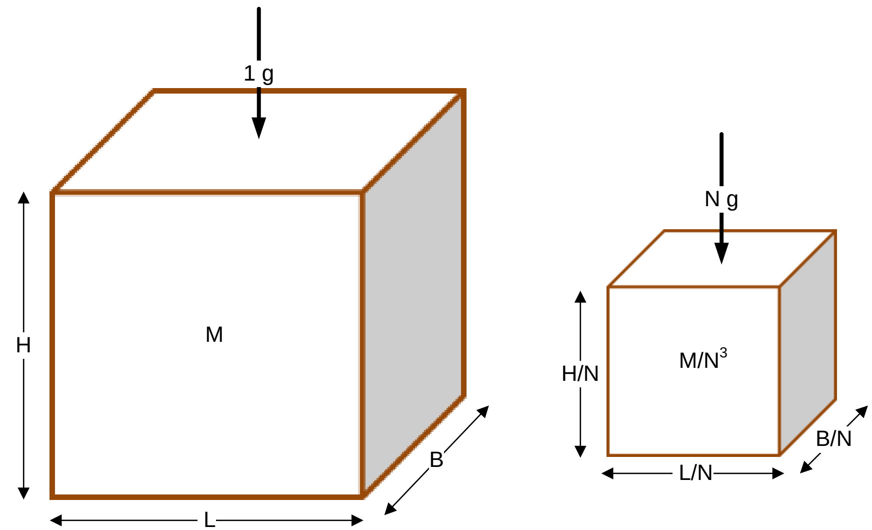
*Chian, S., Tokimatsu, K., and Madabhushi, S., (2014), Soil Liquefaction–Induced Uplift of Underground Structures: Physical and Numerical Modeling, ASCE Journal of Geotech. Geoenviron. Eng., 140(10), 04014057.

Centrifuge Modelling

- Testing of small-scale physical models in the enhanced gravity field of a geotechnical centrifuge
- Prototype stresses and strains are recreated in the models
- Earthquake loading can be applied to models in-flight, through power earthquake actuators
- We need specialist model containers to minimise boundary effects

A view of the 10m diameter Turner Beam Centrifuge at University of Cambridge

Principle of Centrifuge Modelling



$$\sigma_v = \frac{M\ g}{L \times B}$$

$$\sigma_v = \frac{\frac{M}{N^3} \times Ng}{\frac{L}{N} \times \frac{B}{N}} = \frac{M\ g}{L\ \times B}$$

$$\varepsilon = \frac{\delta\alpha}{\alpha}$$

$$\varepsilon = \frac{\delta\alpha/_N}{\alpha/_N} = \frac{\delta\alpha}{\alpha}$$

Prototype Stresses and Strains are recreated in Centrifuge Models

Principle of Centrifuge Modelling

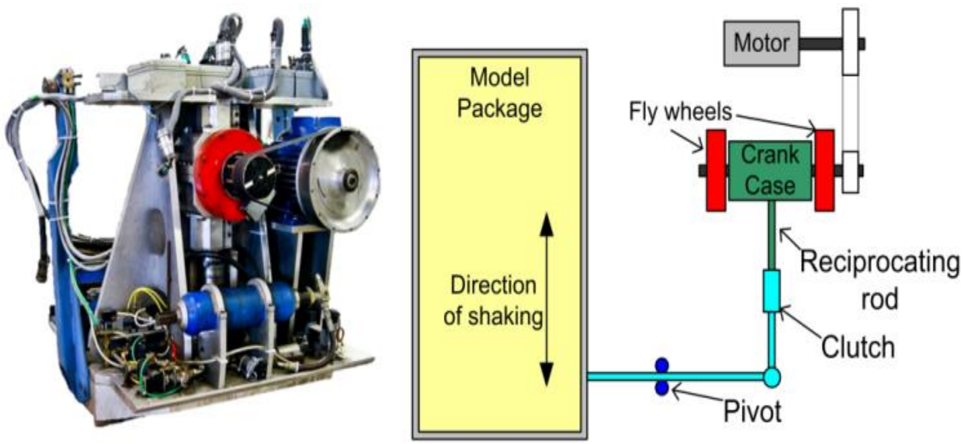
- By scaling the Prototype by a factor of *N* and increasing the gravity by a factor of *N*, prototype stresses and strains are recreated in the model
- This will enable us to capture the non-linear behaviour of soil correctly

- However, in order to recreate earthquake loading, we need to apply lateral shaking to the models in-flight, i.e. we need shaking tables that operate while in-flight
- Further, the earthquake actuators for use on the centrifuge need to be powerful, as they need to deliver the requisite earthquake energy is a very short duration (typically in about 0.5 sec, to model a 30 sec earthquake event at 60g's)

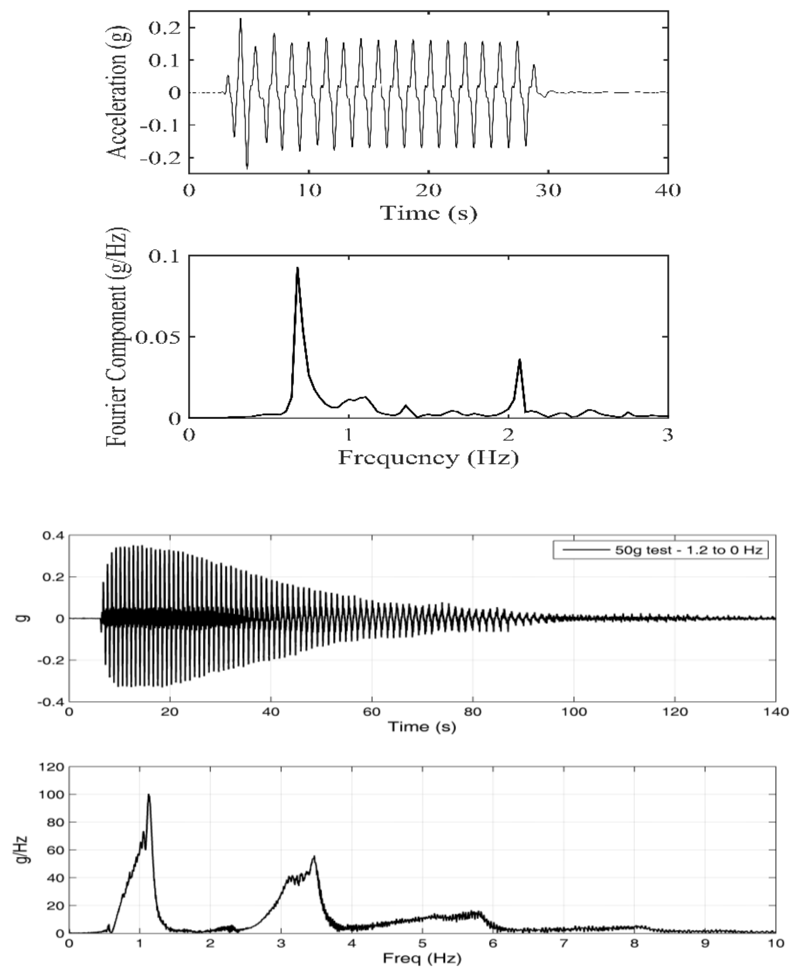
Scaling Laws

	Parameter	Scaling Law Model/Prototype
General scaling laws (slow events)	Length	1/N
	Area	$1/N^2$
	Volume	$1/N^3$
	Mass	$1/ N^3$
	Stress	1
	Strain	1
	Force	$1/ N^2$
	Work	$1/N^3$
	Energy	$1/N^3$
	Seepage velocity	N
	Time (Consolidation)	$1/N^2$
Dynamic events	Time (Dynamic)	1/N
	Frequency	N
	Displacement	1/N
	Velocity	1
	Acceleration / Acceleration due to gravity (g's) }	N

Stored Angular Momentum (SAM) Earthquake Actuator

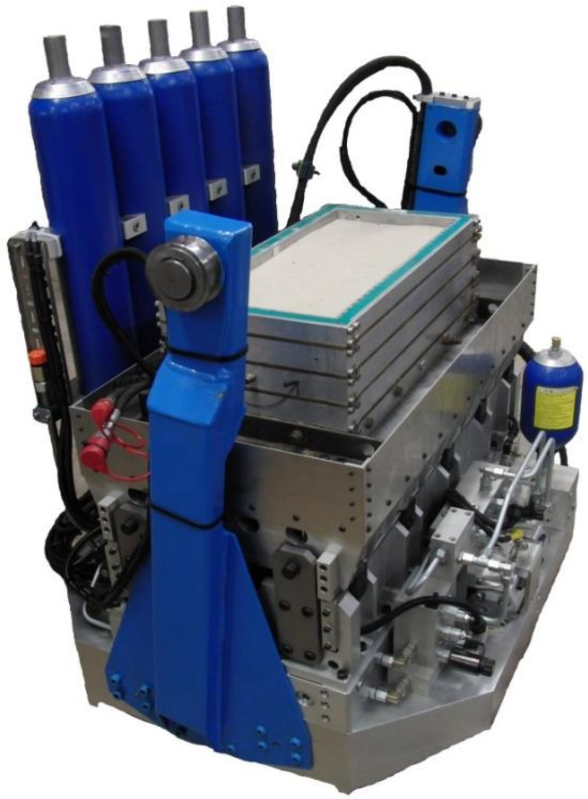


SAM Actuator

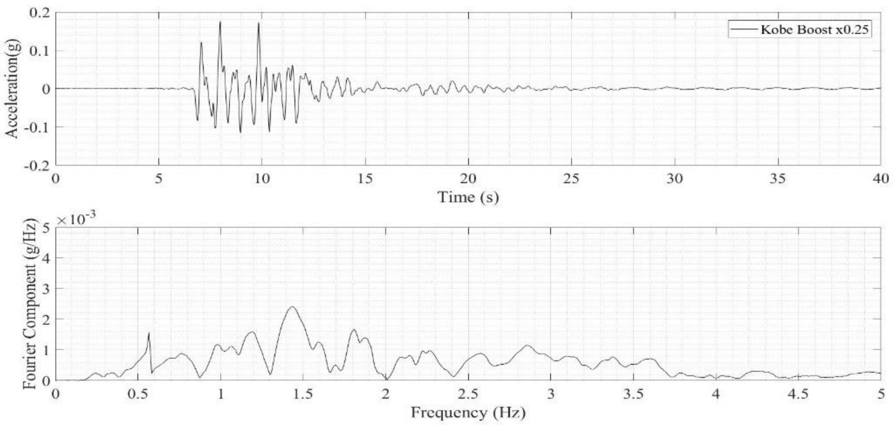


Example Input motions

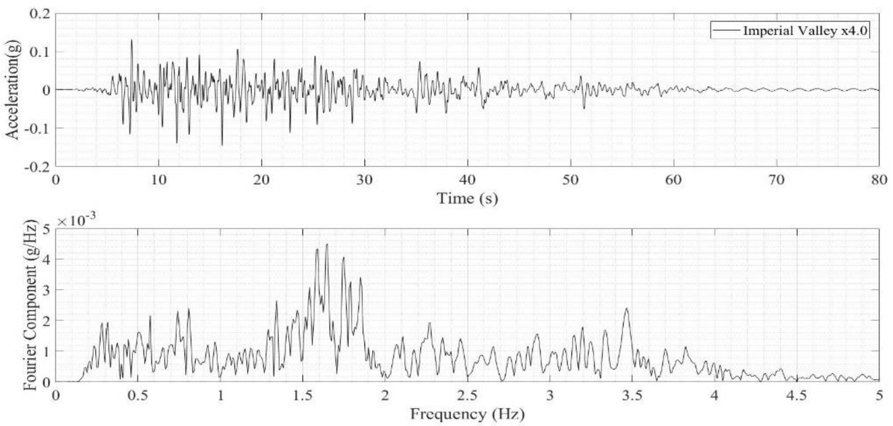
Stored Angular Momentum (SAM) Earthquake Actuator



Servo-Hydraulic Earthquake Actuator

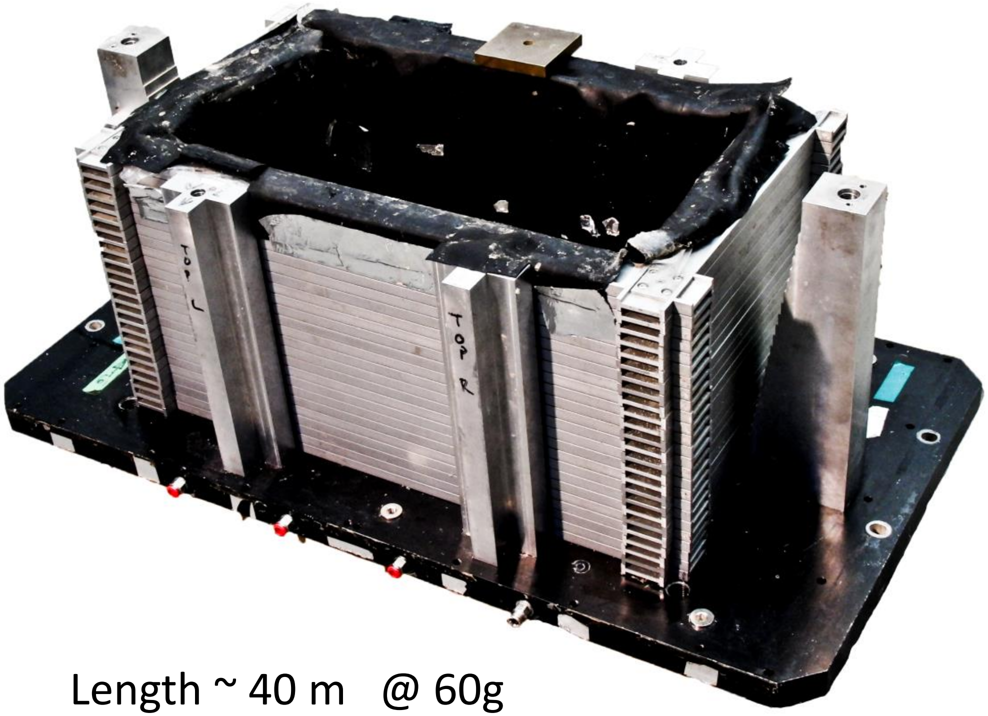


Kobe Motion



Imperial Valley Motion

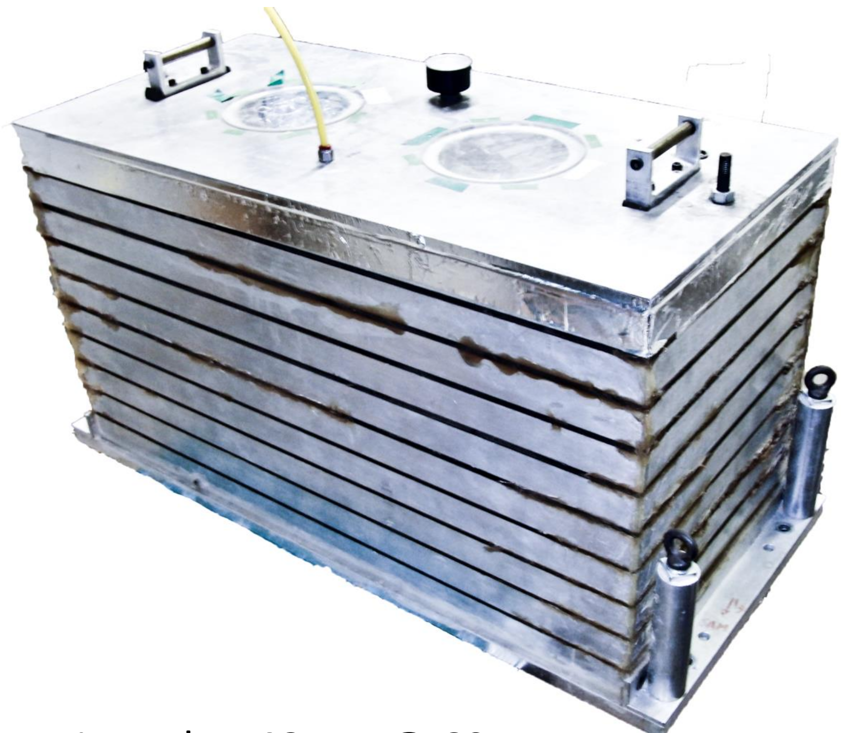
Specialist Model Containers: Laminar Box



Length ~ 40 m   @ 60g
Depth ~ 20 m   @ 60 g
Width ~ 14 m   @ 60g

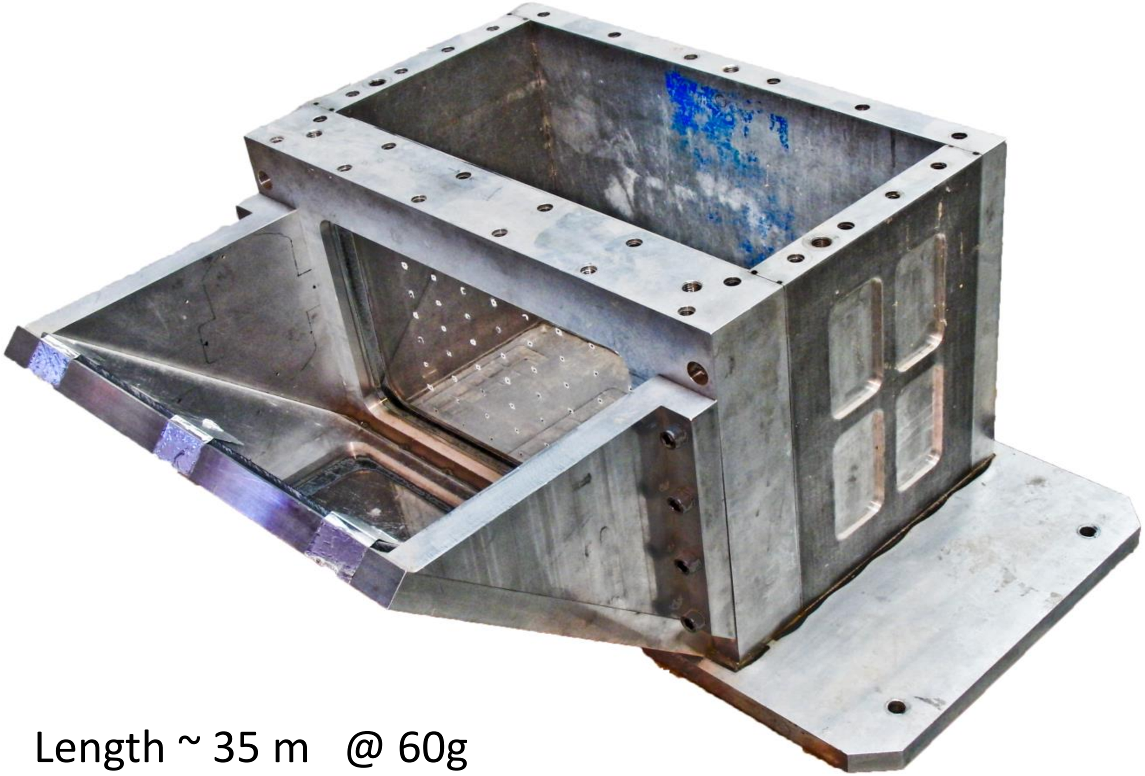
Specialist Model Containers: Equivalent Shear Beam (ESB) model containers

Length ~ 35 m @ 60g
Depth ~ 10 m @ 60 g
Width ~ 14 m @ 60g



Length ~ 48 m @ 60g
Depth ~ 25 m @ 60 g
Width ~ 14 m @ 60g

Specialist Model Containers: Transparent Window Model Container (with 45º mirror)

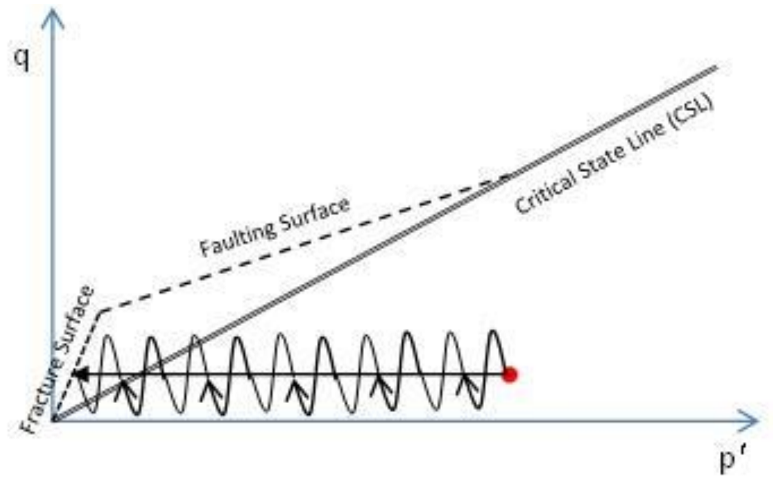


Length ~ 35 m @ 60g
Depth ~ 15 m @ 60 g
Width ~ 13 m @ 60g

Theoretical framework for liquefaction

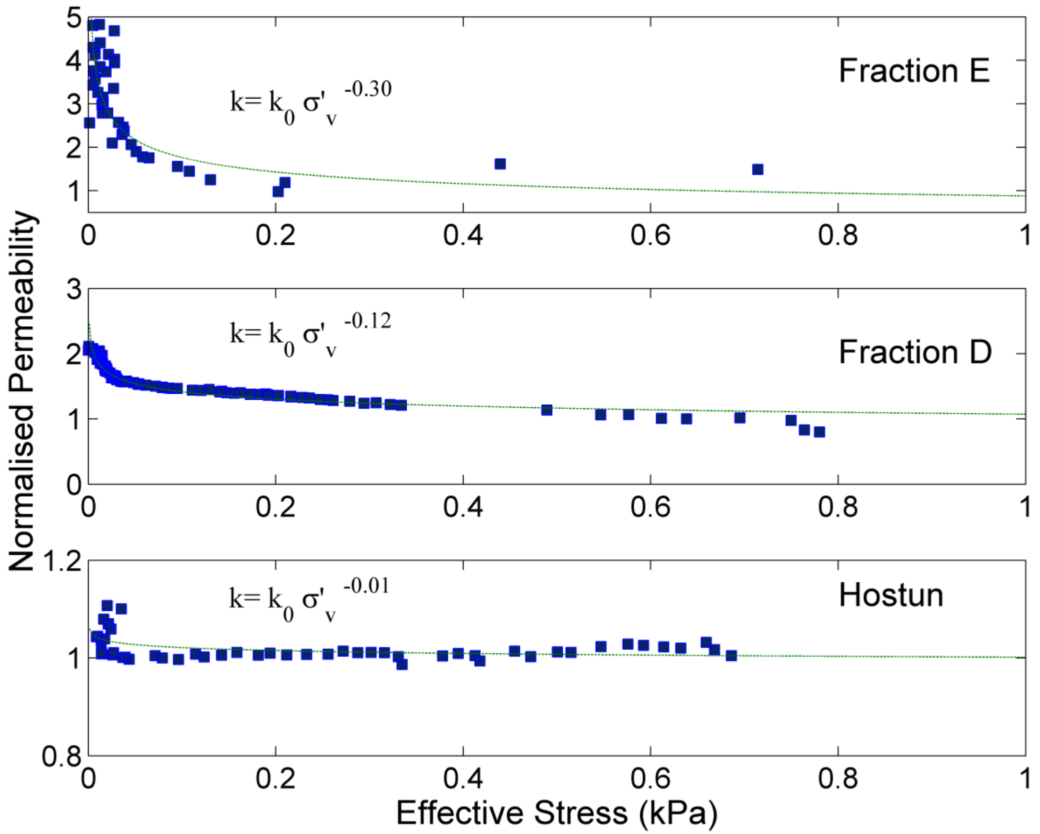
- Excess pore pressures generate when saturated soil is subjected to cyclic shearing
- This will cause a reduction in mean effective stress p'
- The stress state reaches 'Fracture Surface'
- The soil will fracture opening cracks forming sand boils/mud flows

- This implies that the 'soil permeability' and 'soil compressibility' must be ***high*** for liquefied soil



(after Muhunthun & Schofield, 2000)

Permeability of liquefied soil

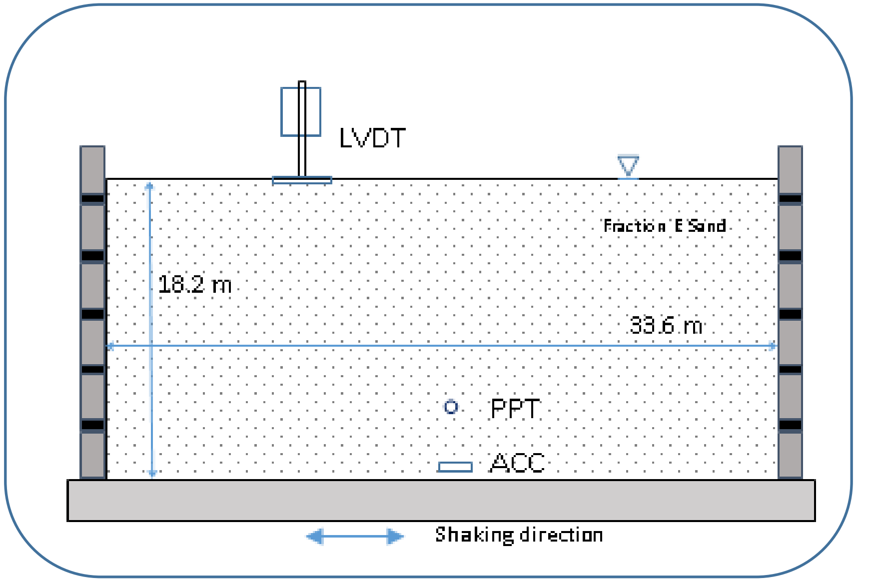


- ➢ Permeability of sands was observed to increase at very low effective stresses (< 1 kPa)

Haigh S.K., Eadington, J. & Madabhushi, S.P.G., (2012), "Permeability and stiffness of sands at very low effective stresses", *Geotechnique*, 62(1), pp. 69-75.

New understanding of liquefaction Phenomena

- Is Liquefaction Really Undrained?
- Do volumetric strains remain zero during liquefaction i.e. during earthquake loading?
- How does soil reconsolidate in the post-liquefaction period?

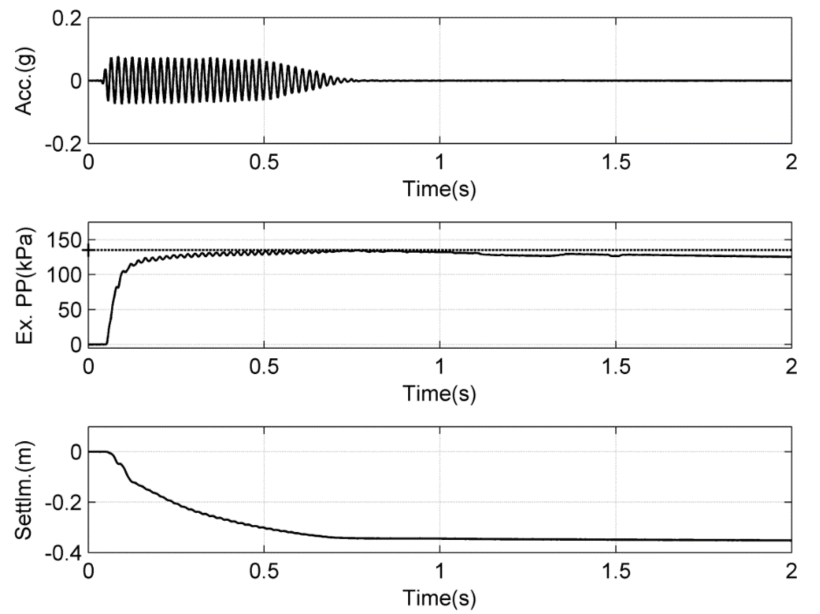


Coelho et al (2007)

Coelho, P.A.L.F., Haigh, S.K., Madabhushi, S.P.G. and O'Brien, A.S., (2007), "Post-earthquake behaviour of footings when using densification as a liquefaction resistance measure", Ground Improvement Journal, 11(1), pp 45-53.

New understanding of liquefaction Phenomena

- Is Liquefaction Really Undrained?
- Level bed of saturated sand at a relative density of 50%
- Full liquefaction is observed (i.e. $r_u = 1$)
- Rate of settlement is much higher during earthquake loading



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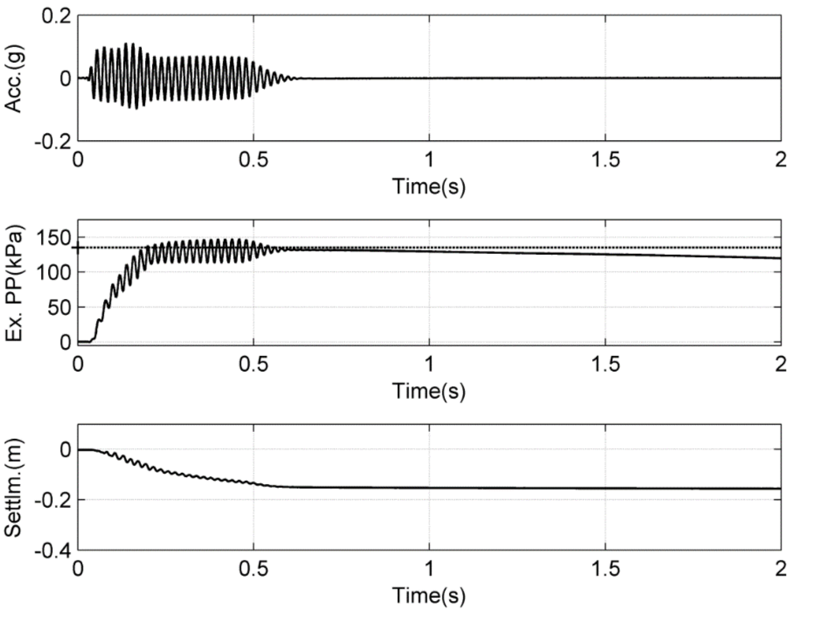
New understanding of liquefaction Phenomena

- Is Liquefaction Really Undrained?
- Level bed of saturated sand at a relative density of 80%
- Full liquefaction is observed (i.e. $r_u = 1$)
- Rate of settlement is higher during earthquake loading

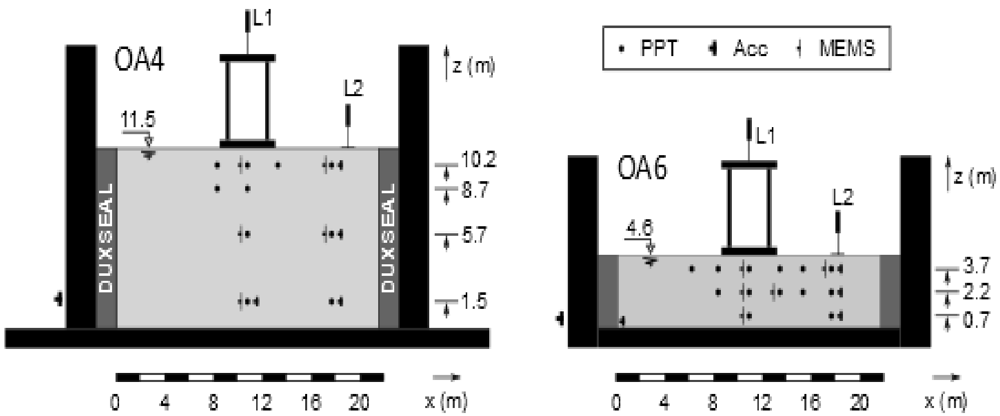


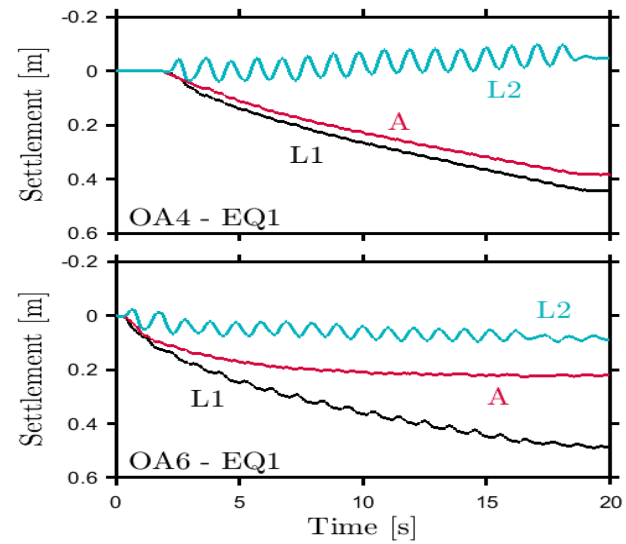
Coelho et al (2007)

So the soil is not really 'undrained' during earthquake loading

Coelho, P.A.L.F., Haigh, S.K., Madabhushi, S.P.G. and O'Brien, A.S., (2007), "Post-earthquake behaviour of footings when using densification as a liquefaction resistance measure", Ground Improvement Journal, 11(1), pp 45-53.

Shallow foundations on liquefiable soils





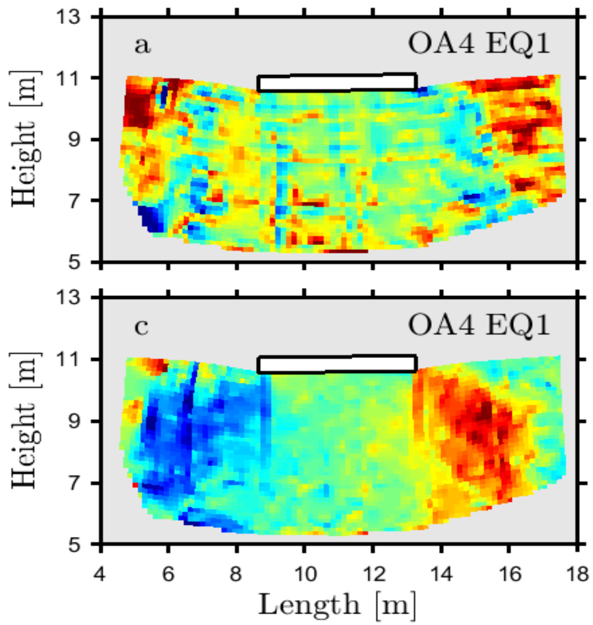
- Foundation Bearing pressure ~ 50 kPa
- Structural and free-field settlements are monitored
- 'A' is the track of settlement from PIV of soil next to foundation
- High speed imaging was used with PIV analyses to produce soil strains

Adamidis & Madabhushi (2016)

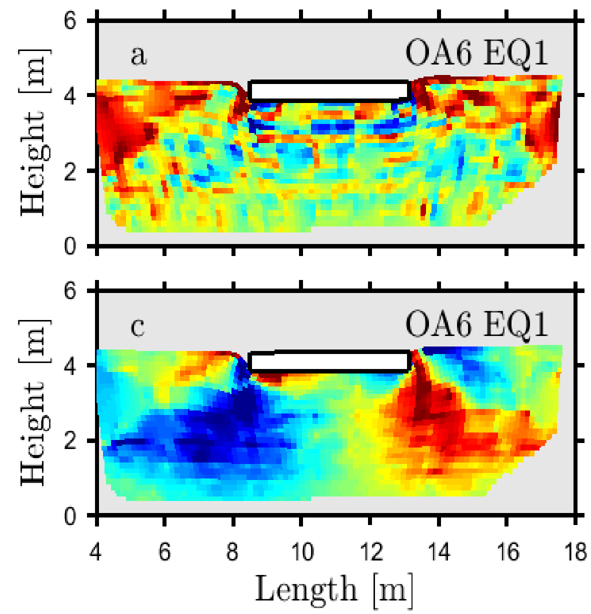
Adamidis, O. and Madabhushi, G.S.P., (2017a), Deformation mechanisms under shallow foundations resting on liquefiable layers of varying thickness, Geotechnique, Thomas Telford, DOI: doi.org/10.1680/jgeot.17.P.067.

Shallow foundations on liquefiable soils

Deep Soil Layer



Shallow Soil Layer



Volumetric & Shear Strains (from beginning to end of earthquake loading)

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Shallow foundations on liquefiable soils

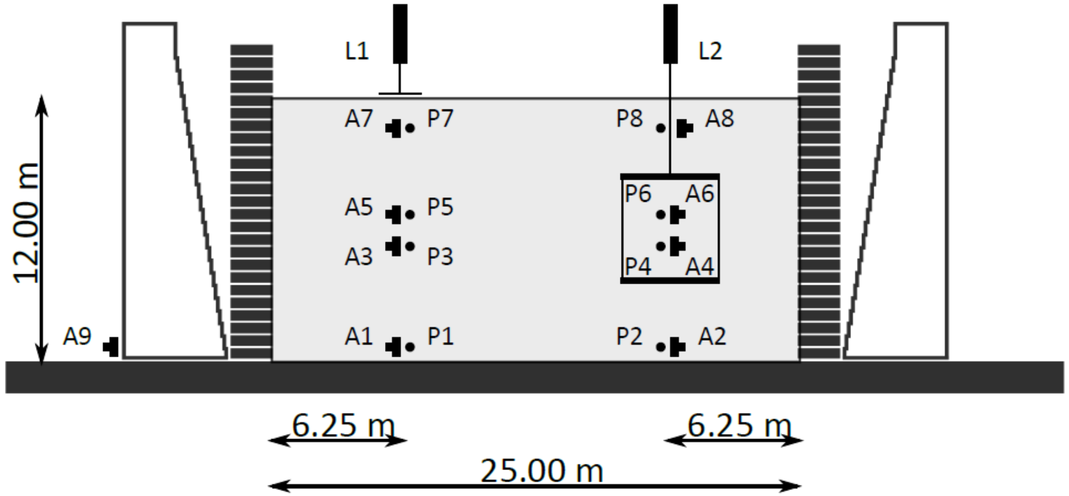
- Settlement of structure is a lot more than the free-field soil (as expected)

- Shear strains are concentrated at the edges of the foundation

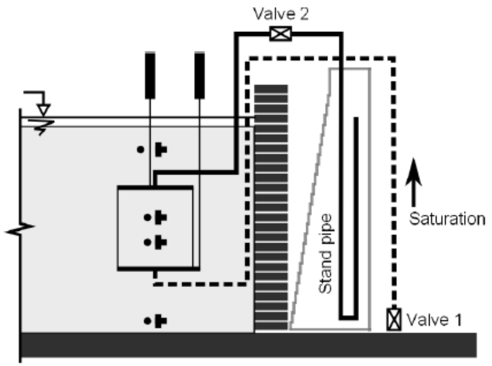
- Volumetric strains are present for both deep and shallow soil layers during the earthquake loading – this again confirms that 'liquefied soil' is not an undrained event

Drainage during liquefaction

- Novel Centrifuge Tests with Triaxial chambers (Tests OA2 and OA3)



A: Accelerometer	P: Pore pressure transducer	L: Displacement transducer



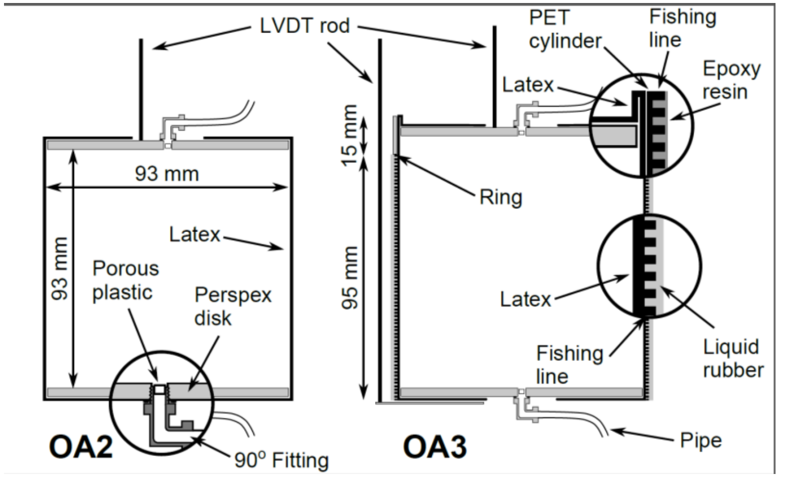
Drainage is controlled from Tx cell

Adamidis, O. and Madabhushi, G.S.P., (2017), Drainage during earthquake-induced liquefaction, Geotechnique, Thomas Telford, DOI://doi.org/10.1680/jgeot.16.p.090.

Drainage during liquefaction

- Test OA2 had the triaxial chamber that is simply made of latex
- This chamber can expand or contract radially, depending on outside liquefied soil pressure relative to the inside horizontal stress

- Test OA3 had the same latex chamber but the chamber is wound with a thin, steel wire (fishing line).
- This prevents outward radial expansion but the liquefied soil can push inwards, if its pressure is higher than the inside horizontal stress



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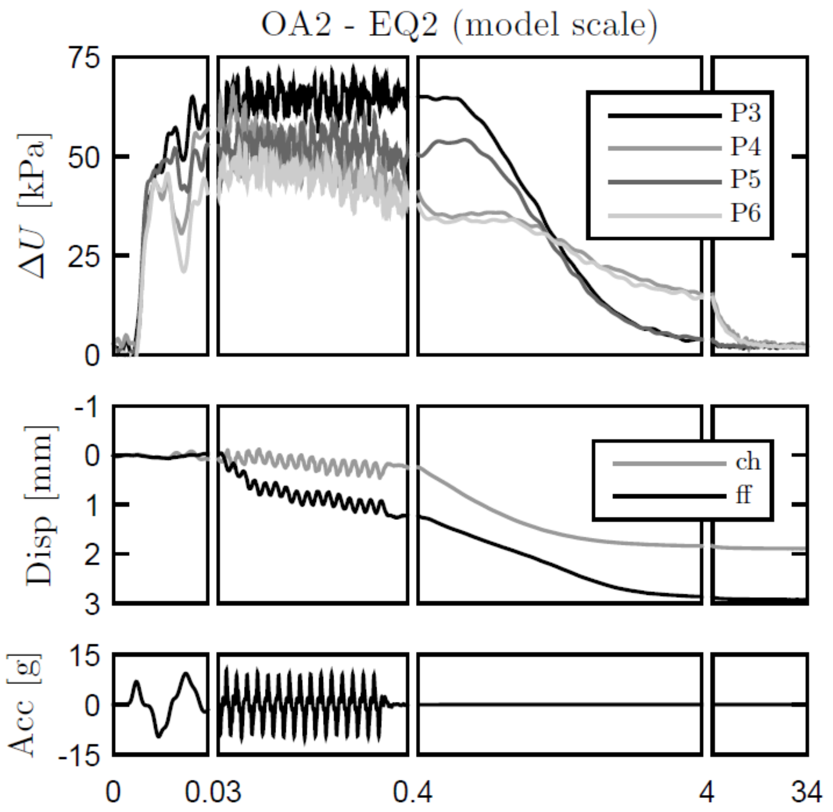

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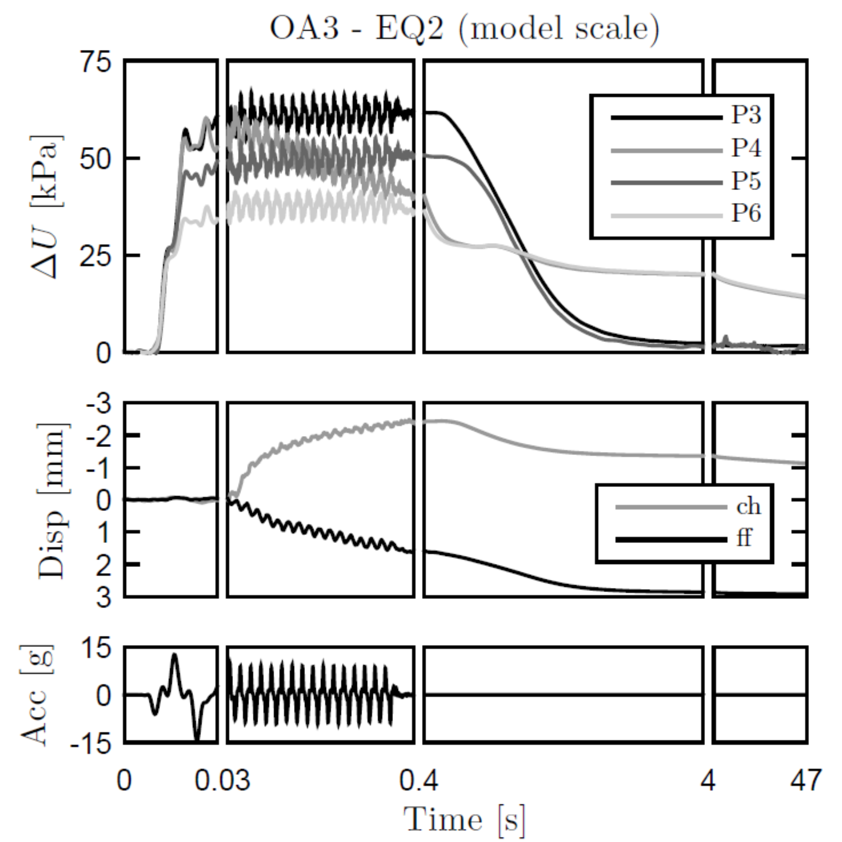

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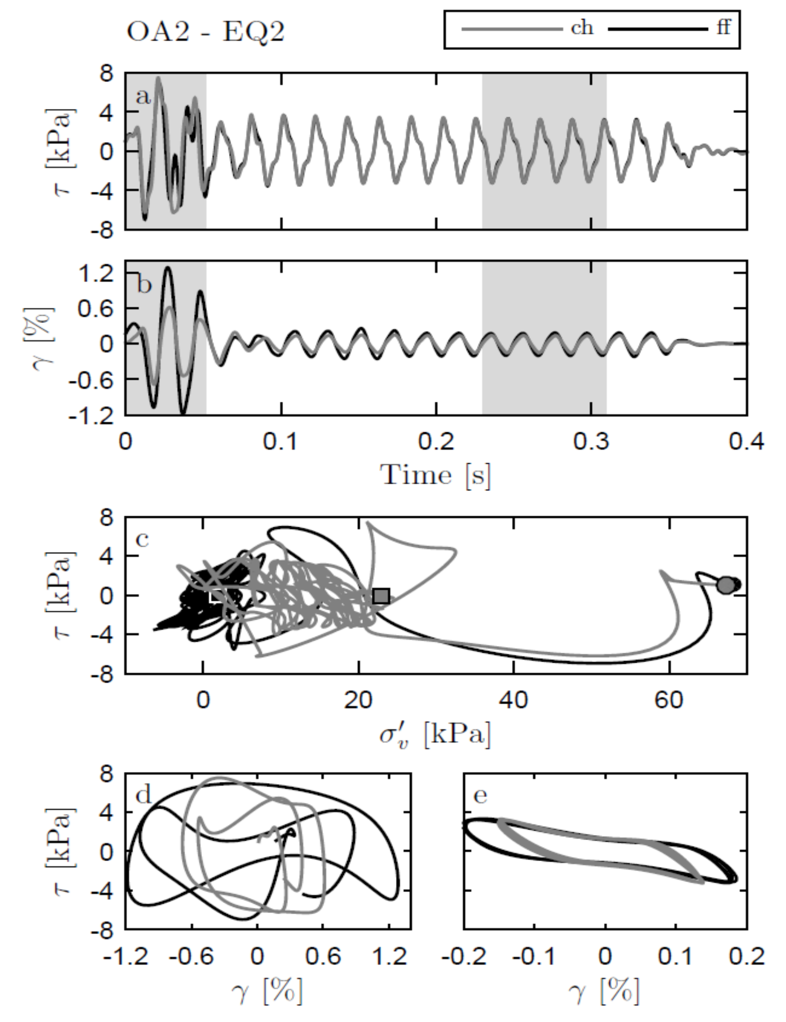

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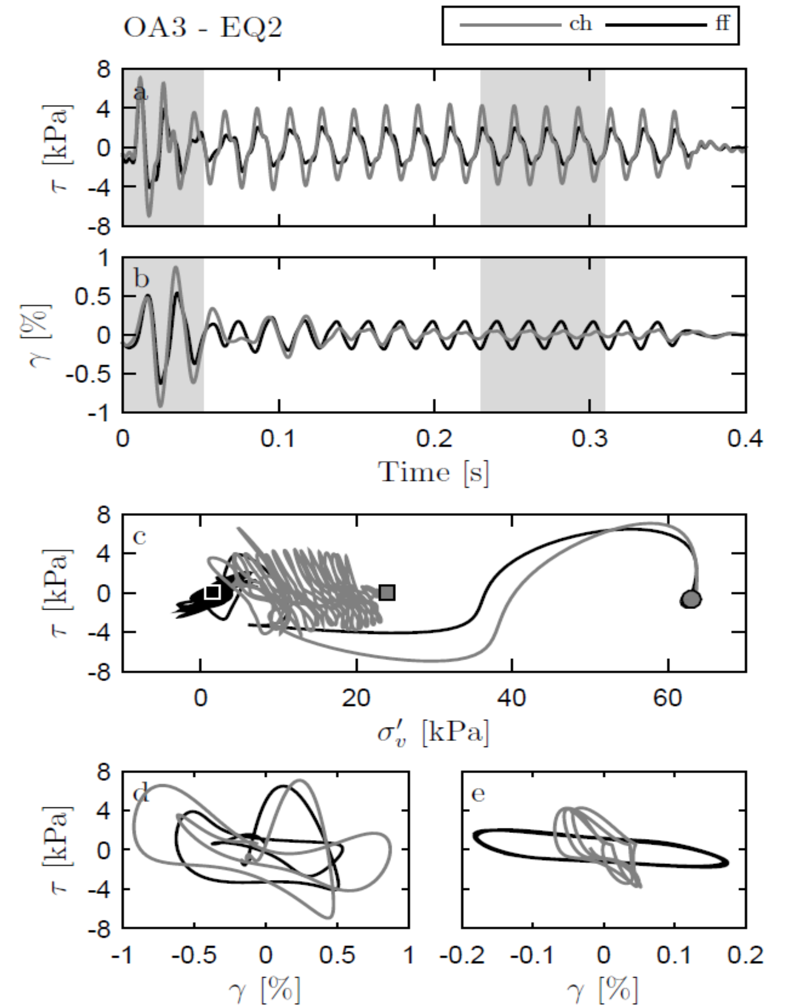
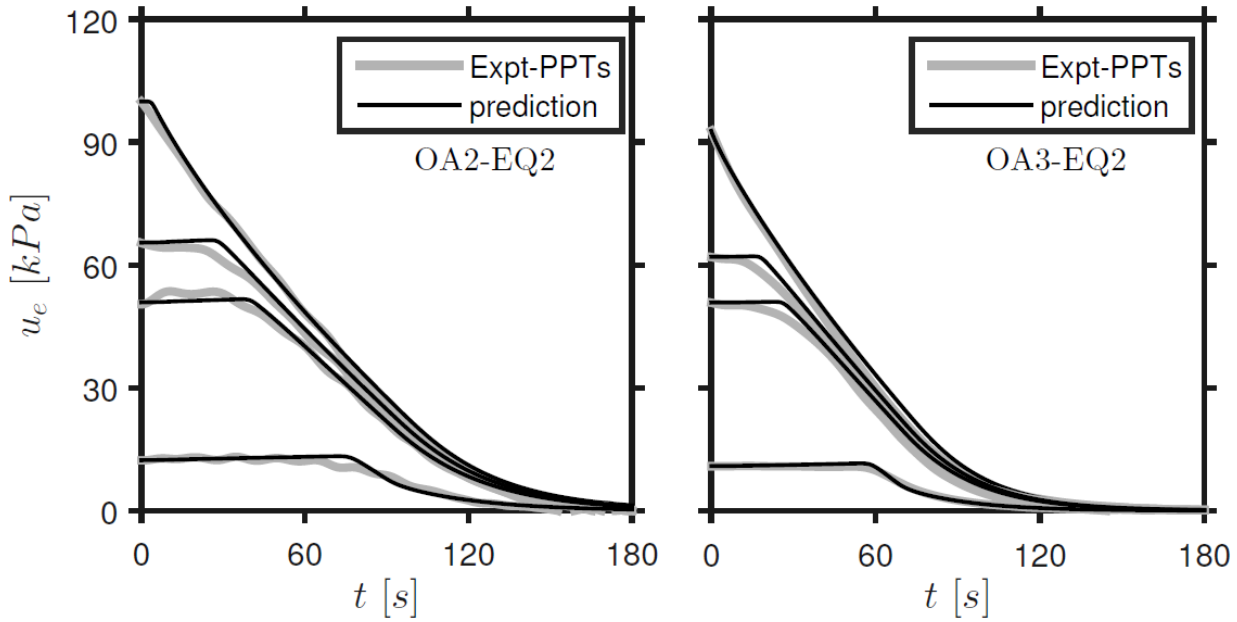


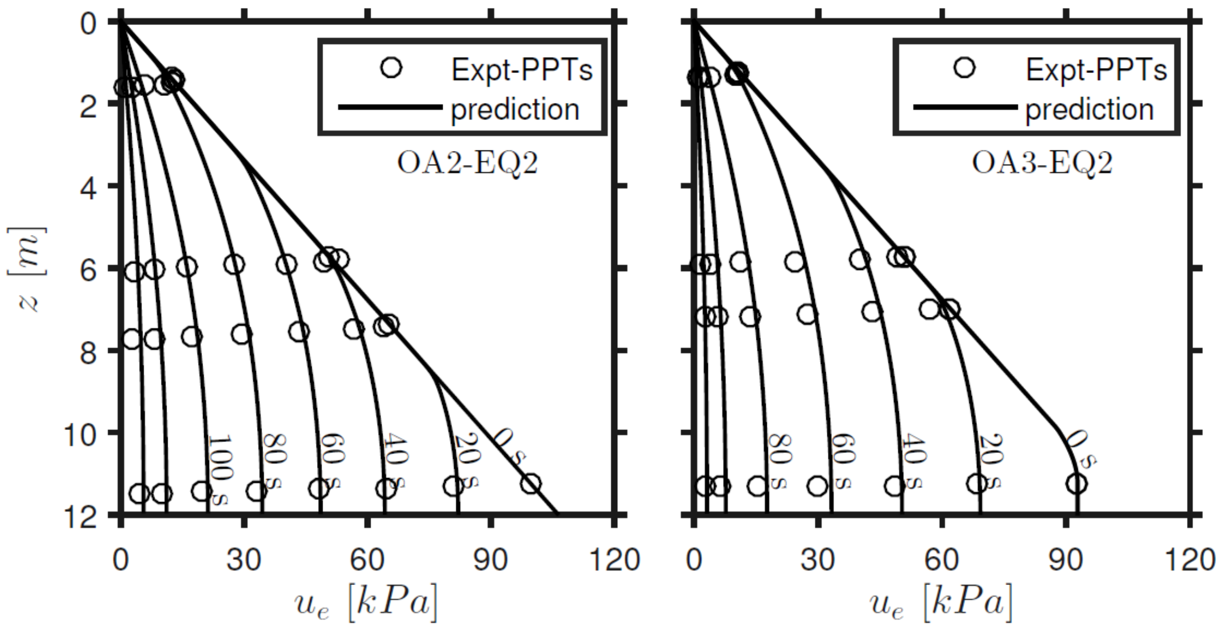
Post liquefaction reconsolidation



- Excess pore pressure time histories from the two centrifuge tests OA2 and OA3
- Predictions are made using modified Terazaghi's consolidation theory and allowing for variable co-efficient of consolidation

Adamidis, O. and Madabhushi, G.S.P., (2016), "Post-liquefaction reconsolidation of sand", *Proceedings of Royal Society A, Mathematical, Physical and Engineering Sciences*, 472:20150745; DOI: 10.1098/rspa.2015.0745.

Post liquefaction reconsolidation



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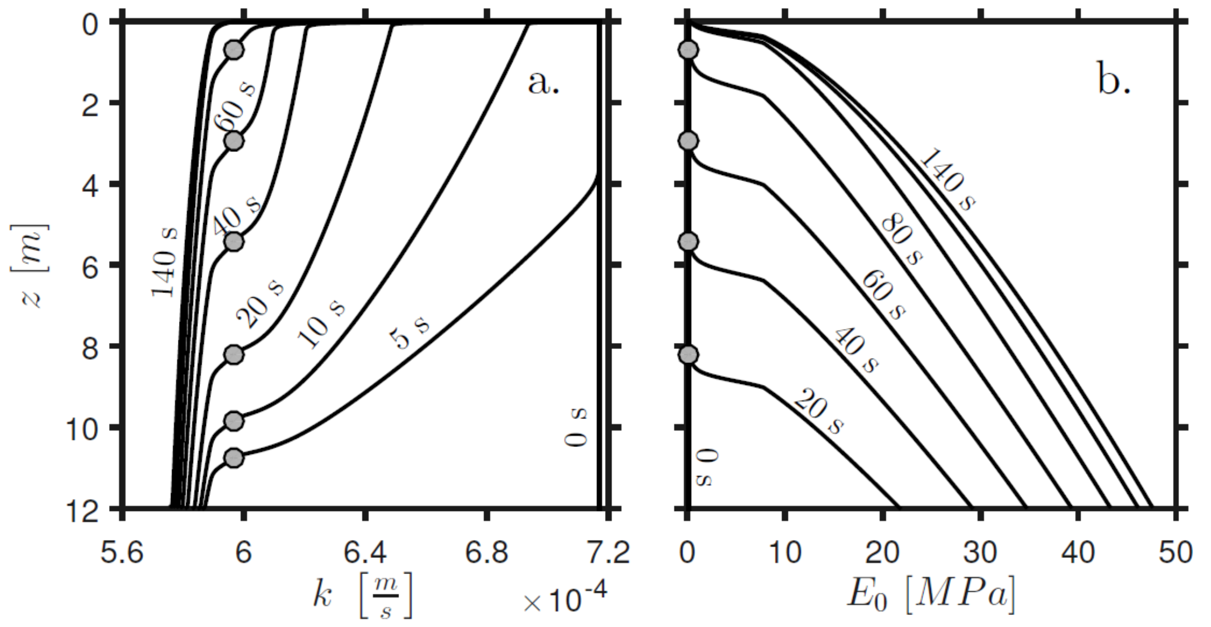
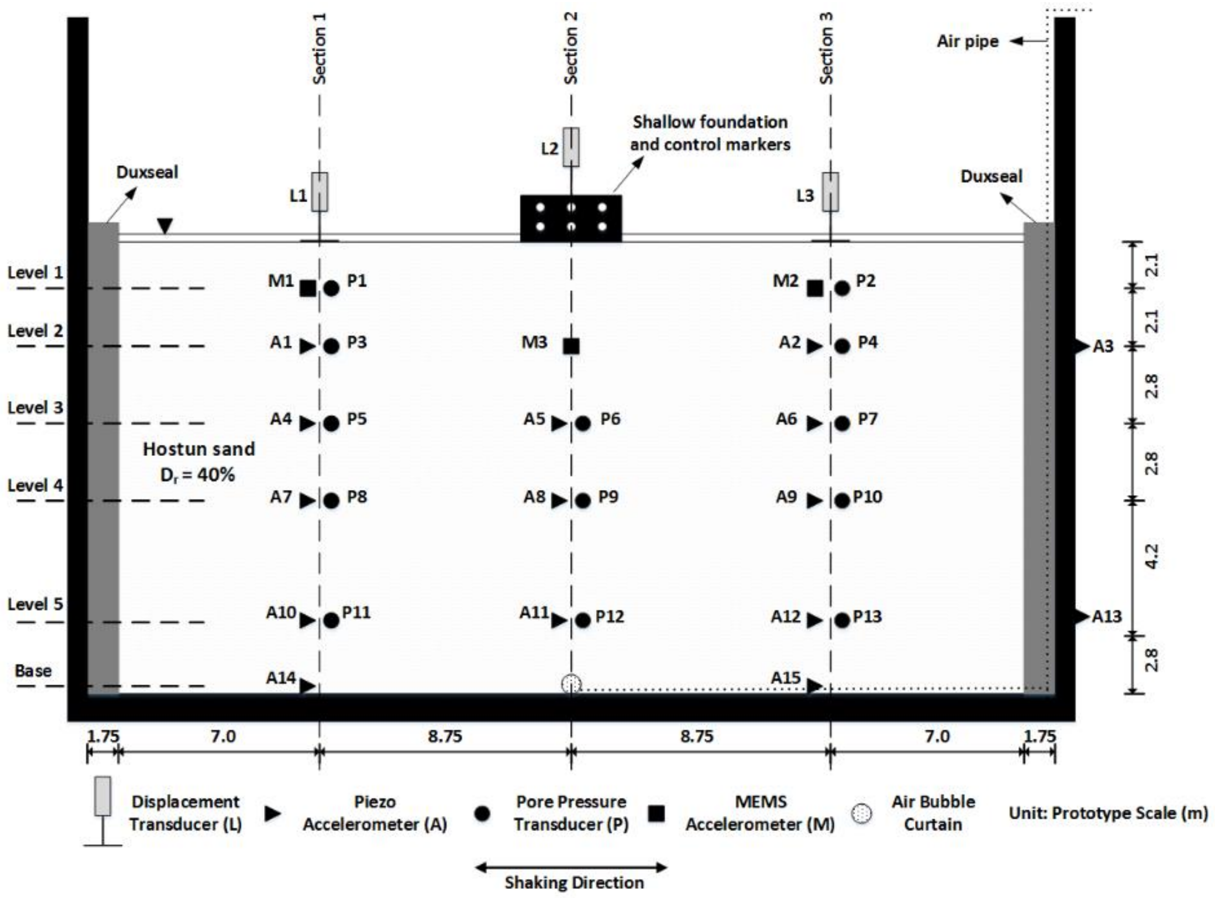
Post liquefaction reconsolidation



- Changes in permeability (*k*) of the liquefied soil with time
- Changes in the 1-D compressibility (E_o) of the liquefied soil with time
- Permeability decreases with time while compressibility increases with time

Adamidis, O. and Madabhushi, G.S.P., (2016), "Post-liquefaction reconsolidation of sand", *Proceedings of Royal Society A, Mathematical, Physical and Engineering Sciences*, 472:20150745; DOI: 10.1098/rspa.2015.0745.

Novel liquefaction mitigation using Air-Sparging



Zeybek, A. and Madabhushi, S.P.G., (2016), Effect of bearing pressure and degree of saturation on the seismic liquefaction behaviour of air-induced partially saturated air-sparged soils below shallow foundations, Bulletin of Earthquake Engineering, DOI 10.1007/s10518-016-9968-6.

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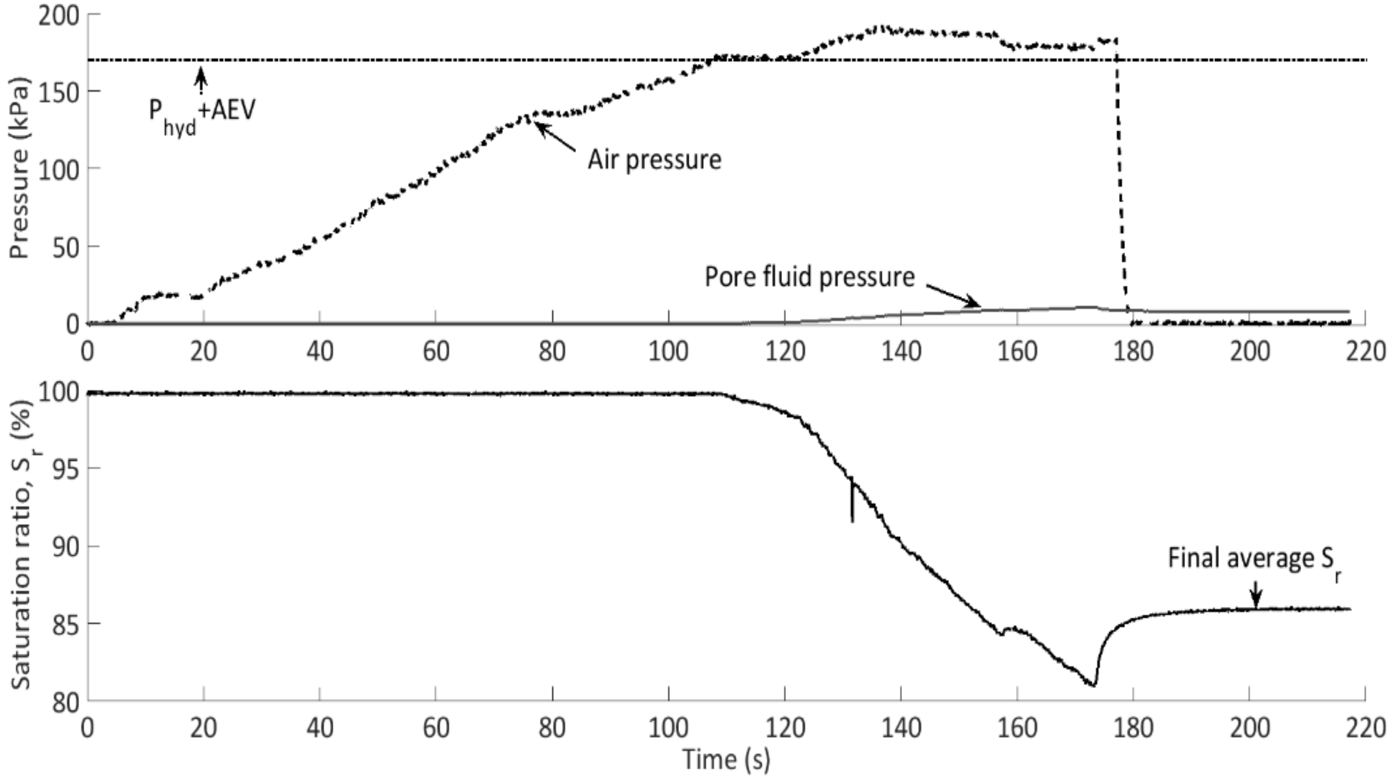

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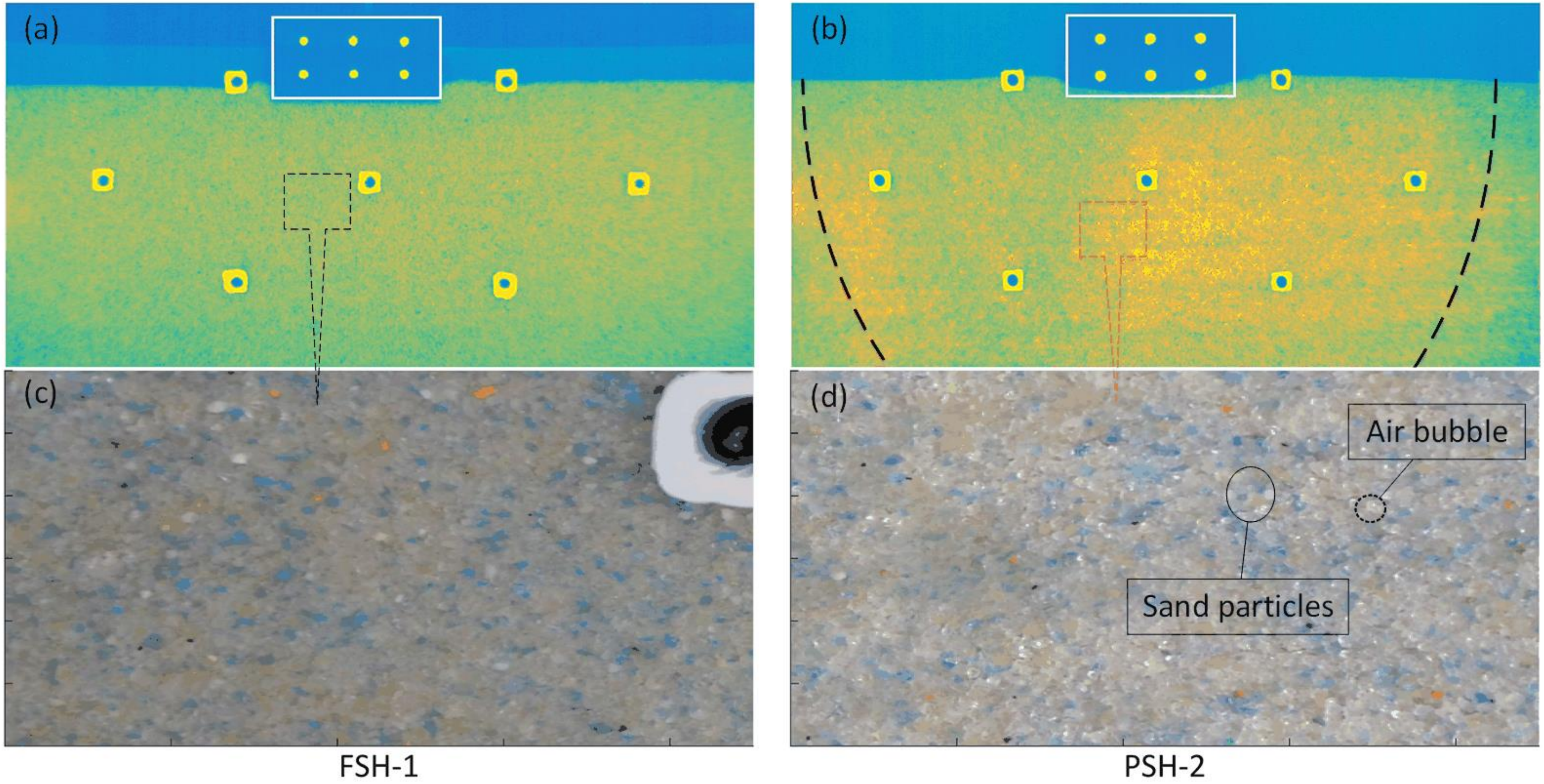

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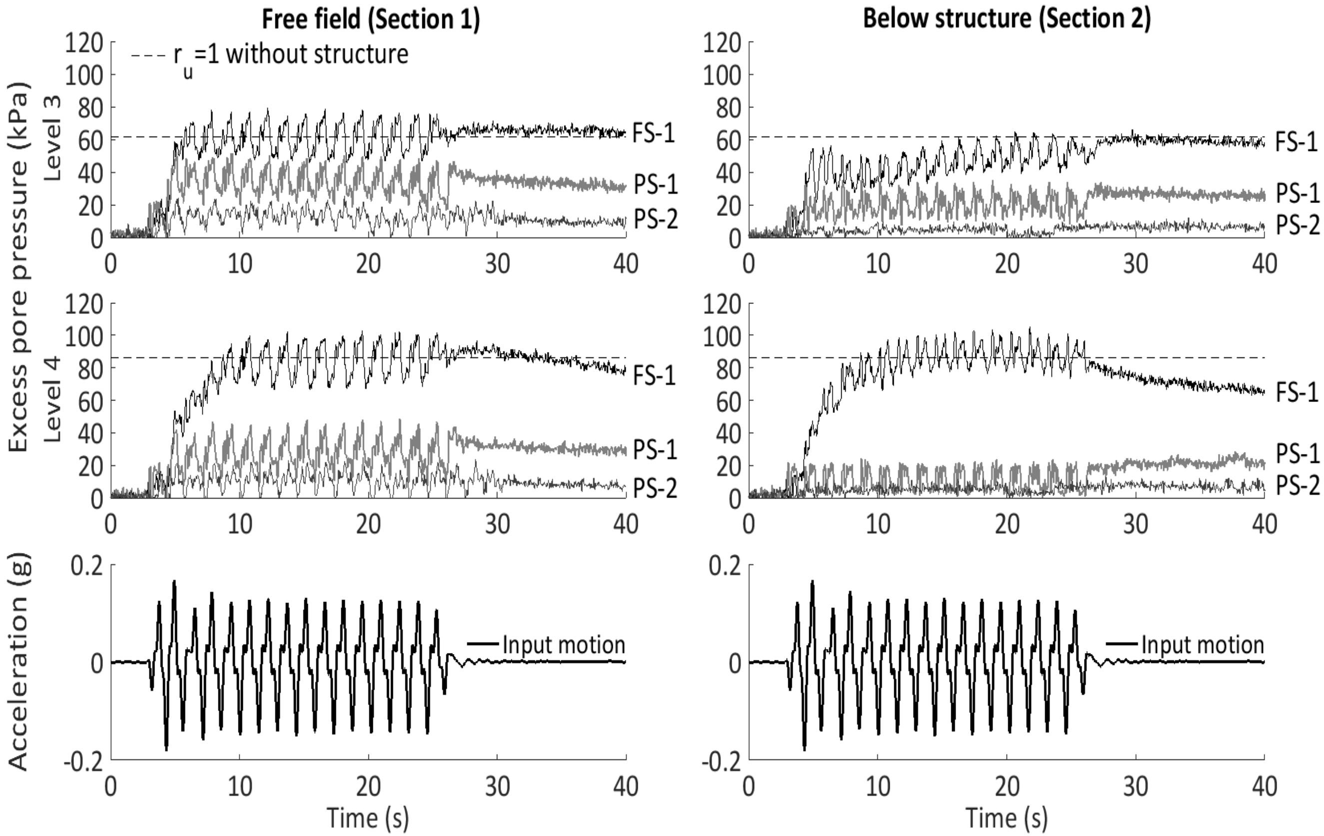
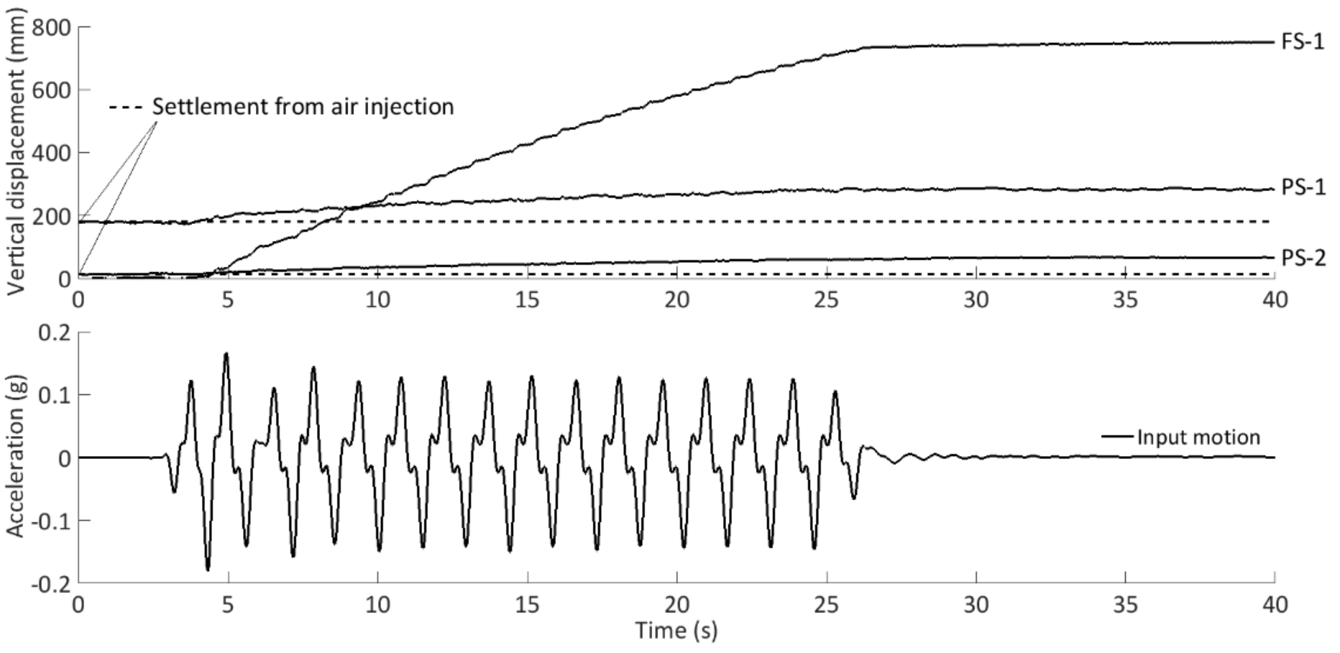


- Excess pore pressures are much smaller in air-injected cases (PS-1&2) compared To the Fully saturated case (FS-1)

Novel liquefaction mitigation using Air-Sparging



- Settlements are much smaller in air-injected cases (PS-1&2) compared To the Fully saturated case (FS-1)

Zeybek, A. and Madabhushi, S.P.G., (2016), Effect of bearing pressure and degree of saturation on the seismic liquefaction behaviour of air-induced partially saturated air-sparged soils below shallow foundations, Bulletin of Earthquake Engineering, DOI 10.1007/s10518-016-9968-6.

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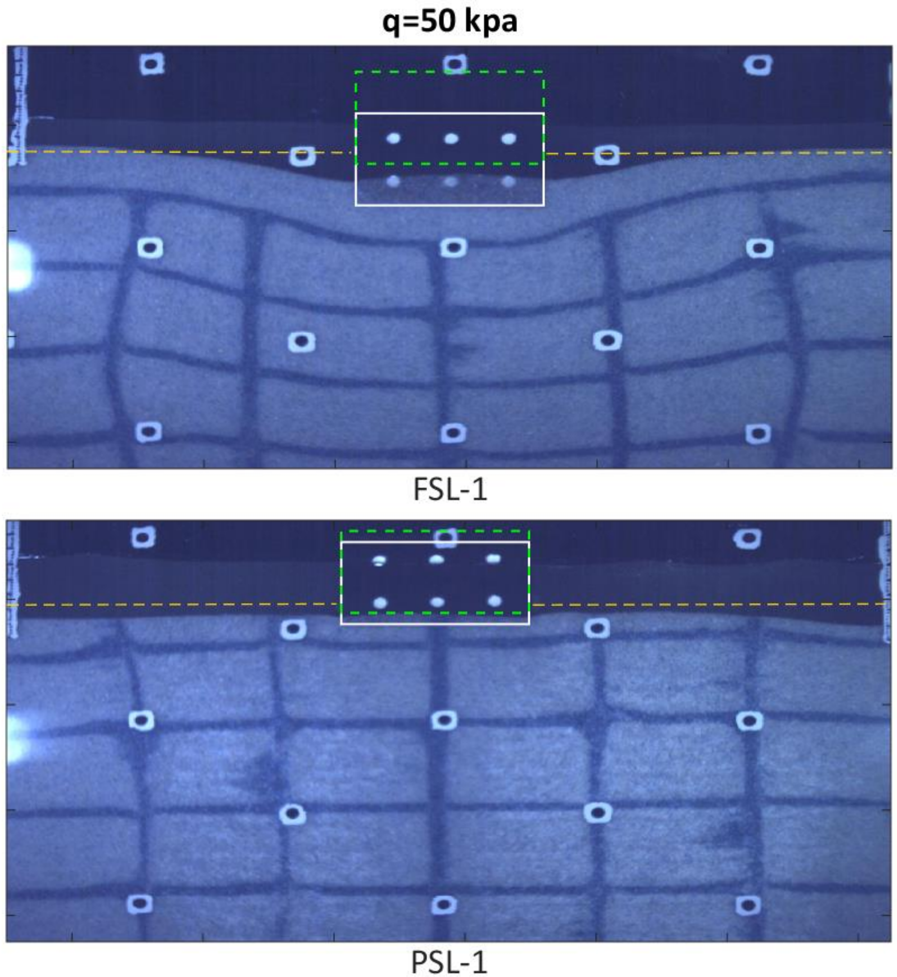
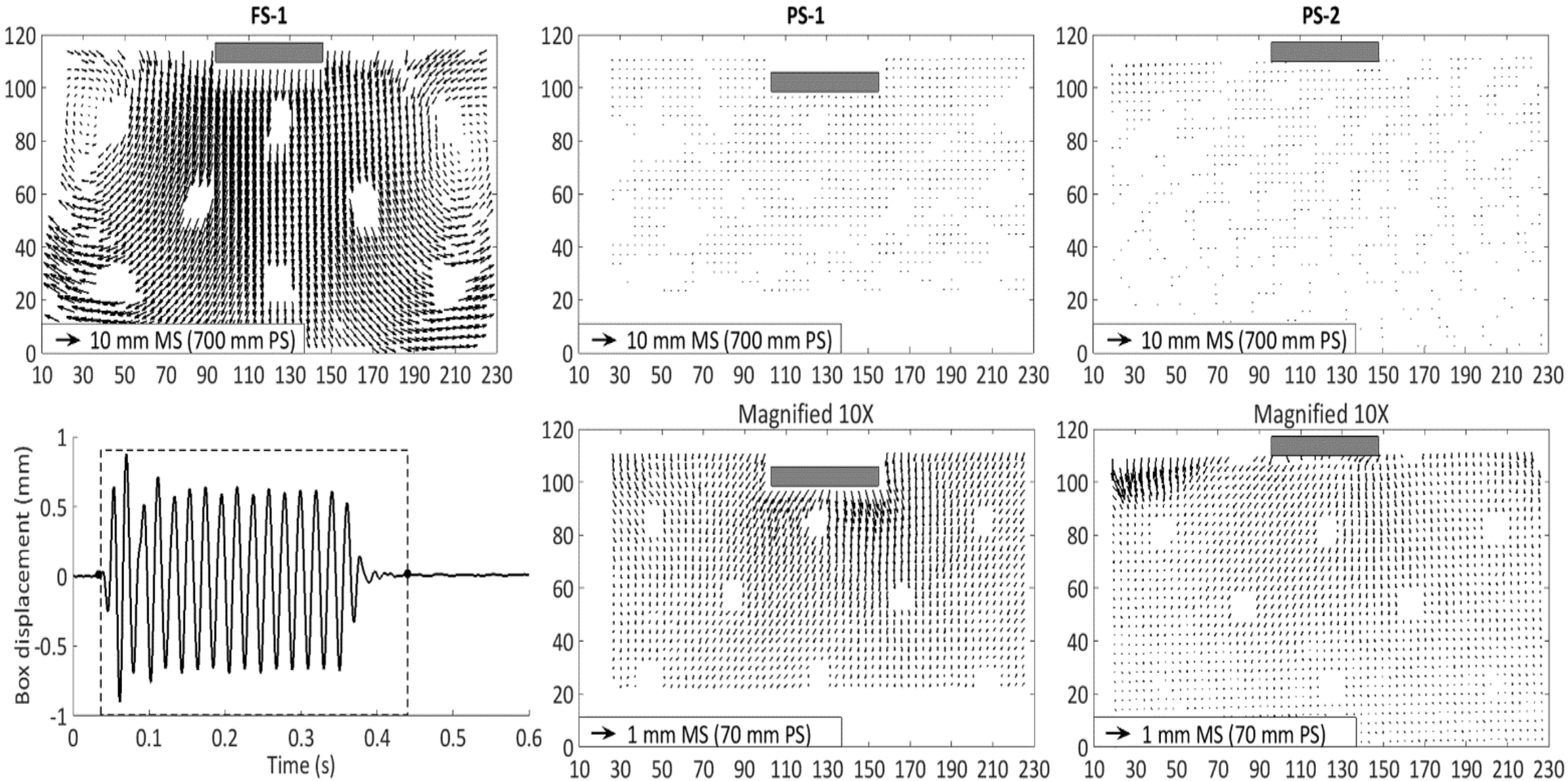


Zeybek, A. and Madabhushi, S.P.G., (2017), Influence of air injection on the liquefaction-induced deformation mechanisms beneath shallow foundations, Journal of Soil Dynamics and Earthquake Engineering, Vol. 97, pp 266-276.

Novel liquefaction mitigation using Air-Sparging



- PIV Analysis reveals the differences in deformation mechanisms

Zeybek, A. and Madabhushi, S.P.G., (2017), Influence of air injection on the liquefaction-induced deformation mechanisms beneath shallow foundations, Journal of Soil Dynamics and Earthquake Engineering, Vol. 97, pp 266-276.

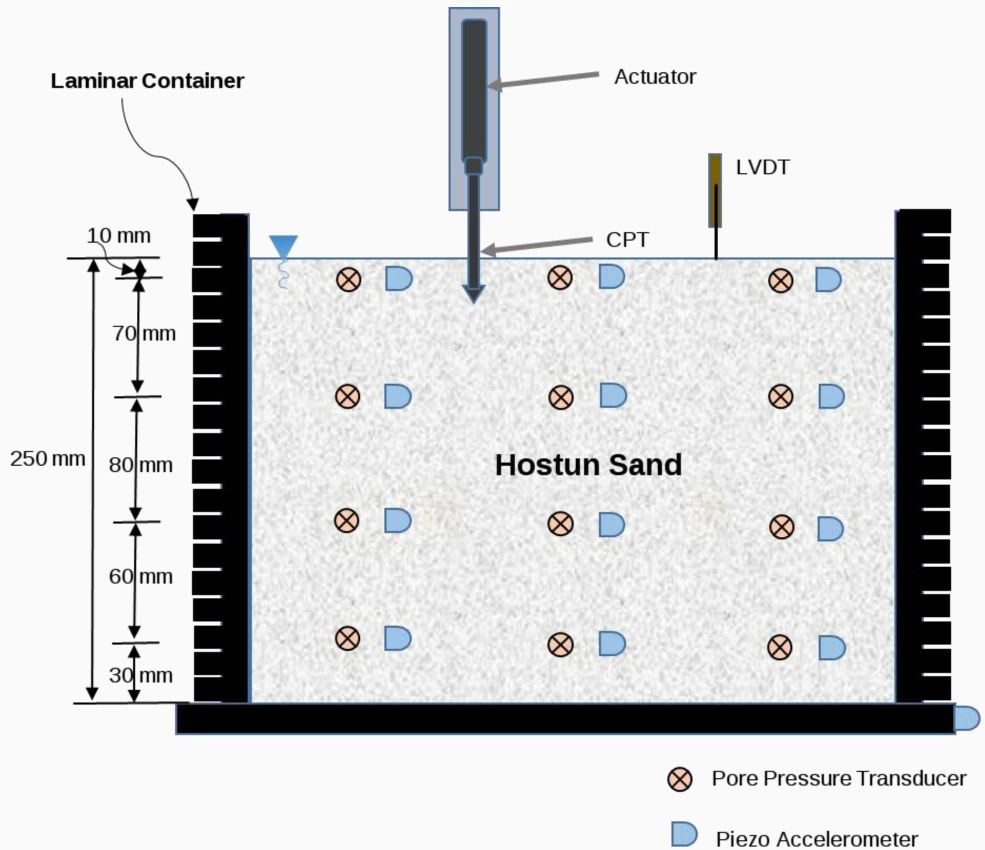
IN-FLIGHT CPT TESTING IN A DYNAMIC CENTRIFUGE TEST

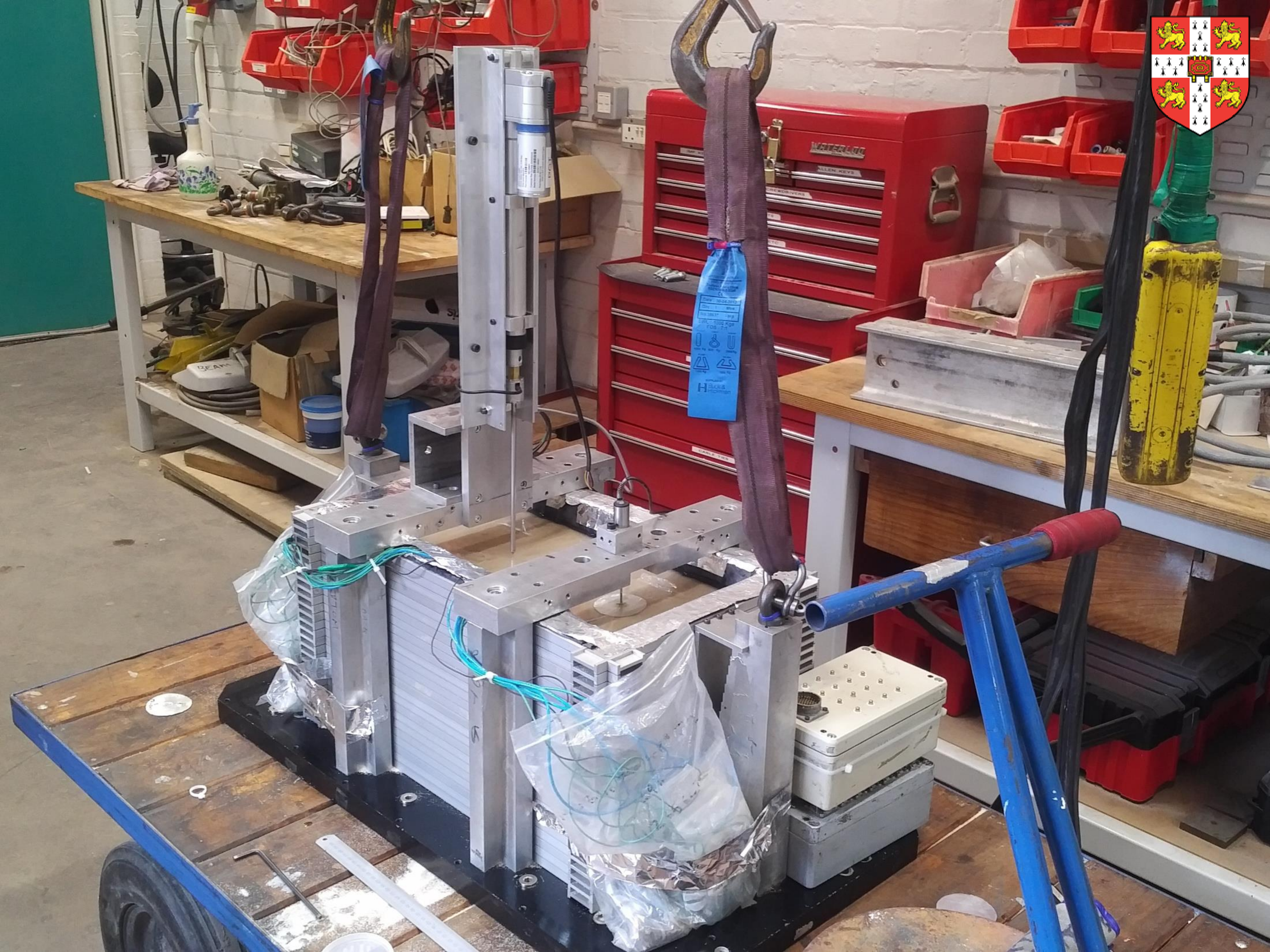
Test ID : **AD01**

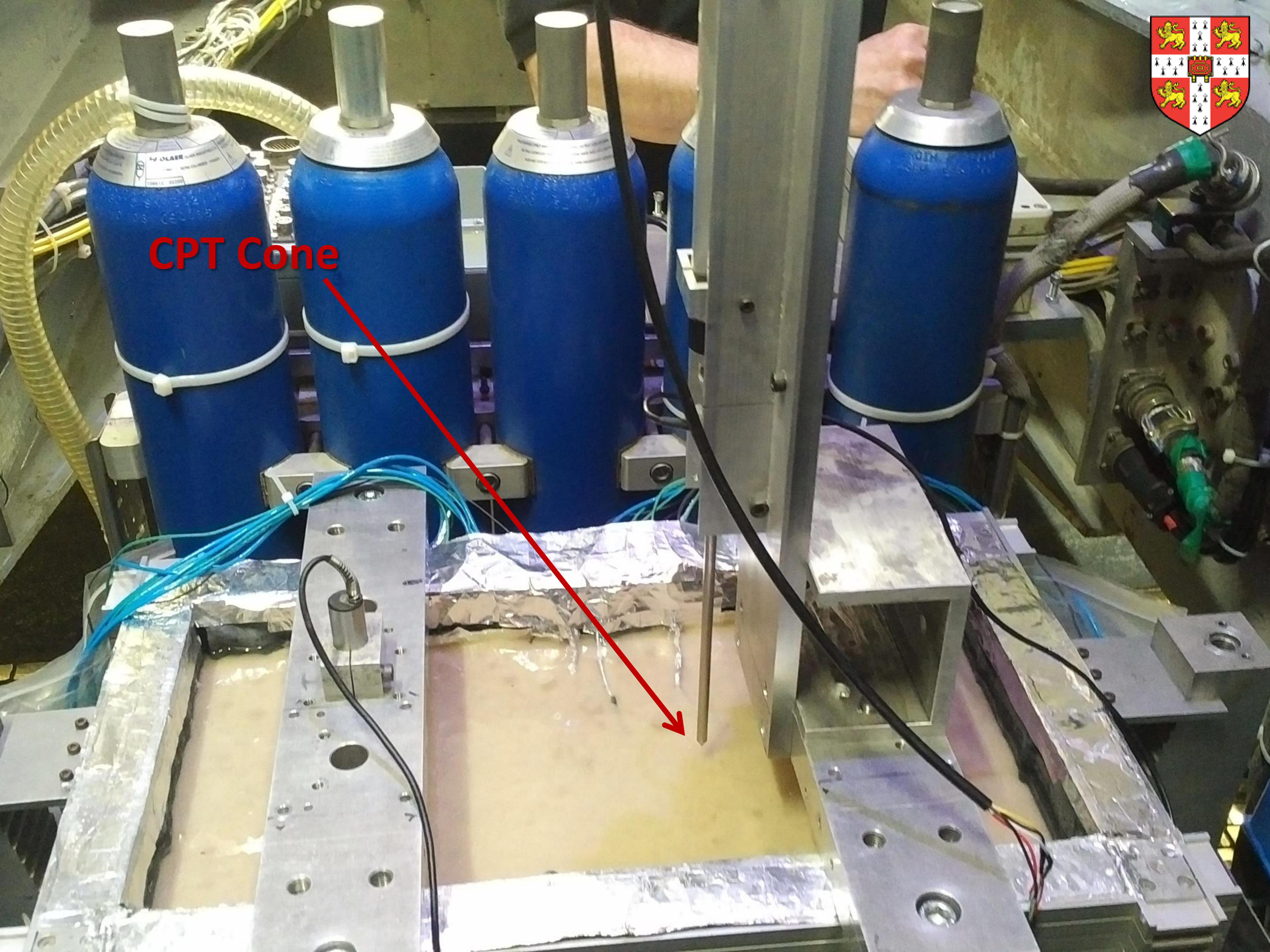
Fully saturated level bed

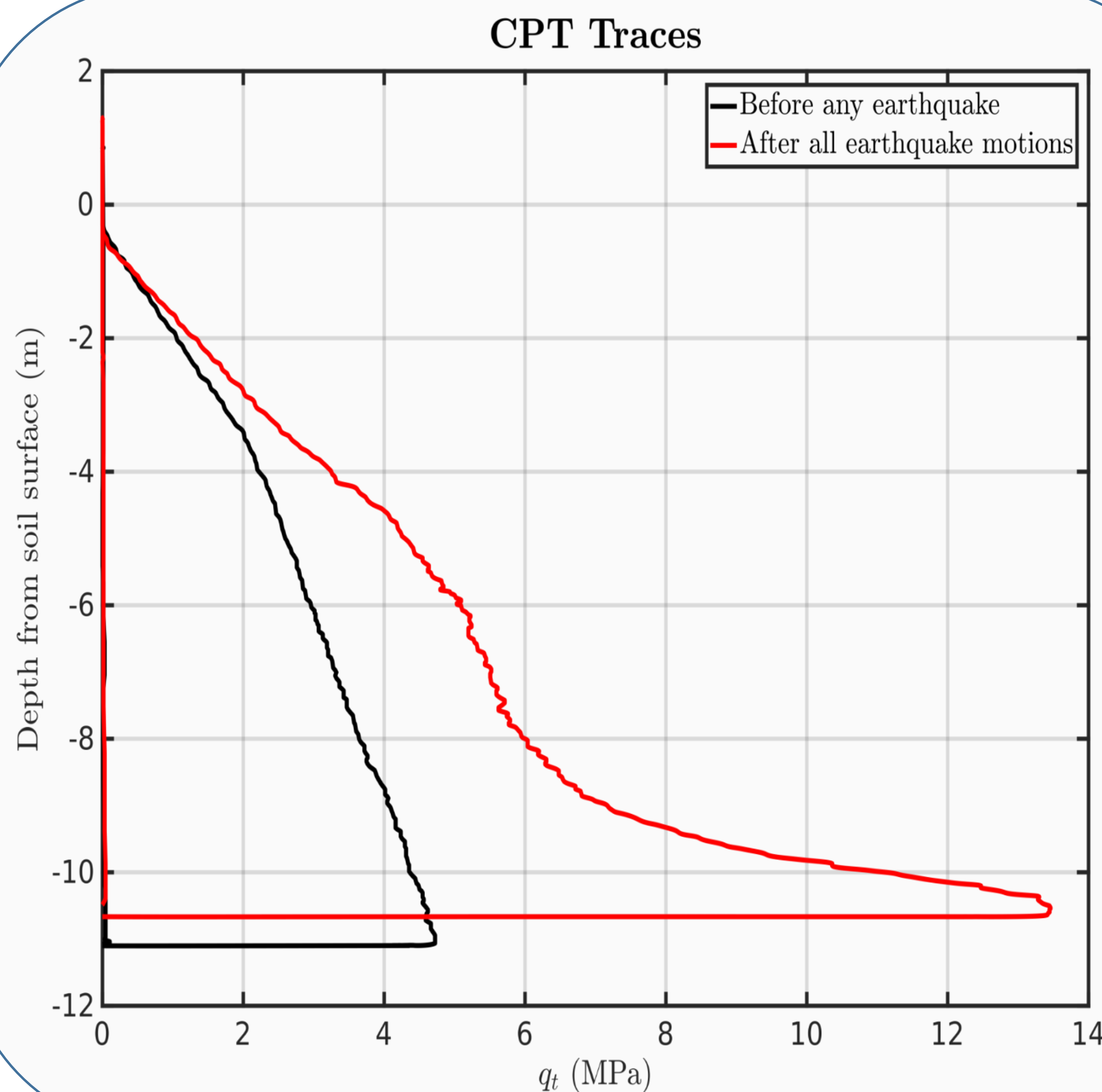
Hostun Sand

RD = **30%**

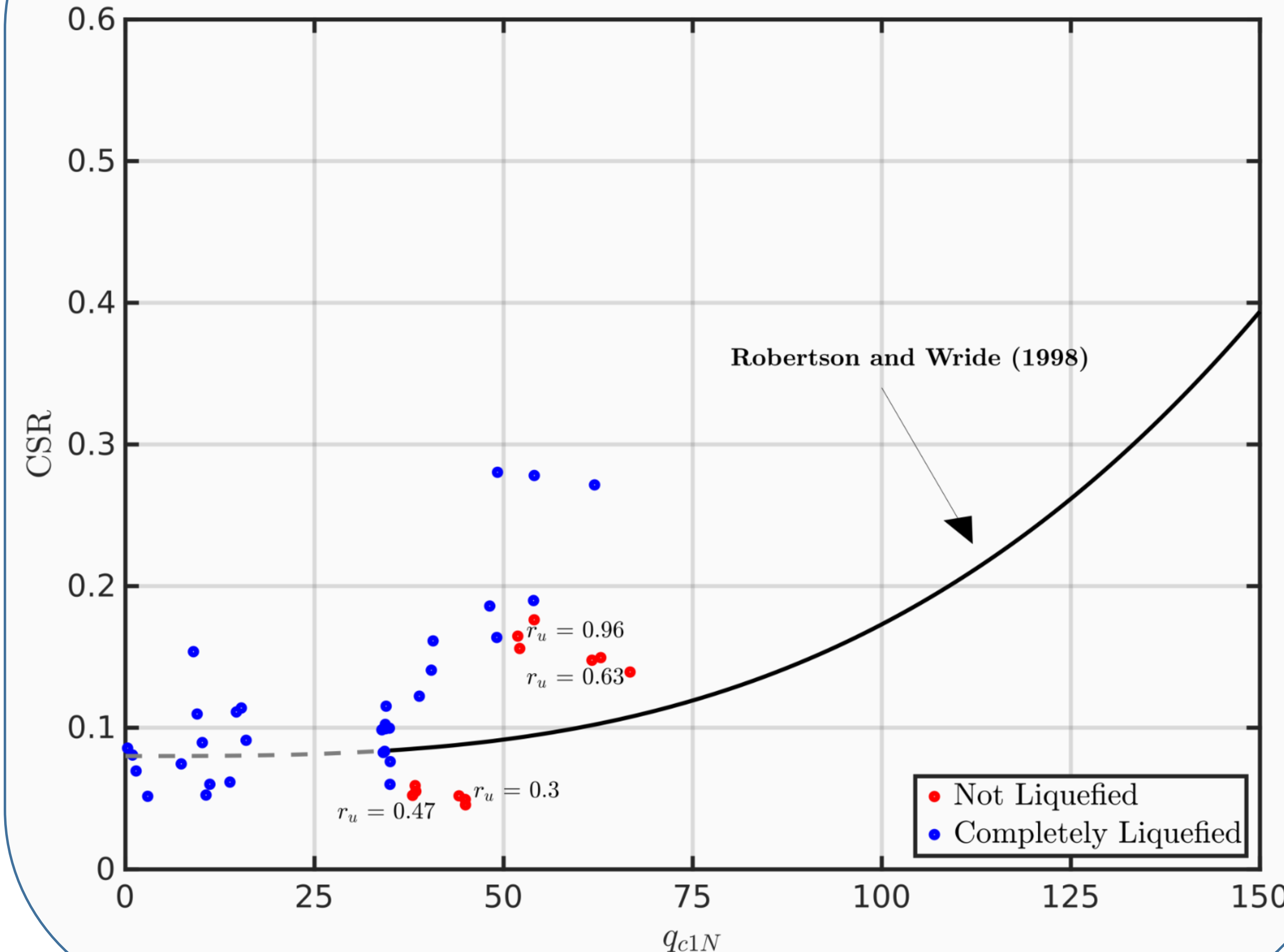



WATERLOO
ALLEN KEYS

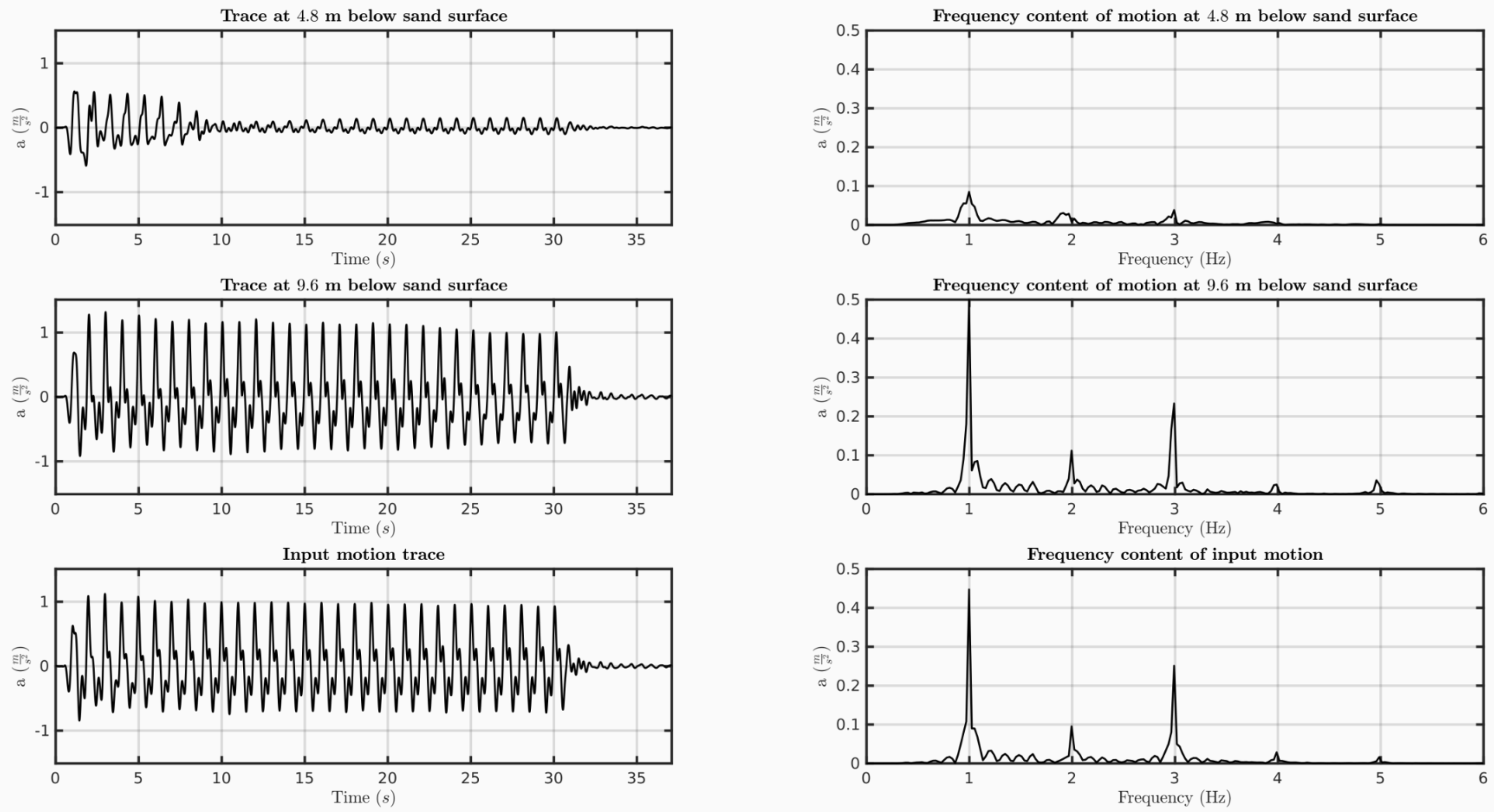

CPT Cone


CPT Traces
Before any earthquake
After all earthquake motions
Depth from soil surface (m)
2
0
-2
-4
-6
-8
-10
-12
0
2
4
6
8
10
12
14
q_t (MPa)

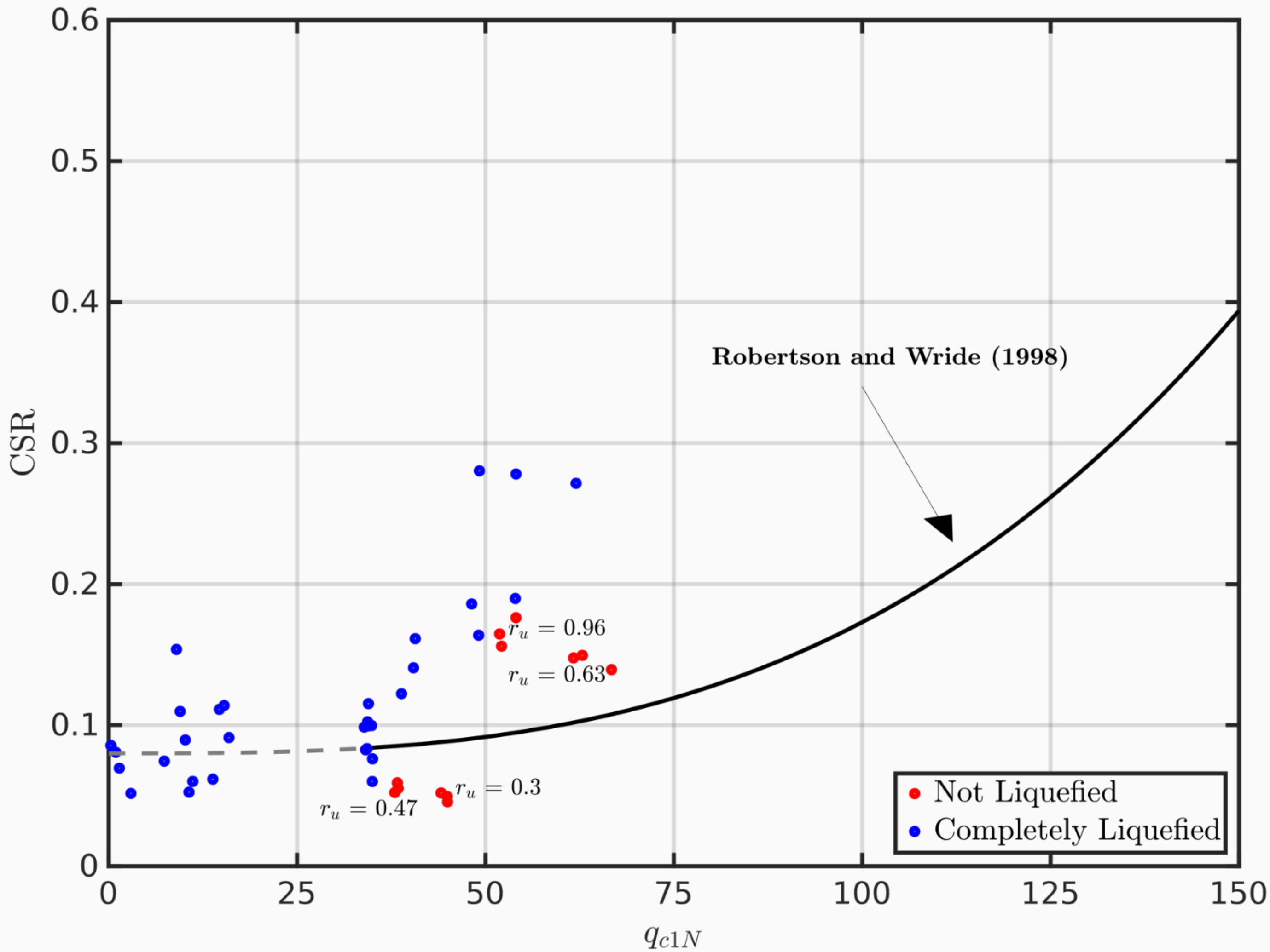
Comparison between AD01 Test data and Literature



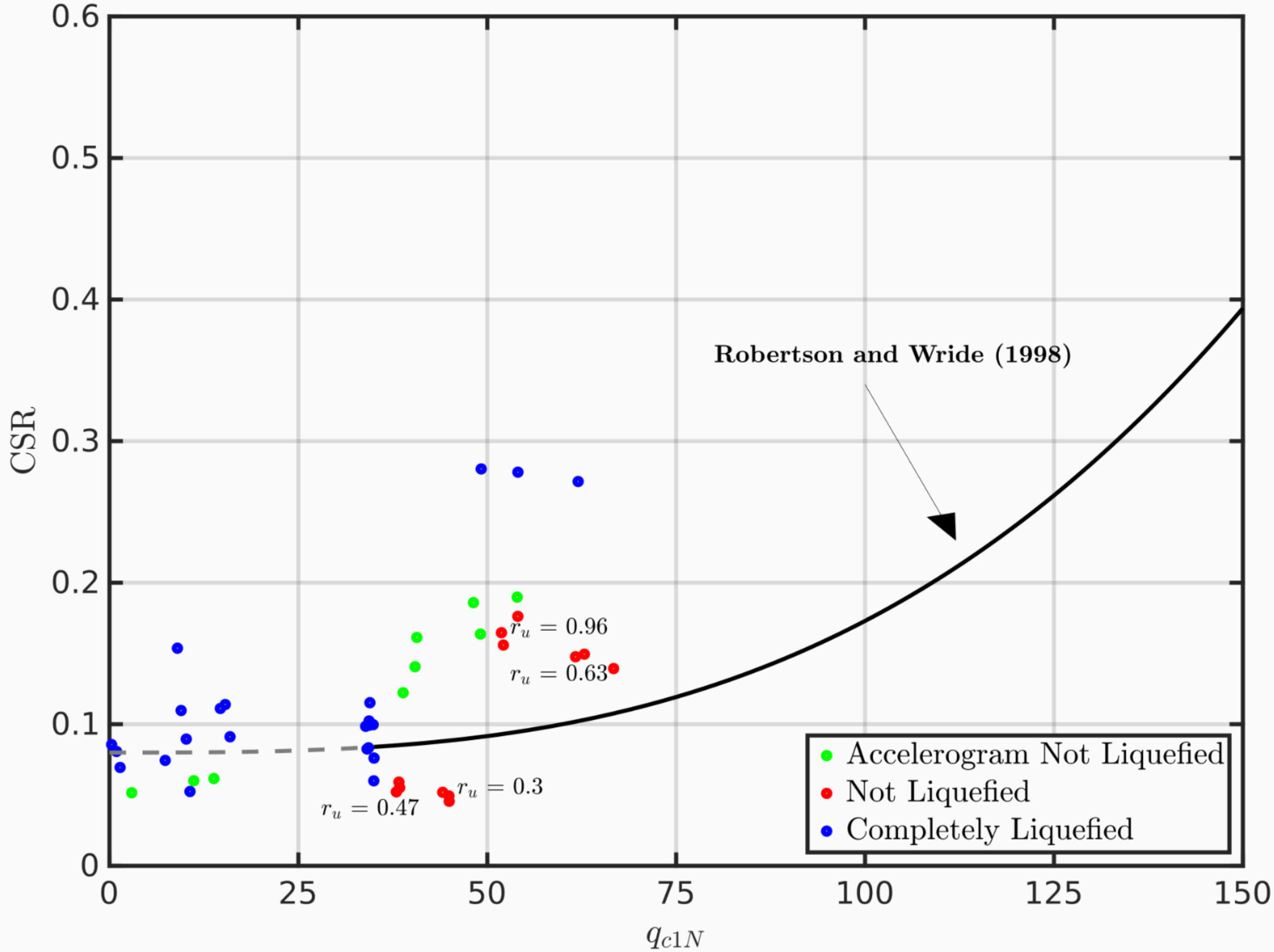
LIQUEFACTION ASSESSMENT THROUGH SEISMIC ISOLATION



Comparison between AD01 Test data and Literature



Comparison between AD01 Test data and Literature



Summary

- Recent earthquakes such as Muisine earthquake, Ecuador (2016) have produced similar liquefaction failures as those observed previously.
- Clearly we need to make further advances in our understanding of soil liquefaction
- We need to revisit and modify our concepts of treating soil liquefaction as an ‘undrained event’
- We must question whether undrained cyclic triaxial tests truly represent the liquefaction behaviour (and any constitutive models that are made simulate the cyclic triaxial data)

Summary

- In this presentation, we have seen that level soil beds, once liquefied, settle faster during earthquake loading
- Shallow foundations also do the same. Further, volumetric strains are clearly observed in the earthquake period
- Novel centrifuge tests with simulated triaxial chambers demonstrated the importance of fluid drainage, and how different boundary conditions of triaxial chamber can beget vastly different behaviour in liquefied soils
- Modifying the Terazaghi's consolidation theory and allowing variable co-efficient of consolidation, can capture the changes in permeability and compressibility in liquefied soil
- Novel liquefaction remediation measures such as air-sparging can lead to smaller settlements in structures
- Interesting results are coming from in-flight CPT tests to establish the efficacy of the CPT based Liquefaction Criteria