

The Real World at Small Scale
Centrifuge Modelling and Its Applications in Geotechnical Earthquake Engineering

Alireza Ghadamgahi

a.ghadamgahi@iiees.ac.ir

IIEES

Headings

1. Introduction to Modeling
2. Types of Modeling
3. Physical models
4. Geotechnical centrifuges
5. Equipment
6. Instrumentation
7. Data acquisition systems
8. Some examples of geotechnical problems

- Model containers
- Model preparation techniques
- Earthquake simulators
- In-flight actuators

1. Introduction to Modeling

- ✓ A ***model*** is an appropriate simplification of reality.
- ✓ The skill in Modeling is to spot the appropriate level of simplification to recognize those features which are ***important*** and those which are ***unimportant***.
- ✓ Some problems may arise precisely because the assumptions that have been made are inappropriate in a particular application.



1. Introduction to Modeling

- ✓ Engineering is fundamentally concerned with ***Modeling*** *and* finding solutions to real problems.
- ✓ We need to be able to see through to the ***essence of the problem*** and identify the ***key features*** which need to be modelled. In fact, those features we need to take account and include in the design.
- ✓ One aspect of engineering judgment is the identification of those features which we believe it ***safe to ignore***.

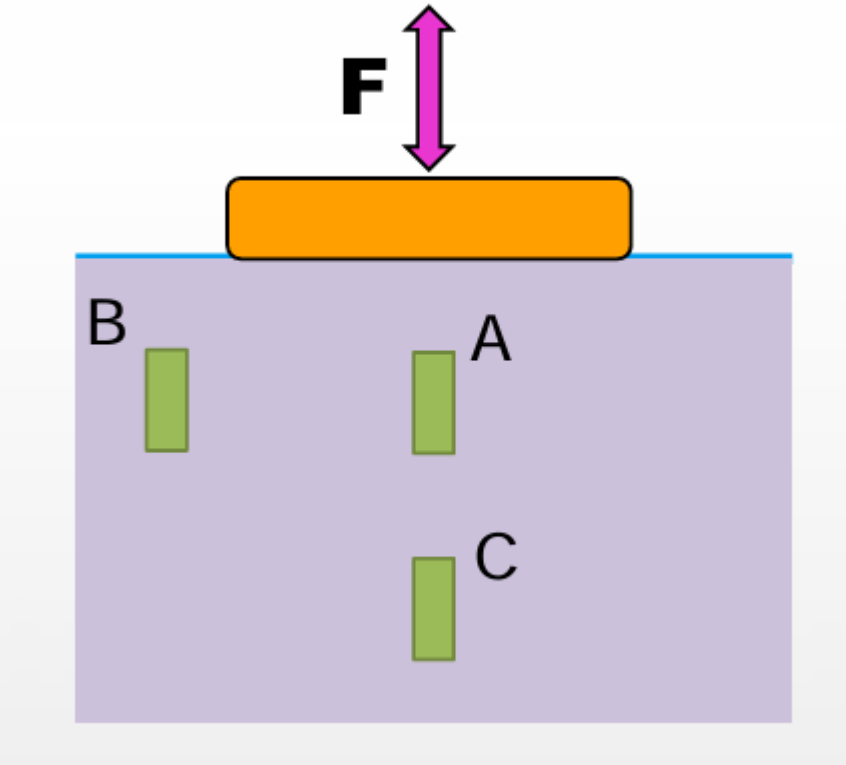


2. Types of Modeling

- *Empirical models*
- *Theoretical models*
- *Numerical Modeling*
- *Constitutive Modeling*
- ***Physical models***
- *Geological model*
- *Classification model*

Methods of study

- *Element study*
- *Investigating the whole structure*



Objectives of Physical Modeling

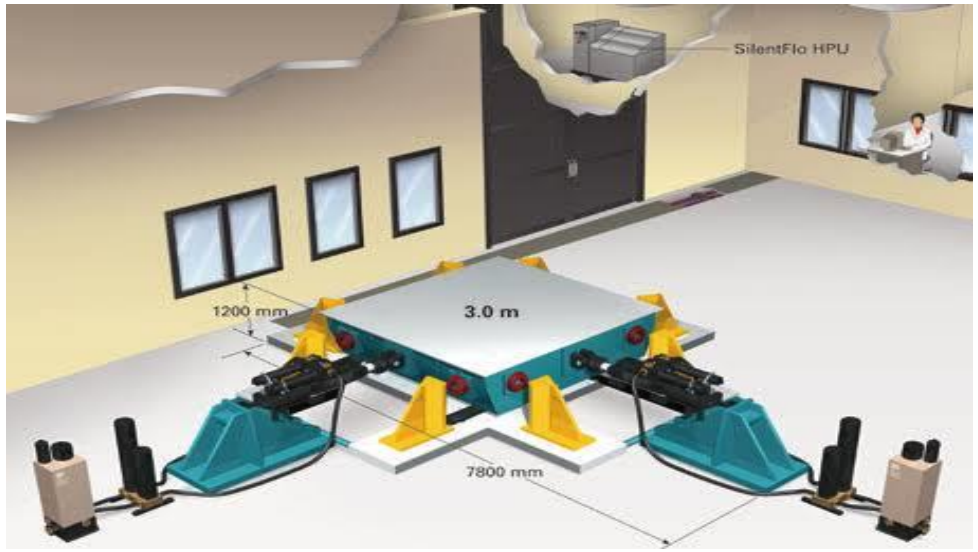
- Developing physical models to verify the accuracy of numerical and analytical models.
- Studying the behavior of complex geotechnical structures, where investigating their behavior using numerical and analytical models is highly difficult or even impossible.
- Conducting parametric studies for the development of large-scale physical models.
- Conducting parametric studies to develop design methods for special structures.

3. Physical models

Physical models in geotechnics can generally be divided into three main categories:

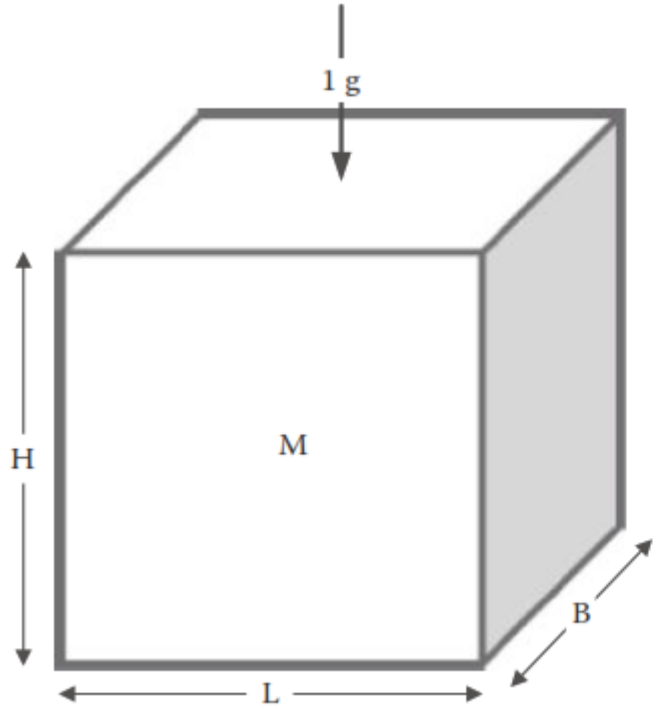
- Models under multiple times Earth's gravitational acceleration (centrifuge models).
- Conventional models under Earth's gravitational acceleration (1g models), such as shaking table models, etc.
- Models under all-around confining pressure, such as Calibration Chamber (CC) models and Frustum Confining Vessel (FCV) models.





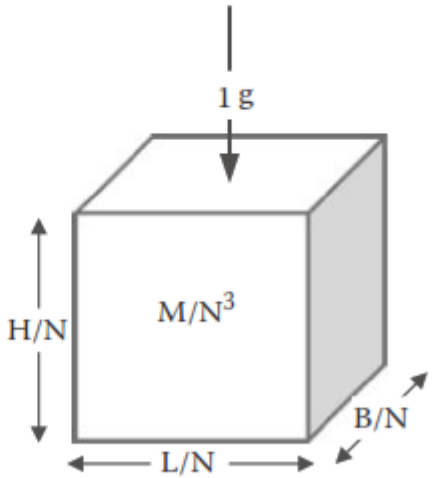
3. Physical models

Prototype

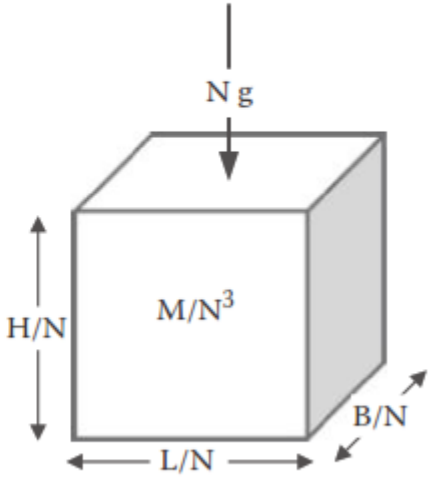


$$\sigma_v = \frac{M\ g}{L \times B}$$

Model

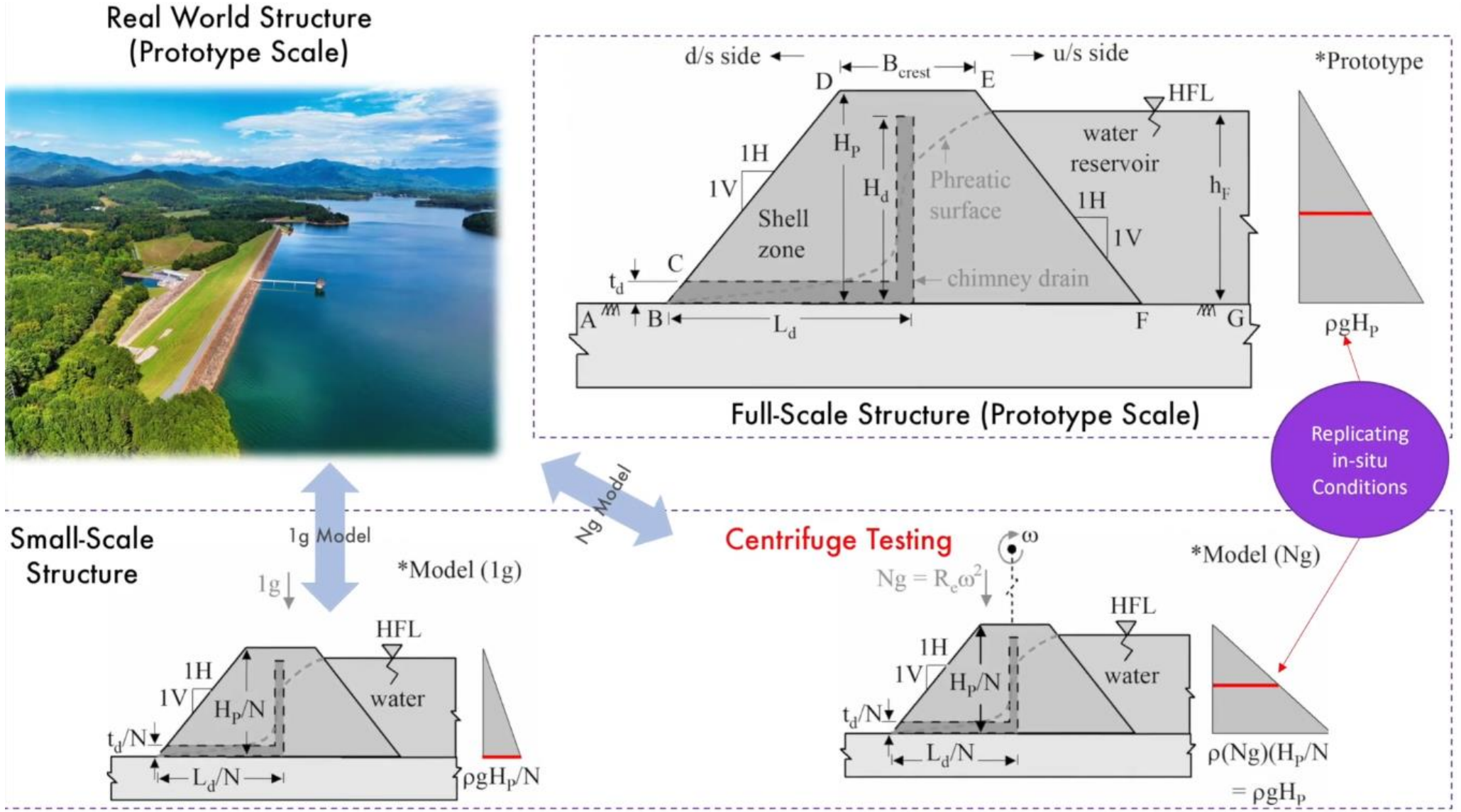


$$\sigma_v = \frac{\frac{M}{N^3} \times g}{\frac{L}{N} \times \frac{B}{N}} = \frac{M\ g}{L \times B} \times \frac{1}{N}$$



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

3. Physical models



Scaling Consideration

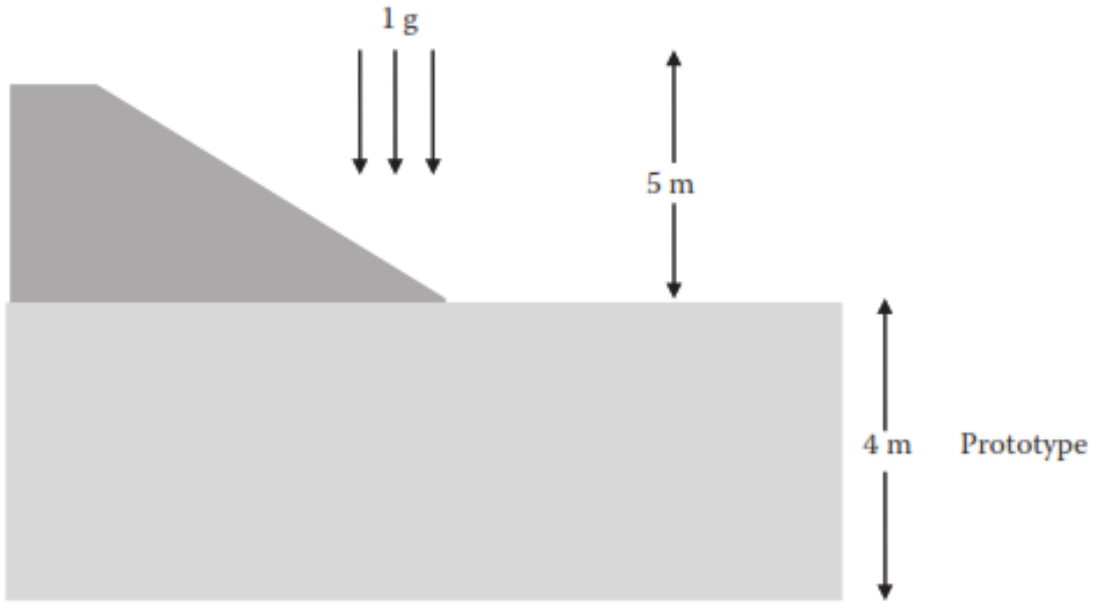
Centrifuge scaling laws

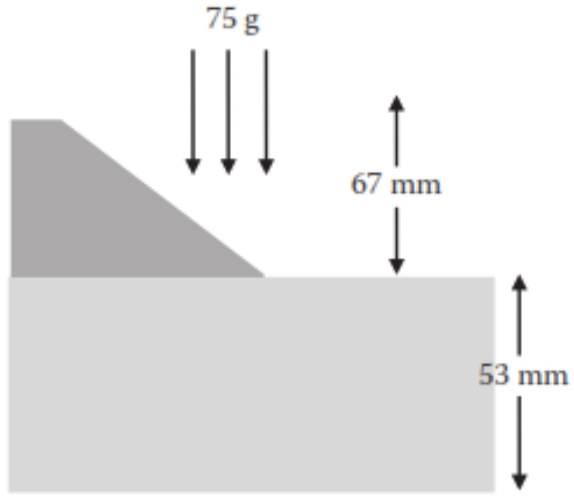
Quantity	Unit	Prototype	Model
Gravity acceleration, g	m/s^2	1	N
Stress, σ	Pa	1	1
Strain, ε	—	1	1
Linear dimension, L	m	1	1/N
Area, A	m^2	1	$1/N^2$
Moment of inertia, I	m^4	1	$1/N^4$
Displacement, δ	m	1	1/N
Density, ρ	kg/m^3	1	1
Young modulus, E	Pa	1	1
Axial stiffness, EA/L	N/m	1	1/N
Flexural rigidity, EI	$N.m^2$	1	$1/N^4$
Force, F	N	1	$1/N^2$
Acceleration, a	m/s^2	1	N
Time, t (dynamic)	s	1	1/N

Comparison between scaling laws for Ng and 1g models

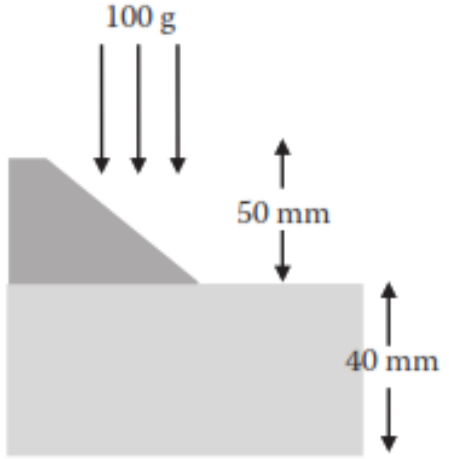
Quantities	Scaling factors (prototype/model)	
	Dynamic centrifuge test	1g shake table test
Displacement, length	N	N
Acceleration, gravity	N^{-1}	1
Mass	N^3	N^3
Density	1	1
Stress	1	N
Strain	1	1
Time (dynamic)	N	$N^{0.5}$

Modeling of Models





Model 1 tested at 75 g



Model 2 tested at 100 g

4. Geotechnical centrifuges

- Baem Centrifuge



9-m-radius beam centrifuge at the Center for Geotechnical Modeling, UC ,Davis

4. Geotechnical centrifuges

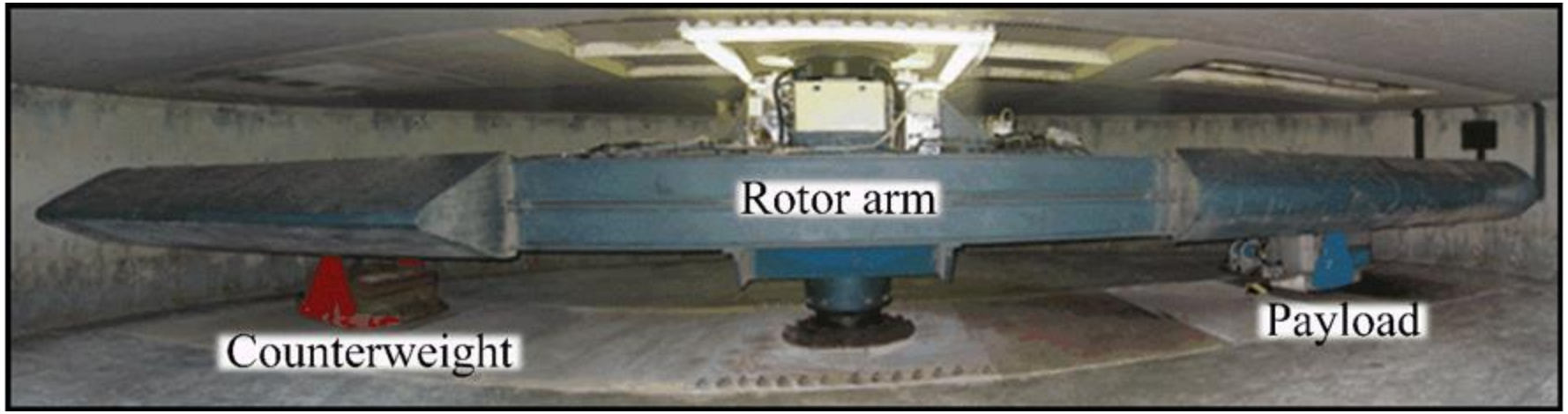
- Baem Centrifuge



6.5-m-radius beam, U.S. Army Engineer Research and Development Center

4. Geotechnical centrifuges

- Baem Centrifuge



5-m-radius Beam centrifuge at Cambridge, UK

4. Geotechnical centrifuges

- Baem Centrifuge



4.5-m-radius beam centrifuge at ETH

4. Geotechnical centrifuges

- Baem Centrifuge



4.5-m-radius centrifuge at The National Centrifuge Facility at the Indian Institute of Technology, Bombay

4. Geotechnical centrifuges

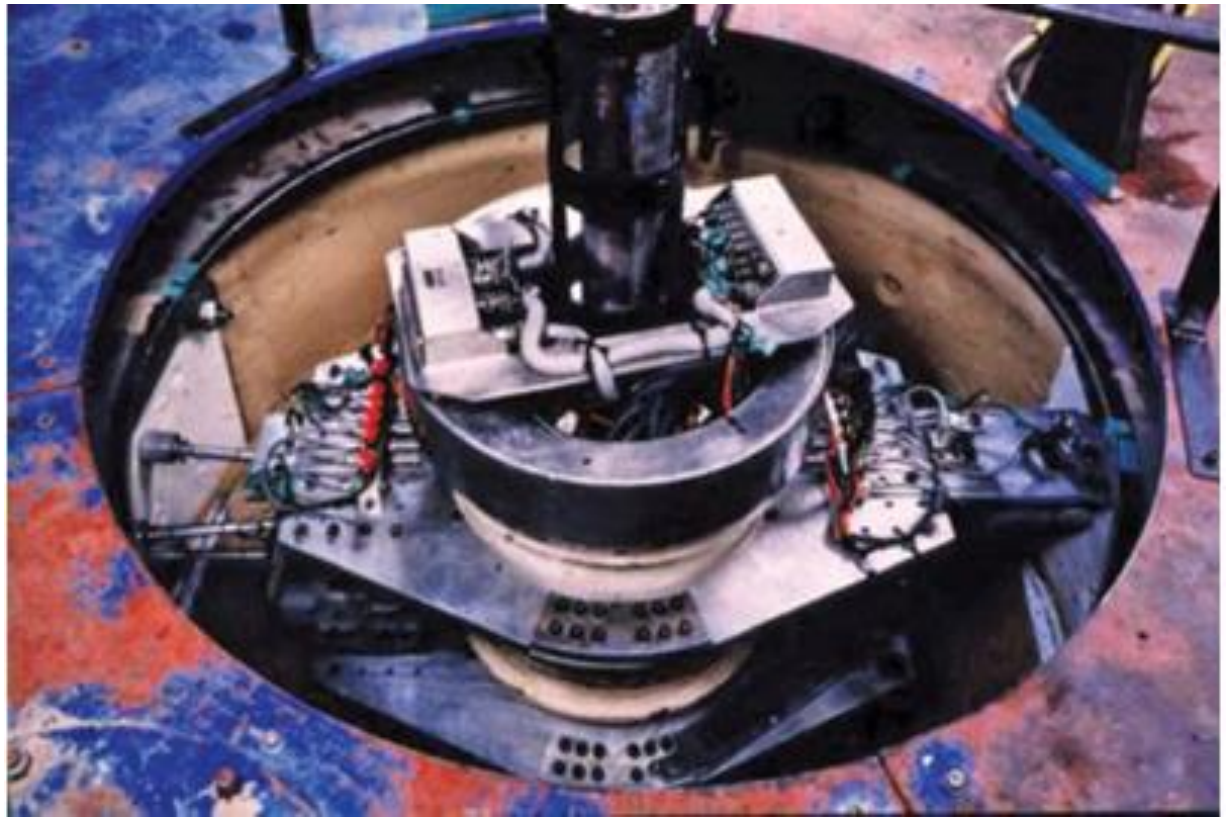
- Baem Centrifuge



The C-67 Centrifuge Facility at IIEES, Iran, 3-m-radius centrifuge

4. Geotechnical centrifuges

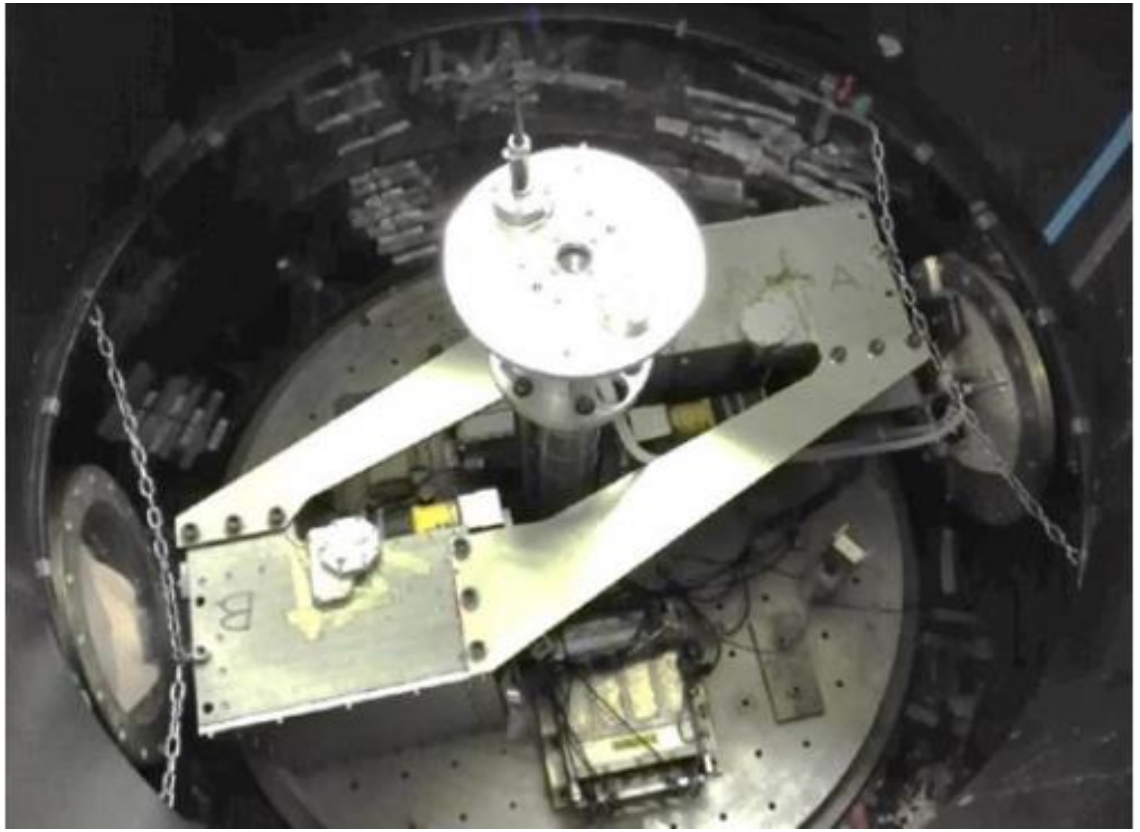
- Drum Centrifuge



Cambridge 2-m-diameter drum centrifuge

4. Geotechnical centrifuges

- Drum Centrifuge



ETH 2.2-m-diameter drum centrifuge with with two cylindrical strongboxes installed

4. Geotechnical centrifuges

Feature	Beam Centrifuge	Drum Centrifuge
Structure	Long rotating arm with a bucket (model container) on one end and a counterweight on the other.	Hollow cylindrical drum rotating around its central axis; model placed in an annular channel.
Model Orientation	Mounted upright; swing platform rotates to stay perpendicular to the resultant acceleration vector.	Requires 90° rotation; placed inside the annular channel.
Model Size/Shape	Built in rectangular boxes (e.g., 1.5m × 1.5m); suitable for localized structures.	Built in long annular channels (e.g., up to 5m in length); simulates long-runout processes.
Main Applications	Slope stability, foundations, retaining walls, earth dams, and localized structural models.	sediment transport, erosion, liquefaction, and large-deformation problems.
Advantages	Allows complex models, advanced instrumentation, and easier model preparation.	Lower cost per test; enables rapid parametric studies on a single long sample.
Disadvantages	Limited model area; time-consuming for extensive parametric testing.	Difficult sample preparation; typically involves simpler models and instrumentation.

Comparison between Beam Centrifuge and Drum Centrifuge

5. Centrifuge equipment

- Model containers
- Model preparation techniques
- Earthquake simulators
- In-flight actuators

Model containers

- The first bit of equipment that is required before embarking on a centrifuge testing program is a well-designed model container.
- Several aspects need to be considered before designing a new model container or choosing one from an existing stock.
- Depending on the type of prototype being modeled, different centrifuge model containers can be used

Model containers

- Rigid Container
- Flexible Container
- Laminar Container
- ESB Container
- Static Container
- Dynamic Container
- Window Container
- Strong Container

Model containers



Preparation room for large centrifuge at UC, Davis

Model containers



Preparation room for 1 small centrifuge at UC, Davis

Model containers

- Rigid Container : Rigid / Static or Dynamic
- Flexible Container: Flexible (a general term)
- Laminar Container: Flexible / Dynamic
- ESB Container: Flexible / Dynamic
- Static Container: Rigid or Flexible / Static
- Dynamic Container: Rigid or Flexible / Dynamic
- Window Container: Rigid or Flexible / Equipped with windows
- Strong Container: Rigid / Static

Model containers

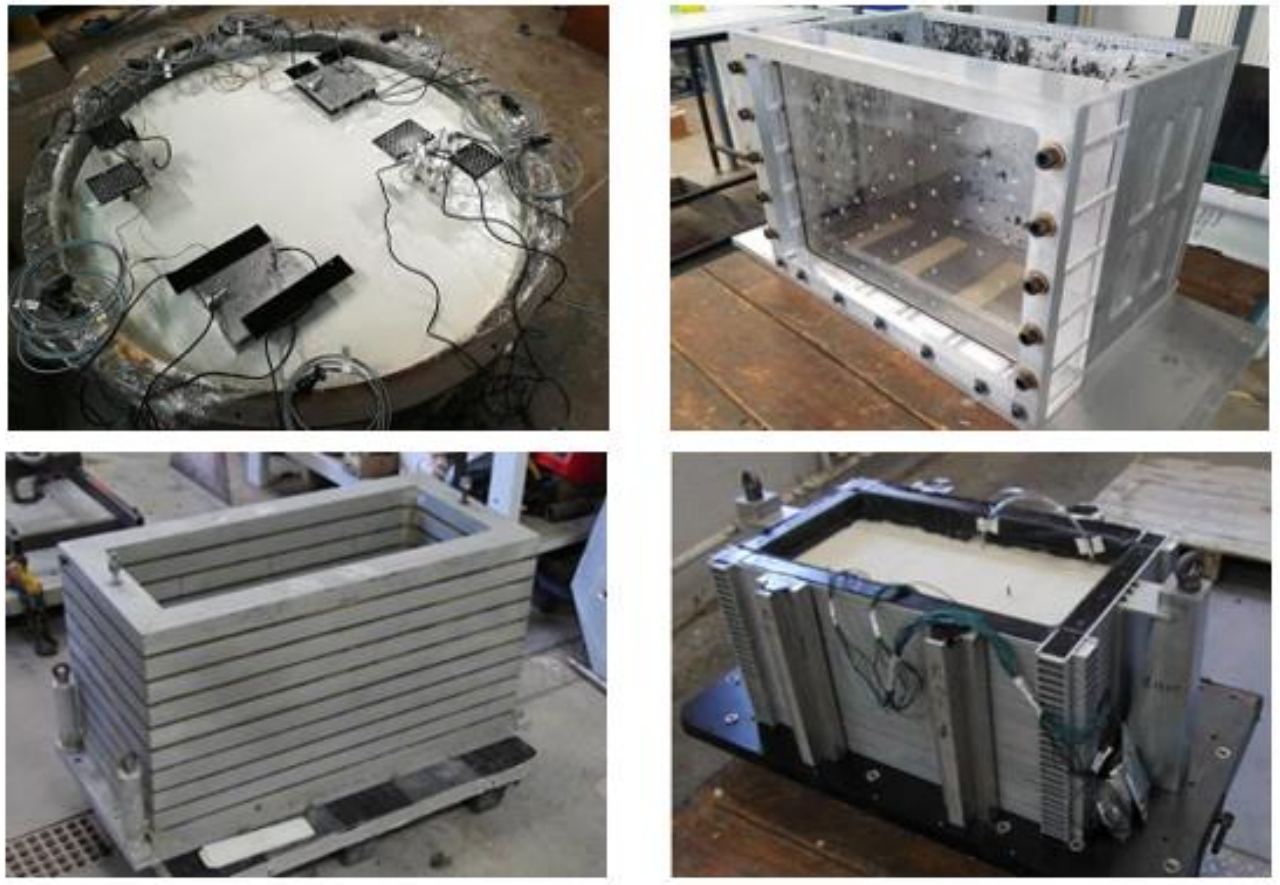
1. Based on Loading Type
- Static
- Dynamic

2. Based on Boundary Behavior (Wall Type)
- Rigid Containers
- Flexible/Compatible Containers

3. Based on Visibility (Visual Features)
- Window Containers
- Blind Containers

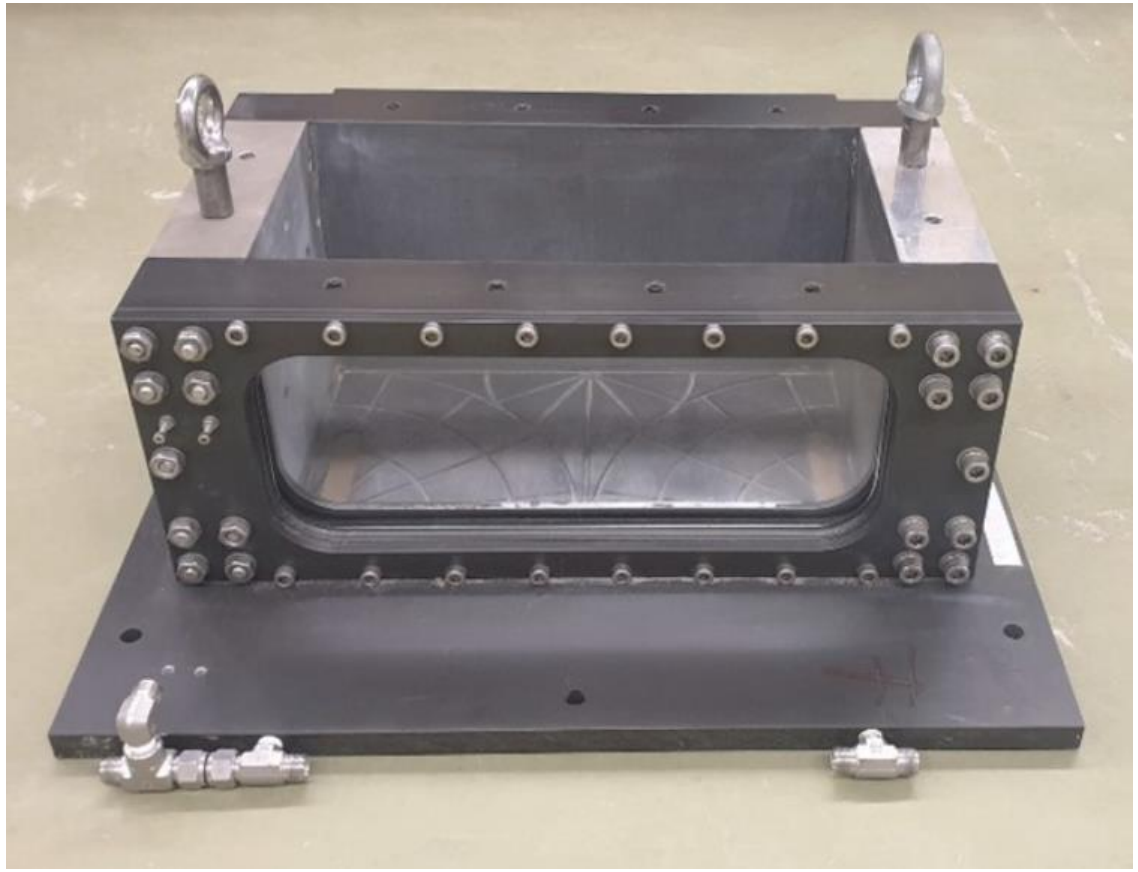
4. Based on Strength
- Strong Containers
- Normal Containers

Model containers

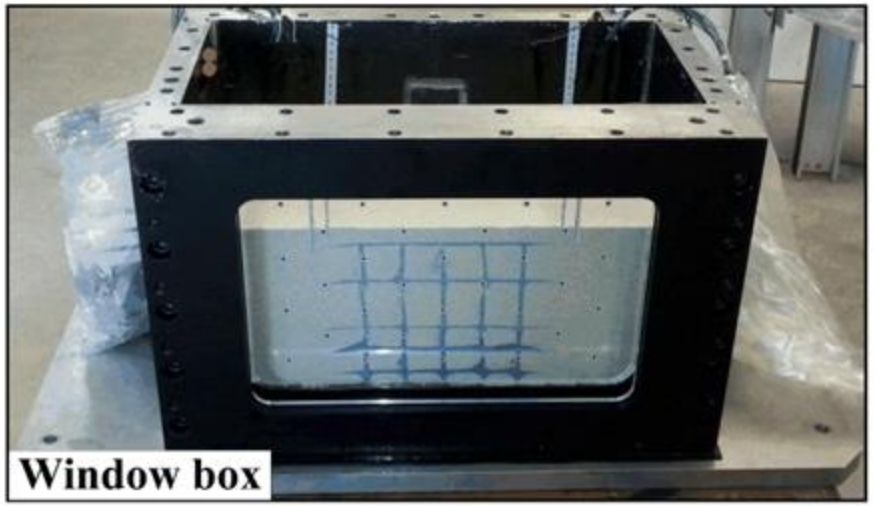


Model containers at Cambige University , Schofield Centre for Geotechnical Modelling

Model containers



Strong Box: Rectangular (40 x 40 x 20 cm) container equipped with Perspex window.





Model containers

Feature	Rigid Container	Laminar Container	ESB (Equivalent Shear Beam) Container
Structure	Completely stiff and fixed walls.	Thin metal frames mounted on nearly frictionless roller bearings.	Light, rigid frames connected by intermediate rubber layers with controlled stiffness.
Boundary Behavior	**Reflective Boundary**. Waves reflect off the walls, severely distorting the wave propagation pattern.	**Free-Field Boundary**. Frames move with the soil, effectively transmitting shear. Ideal for large deformations.	**Absorbing Boundary**. Container stiffness is matched to the soil stiffness so that waves are absorbed rather than reflected.
Main Application	Simple **static** problems or models where boundary effects are not critical. **Not recommended** for dynamic problems.	Simulating **liquefaction** and **large post-liquefaction deformations** such as **lateral spreading**.	Simulating **dry sands**, **saturated sands** under **moderate to strong earthquakes**, and studying the **triggering of liquefaction**.
Advantages	Simple to build, inexpensive, and robust.	High accuracy in simulating 1D ground response under seismic loading.	Creates the least boundary effects, providing a more realistic simulation of field conditions in the pre-liquefaction stage.
Disadvantages	Significant boundary effects under dynamic loading.	Performs poorly in the pre-liquefaction stage (small-strain responses).	Loses its desired performance if the soil stiffness changes drastically (e.g., after full liquefaction occurs).

Comparison between different containers

Model preparation techniques

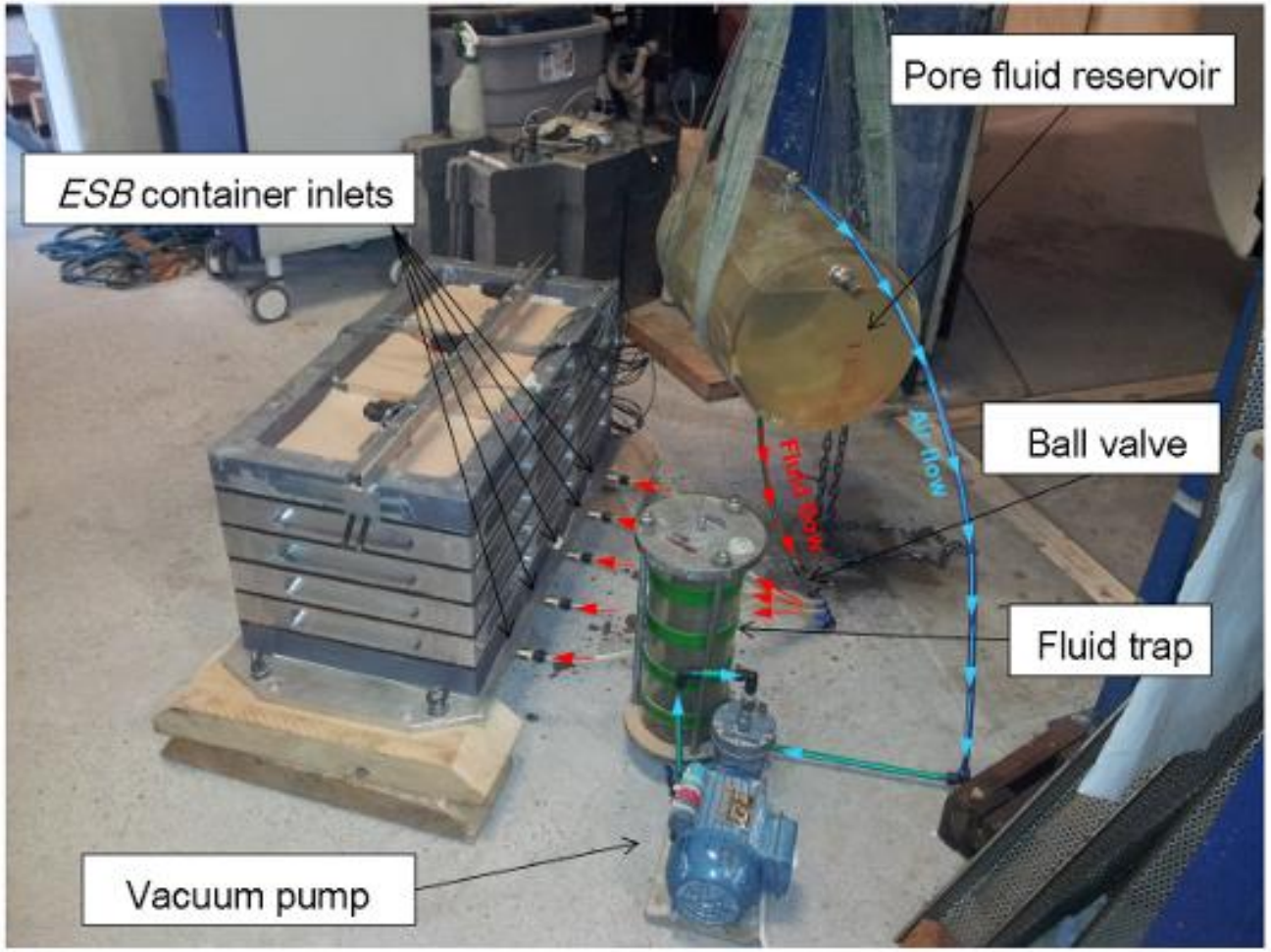
- Air pluviation of sand samples
- Saturation of sand models

Model preparation techniques





Model preparation techniques



Saturation system adopted for centrifuge tests

Earthquake simulators

- Mechanical actuators
- Servo-hydraulic actuators
- Electro-magnetic (E-M) actuators
- Piezo-electric actuators

Earthquake simulators

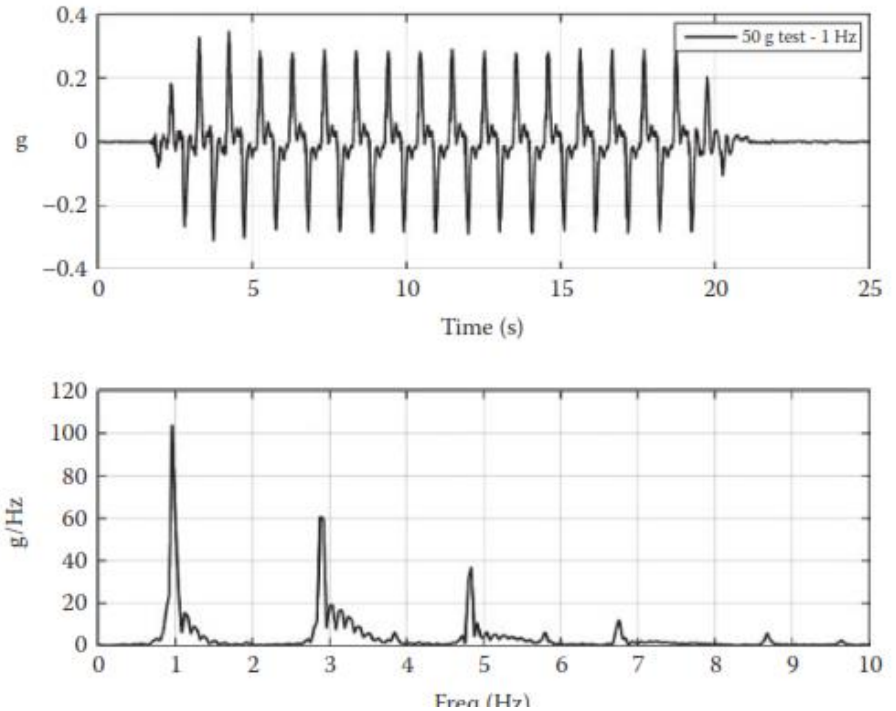
Feature	Mechanical Actuator	Servo-Hydraulic Actuator	Electro-Magnetic (E-M) Actuator	Piezo-Electric Actuator
Primary Mechanism	Converts rotational motion of a cam or release of a spring into linear motion.	Precisely controls high-pressure oil flow (up to 280 bar) via a servo-valve to drive the shake table.	Uses magnetic attraction/repulsion forces between magnetic fields to generate motion.	Deforms a piezoelectric material when an electric field is applied, producing motion.
Advantages	**Low manufacturing and maintenance costs.**	**Very high flexibility** in generating various motion types. **Capable of simulating real earthquake records** (e.g., Kobe, Northridge). **Dominant and leading technology** in this field.	**Capable of producing high-frequency motions.**	**Simple, lightweight, and compact.** **Capable of producing high-frequency motions.** **Potential for accurate earthquake record simulation.**
Limitations / Disadvantages	**Produces limited 1D motion with restricted frequency** (usually a simple sine pulse). **Low flexibility** in adjusting amplitude, frequency, and duration.	**Very high cost** (the most expensive option). **Complex system** requiring specialized maintenance. **Heavy and bulky**, which is challenging for centrifuge balancing and payload.	**Heavy and bulky** relative to the force produced. **Low load capacity** relative to its size. **Poor performance in generating low frequencies.**	**Difficulty generating low frequencies.** **Mechanical resonance issues** at certain operating frequencies. **Output acceleration decays** over time or due to heat generation. **Requires high voltage.**
Typical Applications	**Preliminary and parametric tests** that require simple, repetitive motions.	**The most advanced and common method** for realistic earthquake simulation, especially for complex models.	Specific research areas requiring **high-frequency excitation** where weight constraints are less critical.	**Specialized applications** needing high-frequency, lightweight, and compact excitation, such as small-scale models.

Earthquake simulators



Schematic diagram and a view of a mechanical earthquake actuator.

- The actuator was able to operate in 100-g centrifuge tests and fire earthquakes of desired sinusoidal frequency and duration.
- The peak dynamic force that this actuator can produce is about 100 kN.

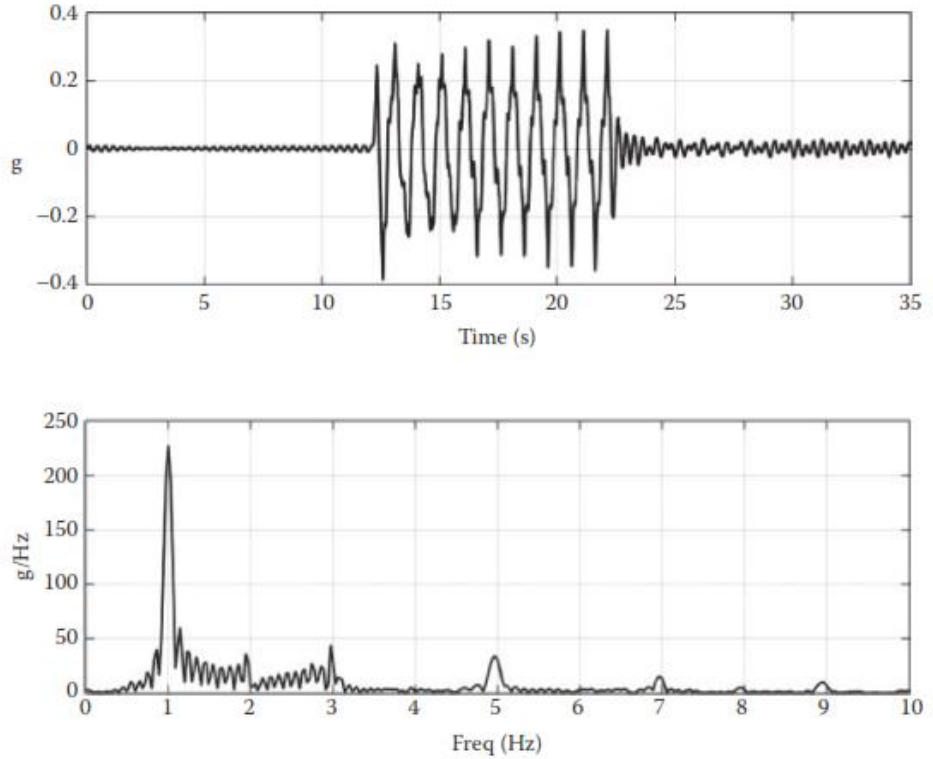


a sinusoidal earthquake generated by the actuator

Earthquake simulators



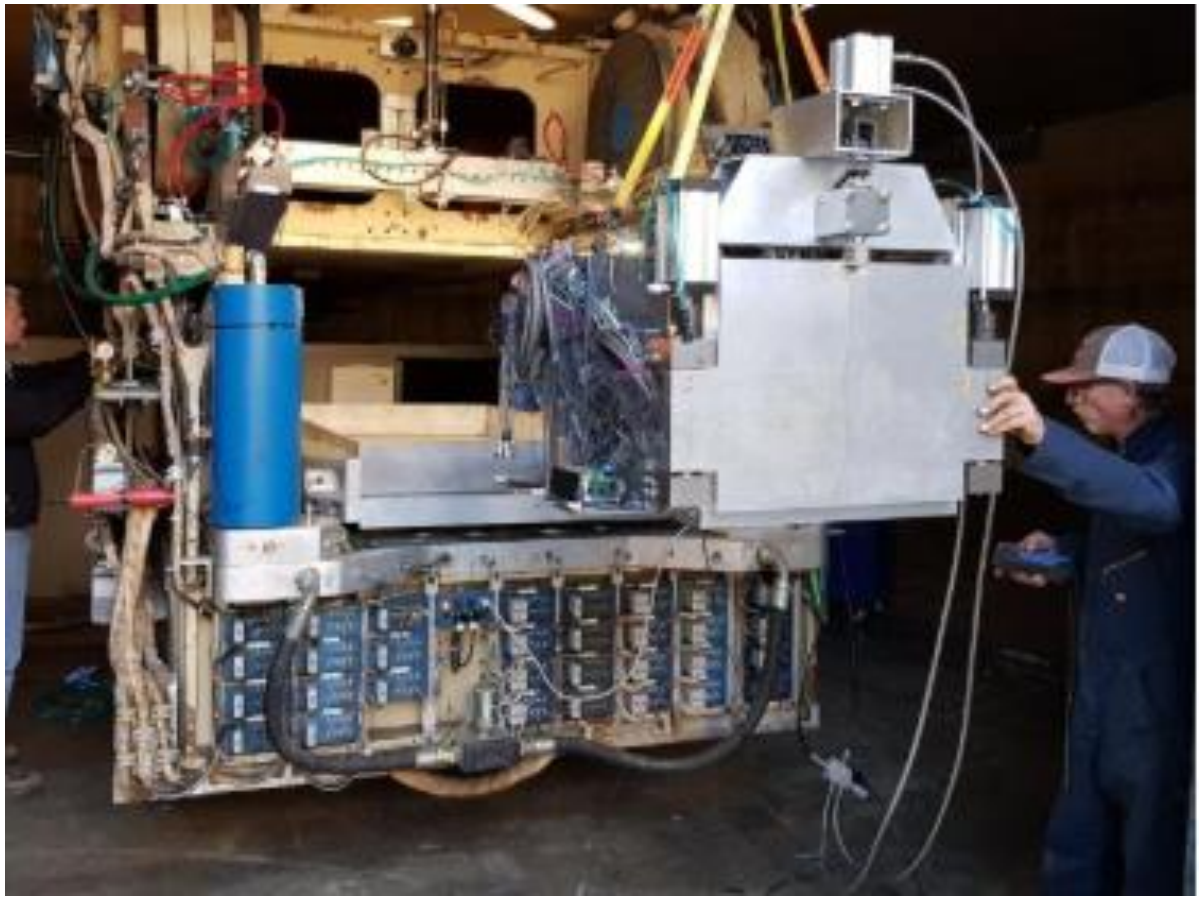
a view of a servo-hydraulic earthquake actuator.



a sinusoidal earthquake generated by the actuator

- It can operate at g levels of up to 80g.
- This actuator can produce a dynamic force of 100 kN and operate in the frequency range of 10-200 Hz.

Earthquake simulators



a view of a servo-hydraulic earthquake actuator at the Center for Geotechnical Modeling, UC ,Davis

It was designed to operate in either a biaxial (horizontal-vertical) or uniaxial (horizontal) shaking mode

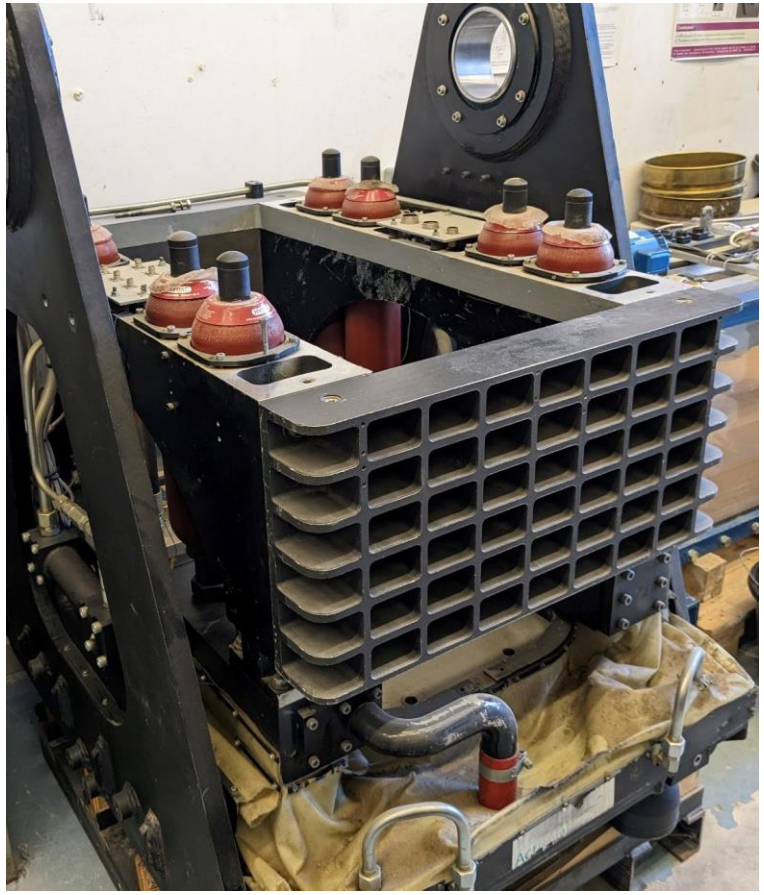
Earthquake simulators



a view of a servo-hydraulic earthquake actuator at ETH

The earthquake simulator is capable of delivering horizontal seismic ground motions of any target waveform at up to 0.5 g peak ground acceleration on packages of up to 700 kg mass over a wide frequency band, at a maximum centrifugal acceleration of 100g.

Earthquake simulators



Servo-hydraulic earthquake simulator at University of Dundee

Max payload moving mass	400 kg
Payload at full shaker acceleration	300 kg
Centrifugal acceleration range	10 to 80 g
Maximum shaking force	150 kN
Peak table displacement	2.5 mm
Peak table velocity	0.75 m/s
Frequency response	40 to 400 Hz
Peak full load acceleration	40 g
Peak acceleration with no paylod	60 g

Earthquake simulators



Geotechnical Centrifuge at New York University Abu Dhabi

Specification	Details
Manufacturer	ACTIDYN SYSTEMS S.A.
Model	C72-4
Platform Radius	5.0m
Max. Capacity	260 g-tons
Max. Payload	2,600kg at 100g
Max. Accelleration	130g with 1,400kg payload
Platform	1.3m x 1.3m
Balancing	Full automatic balancing
Communications	Fluid rotary joints and 1Gbps FORJ for communications

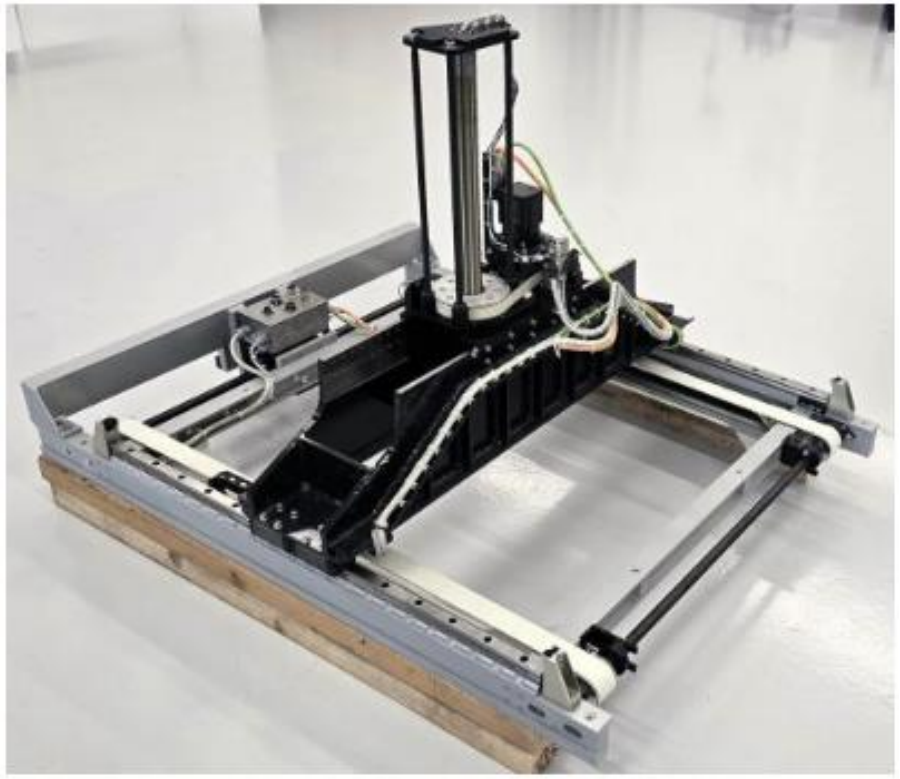
Earthquake simulators



Geotechnical Centrifuge at New York University Abu Dhabi

Specification	Details
Type	Electro-hydraulic servo type
Shaking	Single-directional (X-axis) shaking
Frequency Response	20 to 350 Hz
Inside Dimensions	1.1m x 0.8m x 0.6m
Wave Motion	Arbitrary wave motion
Control System	Hydraulic and electrical control system

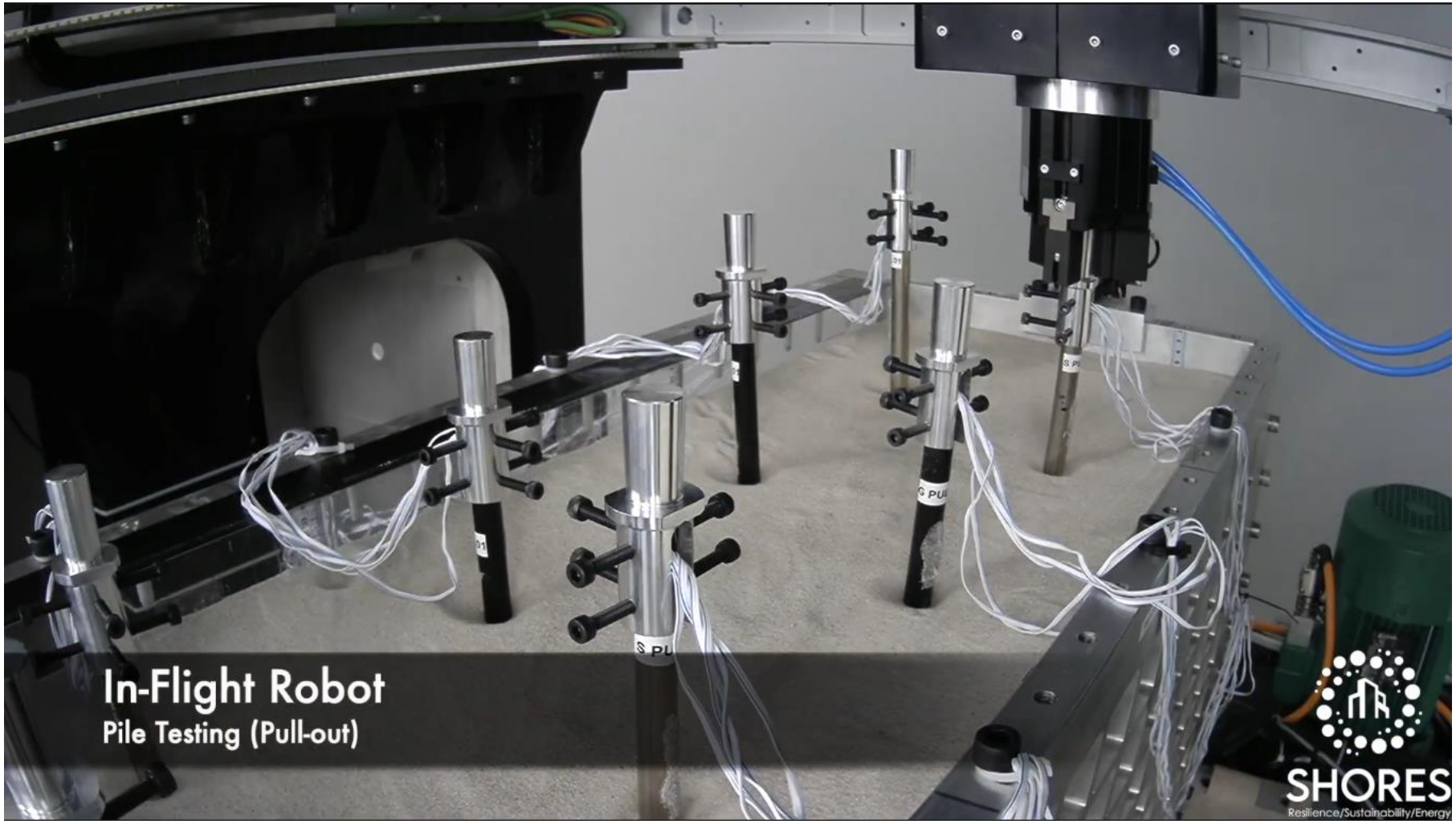
In-flight actuators



Details
2D Loading System P72
4-DoF - X, Y, Z, θz
Operational at 100g environment
Standard head with air, oil, water supply
Tools including CPT

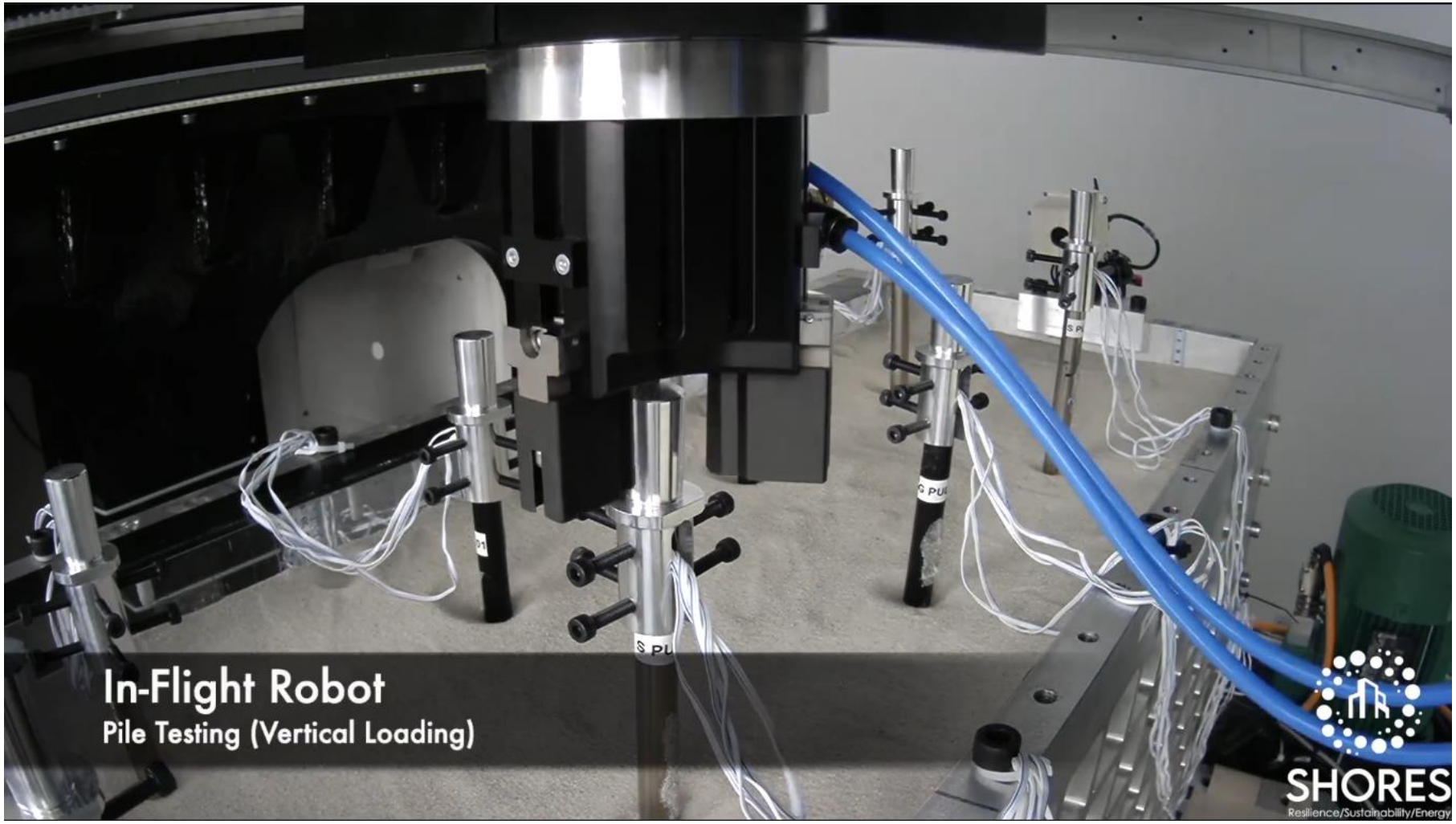
4DoF In-Flight Robot at New York University Abu Dhabi

In-flight actuators



4DoF In-Flight Robot at New York University Abu Dhabi

In-flight actuators



4DoF In-Flight Robot at New York University Abu Dhabi

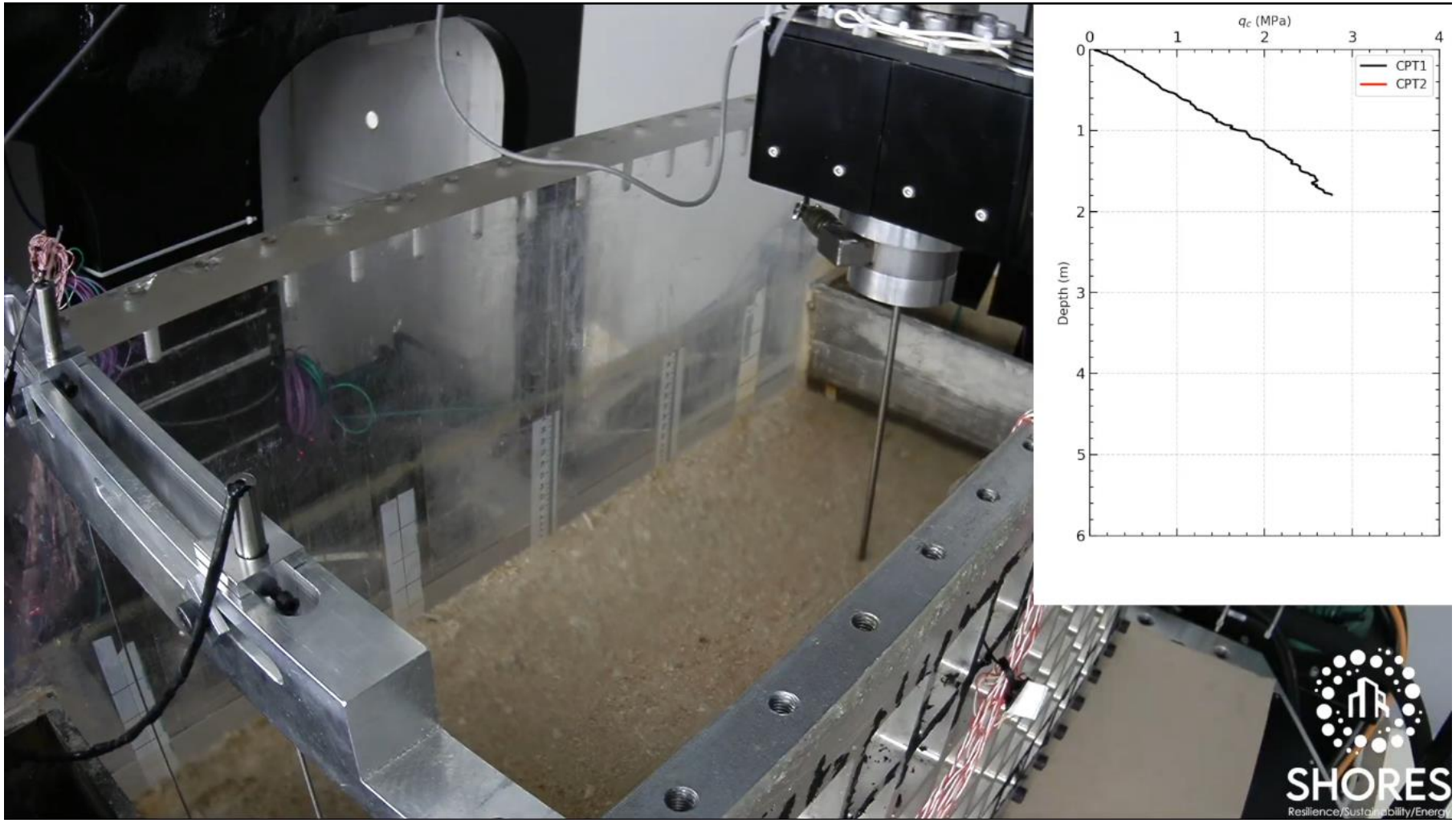
In-flight actuators



Specification	Details
CPT	In-flight CPT for centrifuge testing
Cone Diameters	4mm, 6mm, and 10mm
Penetration	0.25-0.5m
Load	100-1,000lbs
Soil Profiling	Measures qc and fs for soil profiling
Uses	Ideal for stratigraphy verification & numerical model calibration

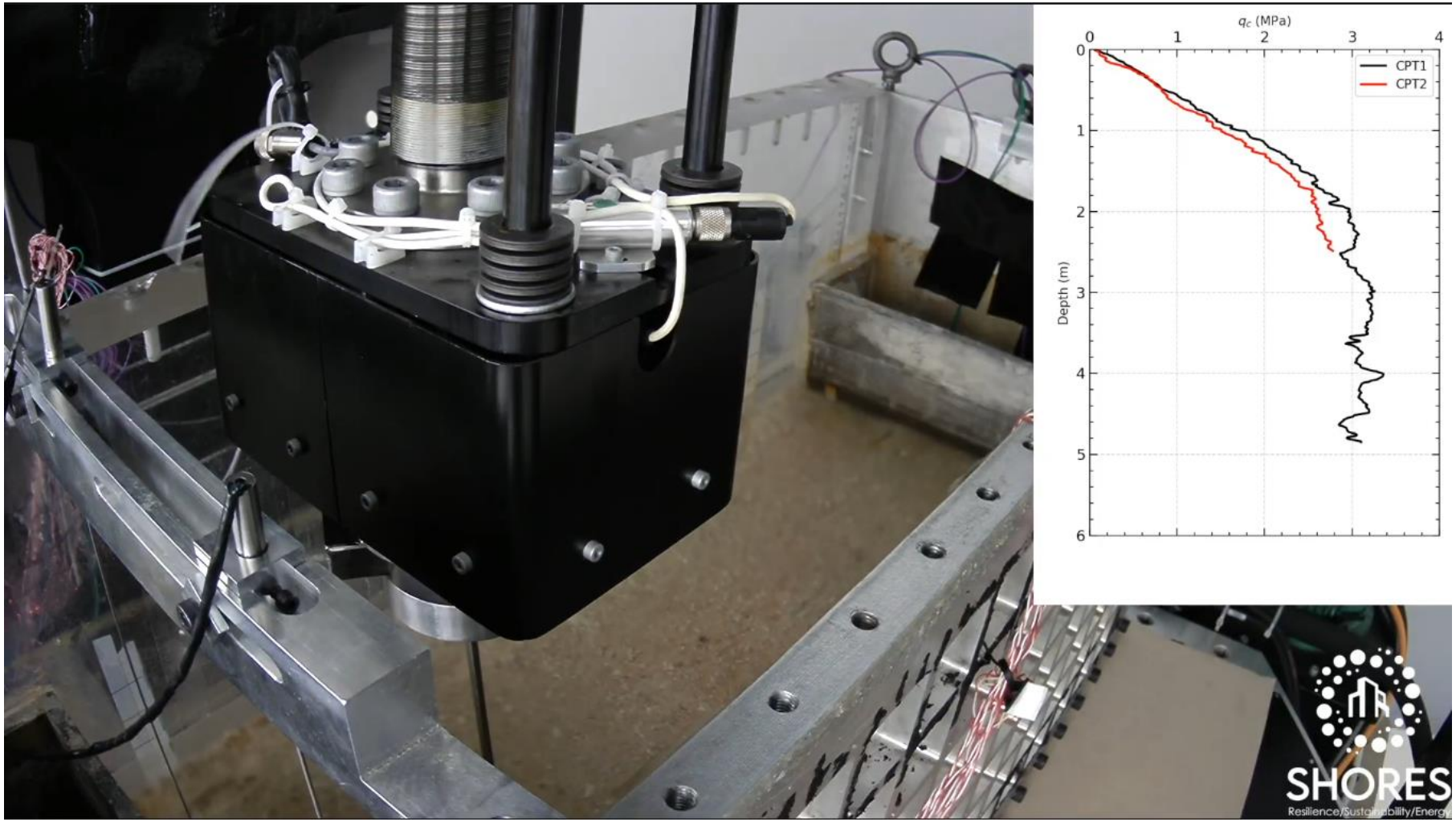
In flight CPT testing at New York University Abu Dhabi

In-flight actuators



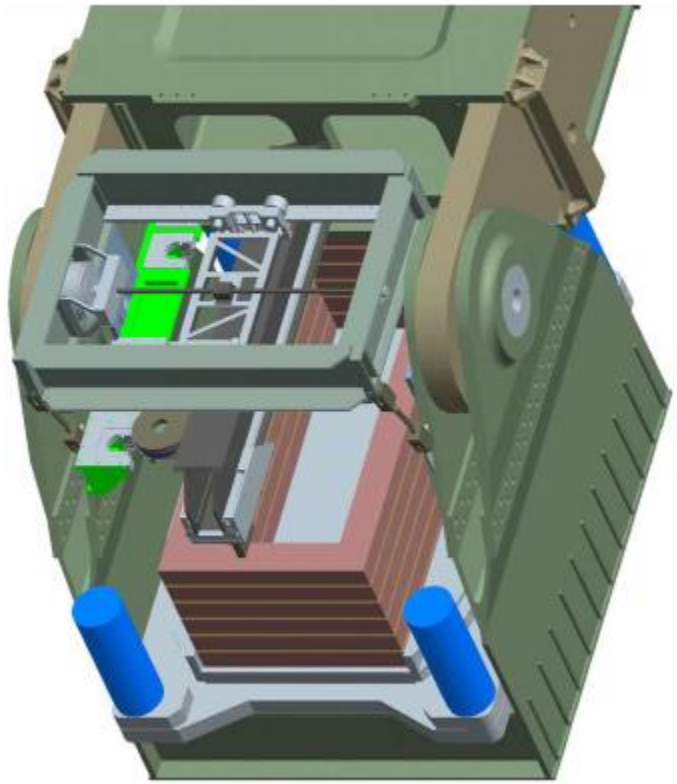
In flight CPT testing at New York University Abu Dhabi

In-flight actuators



In flight CPT testing at New York University Abu Dhabi

In-flight actuators

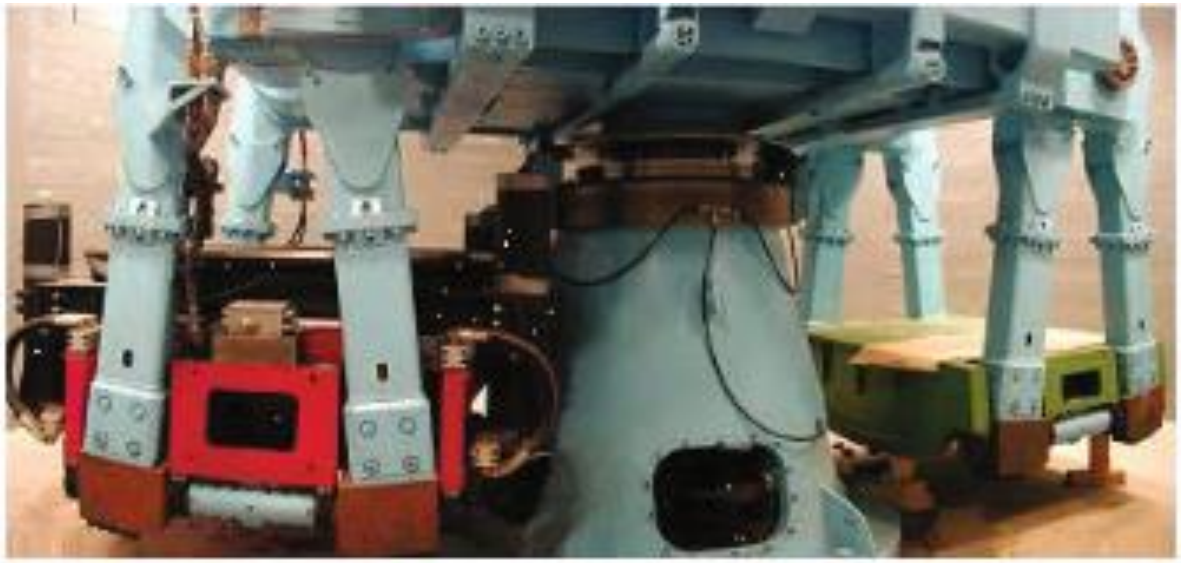


- A 4 degree-of-freedom robot can be added to the Centrifuge at center of geotechnical modeling, UC, Davis.
- The robot will be fully operational with shaking table tests
- Users will be able to use the gripper tool to drive piles sequentially, apply load cycles to structures, and manipulate objects to simulate construction processes.
- The robot will also be used to perform in-flight in-situ site characterization tests using geophysical testing methods
- Soil strengths will be indexed using the cone penetrometer and vane shear robot tools.

In-flight actuators



The bi-axial shaking table at HKUST



The 8.5 m-diameter (400g-t) beam centrifuge at HKUST



The four-axis robotic manipulator at HKUST

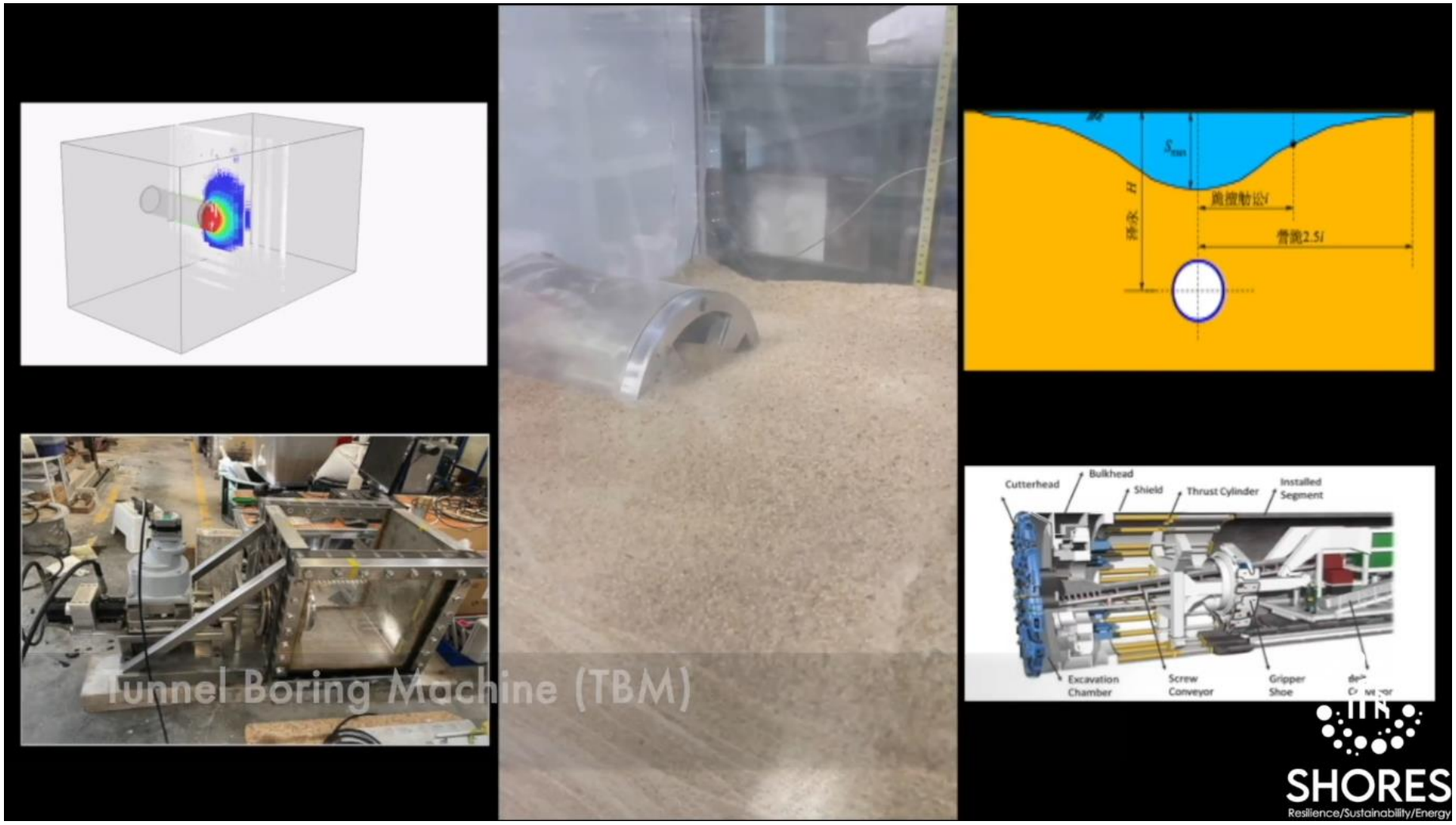
In-flight actuators



Centrifuge TBM Model at New York University Abu Dhabi

Specification	Details
Type	Miniature tunneling machine
Drive System	Realistic drive system (advance and rotation control)
Diameters	3.0-8.0m (Prototype scale)
Cutterhead	Cutterhead with different opening ratios

In-flight actuators



Centrifuge TBM Model at New York University Abu Dhabi

In-flight actuators



Dynamic Loading System at New York University Abu Dhabi

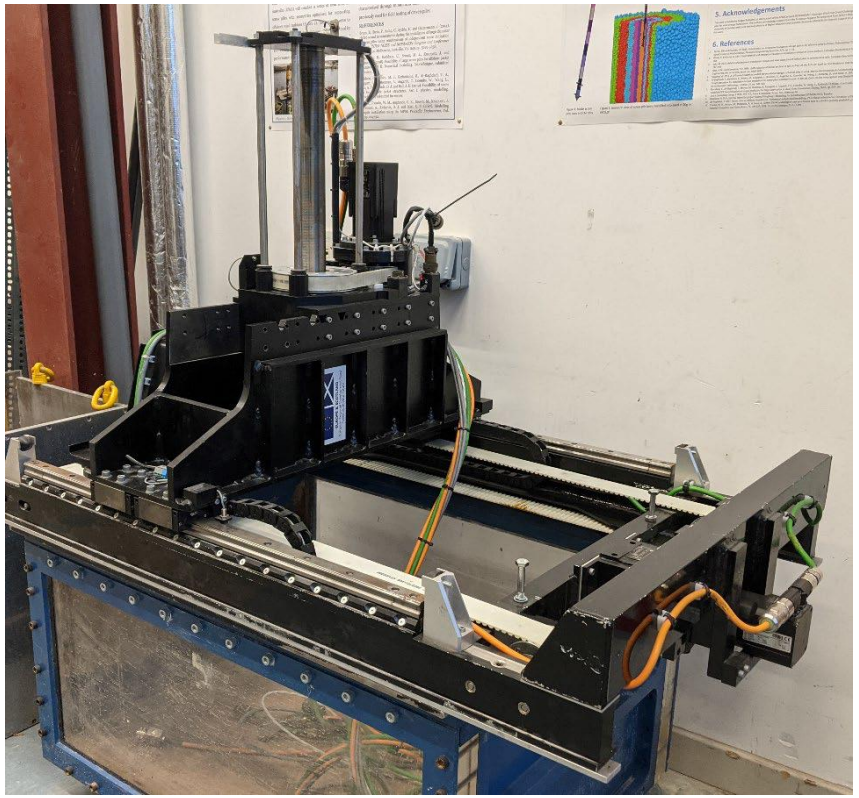
Details
Electro-hydraulic servo type
Position and force control strategy
Sine sweep and fixed frequency sines
Hydraulic and electric control system

In-flight actuators

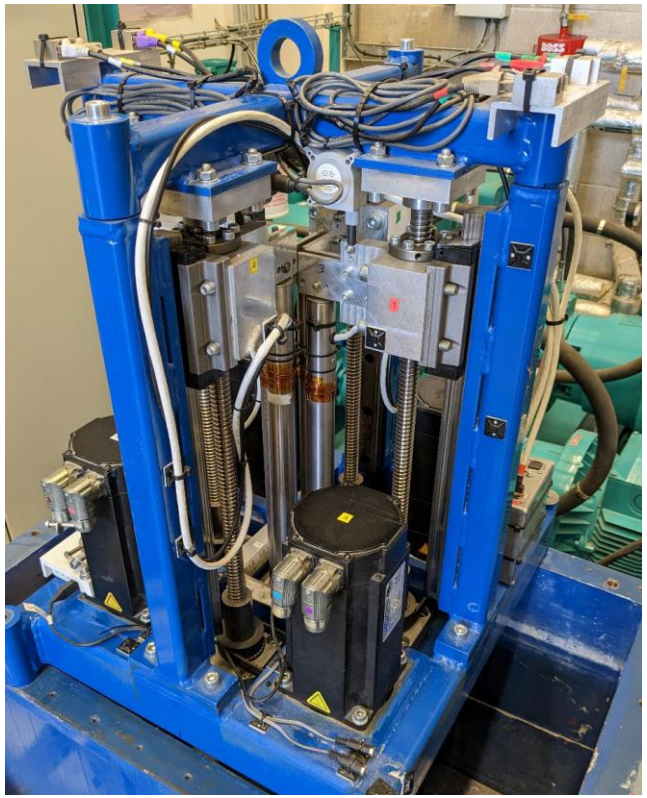
University of Dundee Geotechnical Centrifuge



Dual-axis vertical/rotary actuator
for the installation and axial loading of screw piles, testing of many other types of foundations including conventional piles and transmission tower footings

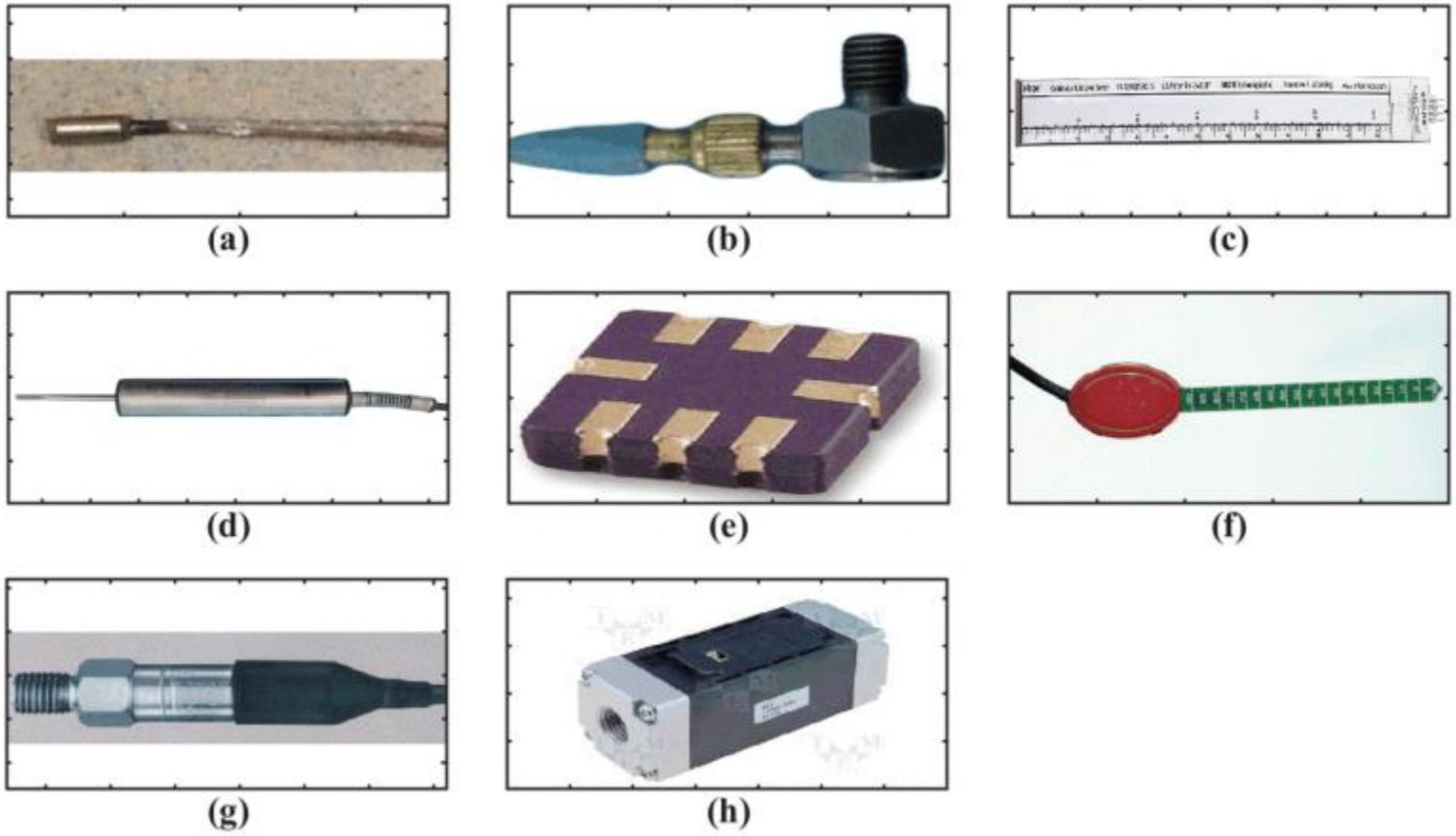


3-axis robotic loading system
Foundation loading actuator is a high accuracy large force bi directional actuator with additional rotational head
Ability to characterize the soil beds during centrifuge tests



4-axis vertical loading actuator
It can provide the installation and study of offshore foundations

6. Instrumentation



(a) 7 bar PDCR-81 pore pressure transducer (PPT), (b) miniature piezoelectric accelerometer, (c) liquid level sensor (eTape), (d) linear variable displacement transducer (LVDT), (e) micro-electrical mechanical systems (MEMS) accelerometer, (f) soil moisture sensor (VH400), (g) 7 bar PDCR-810 PPT , (h) flow sensor

6. Instrumentation

Feature	Miniature Piezo-electric Accelerometer	MEMS Accelerometer
Principle of Operation	Based on the **piezoelectric effect** – certain materials generate an electrical charge when mechanically deformed.	Based on a **microscopic mass-spring system** (typically capacitive sensing) – measures the displacement of a proof mass.
Size and Cost	Relatively **larger and more expensive**.	**Extremely small and low-cost** (as low as ~$3 per unit).
Measurable Acceleration Type	**Only dynamic (AC) acceleration** – insensitive to steady-state (static) acceleration like gravity.	**Both static (DC) and dynamic acceleration** – measures constant and varying accelerations.
Frequency Range	Optimized for measuring **high-frequency vibrations** and intense dynamic events.	Wide frequency range (e.g., 0 – 3000 Hz), but may not match piezo-electric performance at very high frequencies.
Performance in High-g Environments (Centrifuge)	Exhibits **very high stability** under hypergravity conditions, providing reliable data.	May suffer from **measurement distortion or structural failure** at high gravity levels due to mechanical overloading.
Effect on the Model (Spurious Effects)	Larger attached cables can introduce **false damping (energy dissipation)** into lightweight or soft soil models.	Has **minimal physical impact** on the model due to its tiny size and lightweight cables.
Main Applications in Geotechnical Engineering	The **gold standard** for measuring dynamic parameters like seismic response, pile driving vibrations, etc.	An **emerging alternative** for specific applications, such as measuring acceleration during free-fall penetrometer tests, or in loose/liquefiable soils where piezoelectric sensors struggle.

Comparison between miniature piezoelectric accelerometer and micro-electrical mechanical systems (MEMS) accelerometer

7. Data acquisition systems

- Precision
- Amplification
- Sampling rate
- Electrical noise
- Time and frequency domains
- Filtering

8. Some examples of geotechnical problems

- Seismic performance of vegetated slopes, TENG (2015)
- Seismic performance of pile-reinforced slopes, Al-Defae (2013)
- Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)
- Screw piles as offshore foundations: Numerical and physical modelling (Al-Baghdadi, 2019)
- Seismic behaviour of shallow foundations on layered liqueable soils, Bertalot, 2023
- Influence of foundation type on seismic response of low-rise structures in liquefiable soil, Qi (2022)
- Centrifuge study of seismic response of soil-nailed walls supporting a footing on the ground surface, Ghadamgahi (2021)

Seismic performance of vegetated slopes, TENG (2015)



2001 El Salvador earthquakes | 2008 Wenchuan earthquakes | 2010 Taiwan earthquakes



2010 Haiti earthquakes | 2011 Tōhoku earthquakes | 2011 Christchurch earthquakes

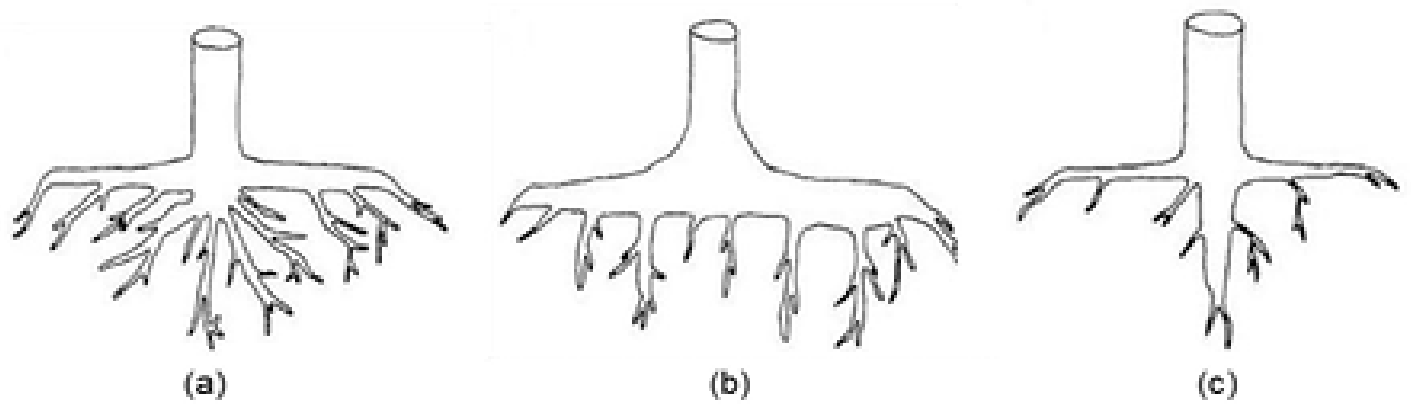


Fig 2.2 Three basic types of tree root system: (a) Heart root system with many branches; (b) Plate root system with large horizontal lateral roots and sinkers; (c) Tap root system with a large central vertical root and small lateral roots (Lal 1998)

Seismic performance of vegetated slopes, TENG (2015)

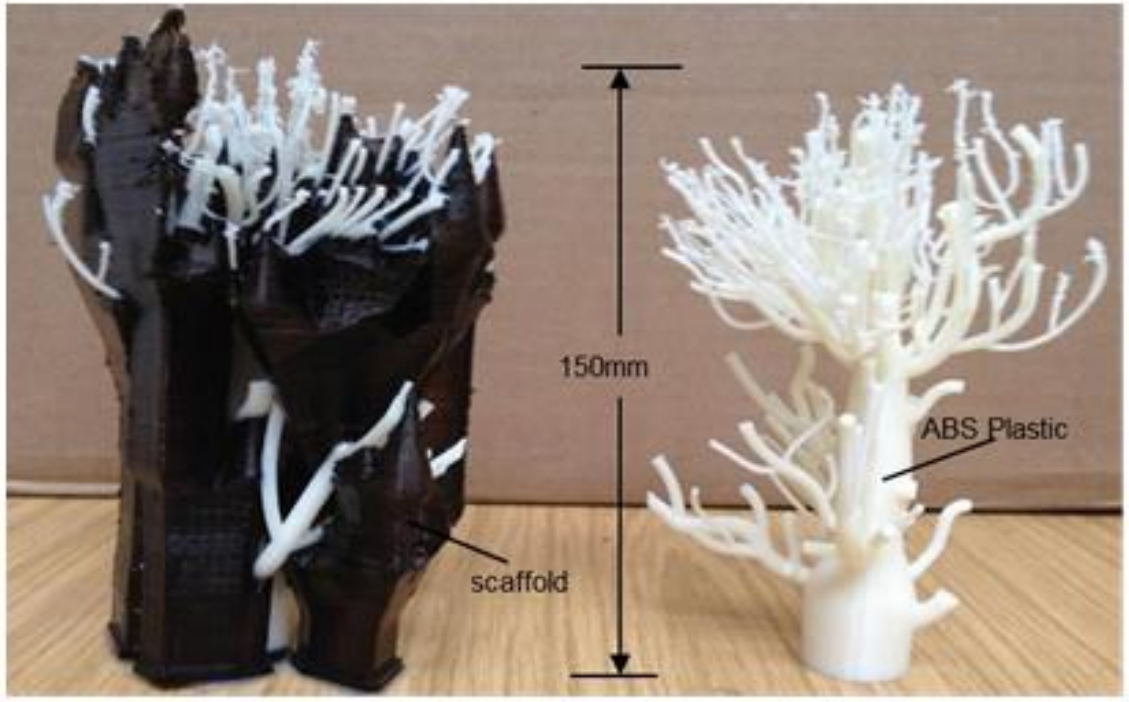
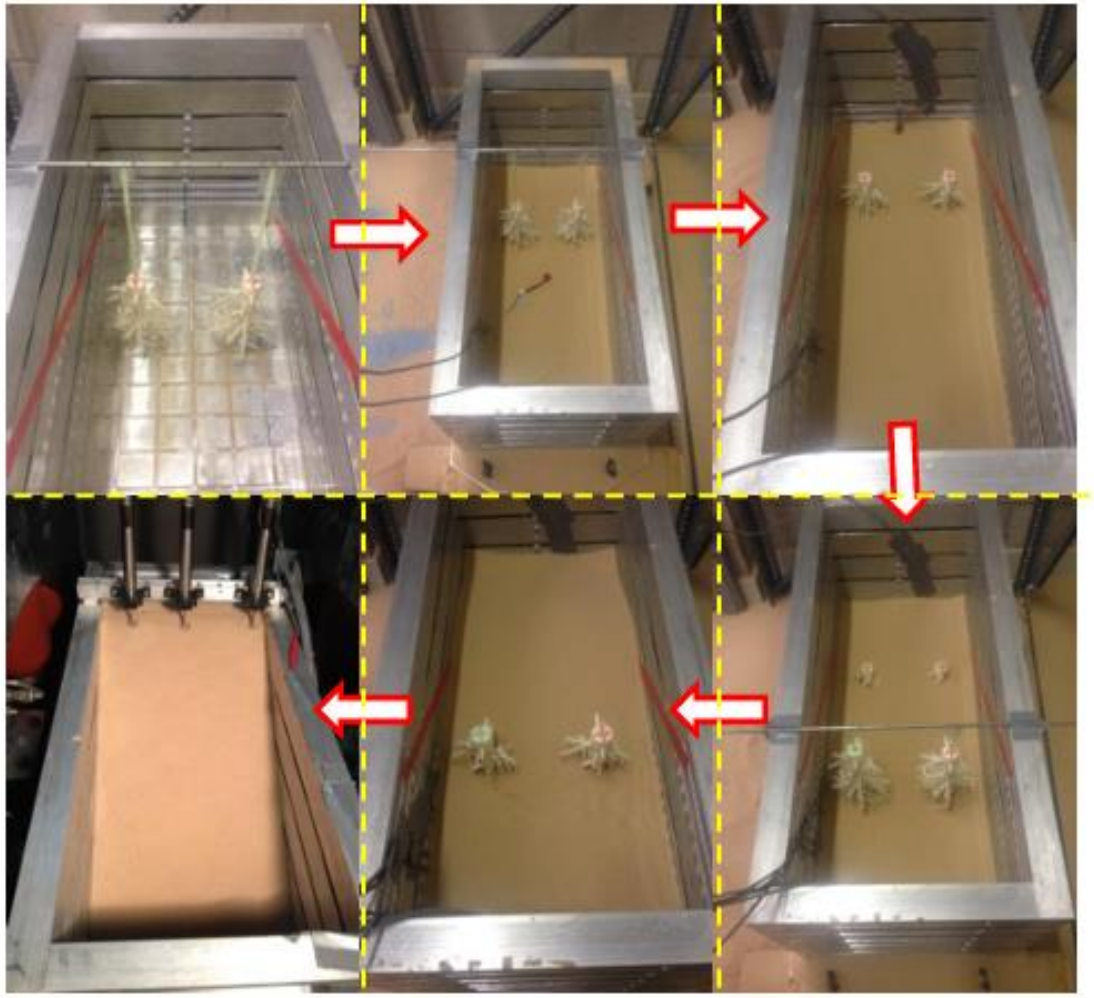


Fig 4.5 ABS plastic root model from 3-D printer showing the temporary support scaffold (left) during printing, and the final model (right), after this has been dissolved



Procedure of 1:10 scale root cluster installation

Seismic performance of vegetated slopes, TENG (2015)

Test identification number	Test scale	Slope height	Root type	root quantity	Motion frequency content(Hz)
TL01	1:10	2.4m	Fallow	0	4-30
TL02	1:10	2.4m	1:10 scale straight root group	4	4-30
TL03	1:10	2.4m	1:10 scale root cluster	4	4-30
TL 04	1:10	2.4m	Fallow	0	4-30
TL 05	1:30	7.2m	Fallow	0	1.33-10
TL 06	1:30	7.2m	1:30 scale root cluster	36	1.33-10
TL 07	1:10	2.4m	1:10 scale root cluster	4	4-30
TL 08	1:30	7.2m	Fallow	0	4-10



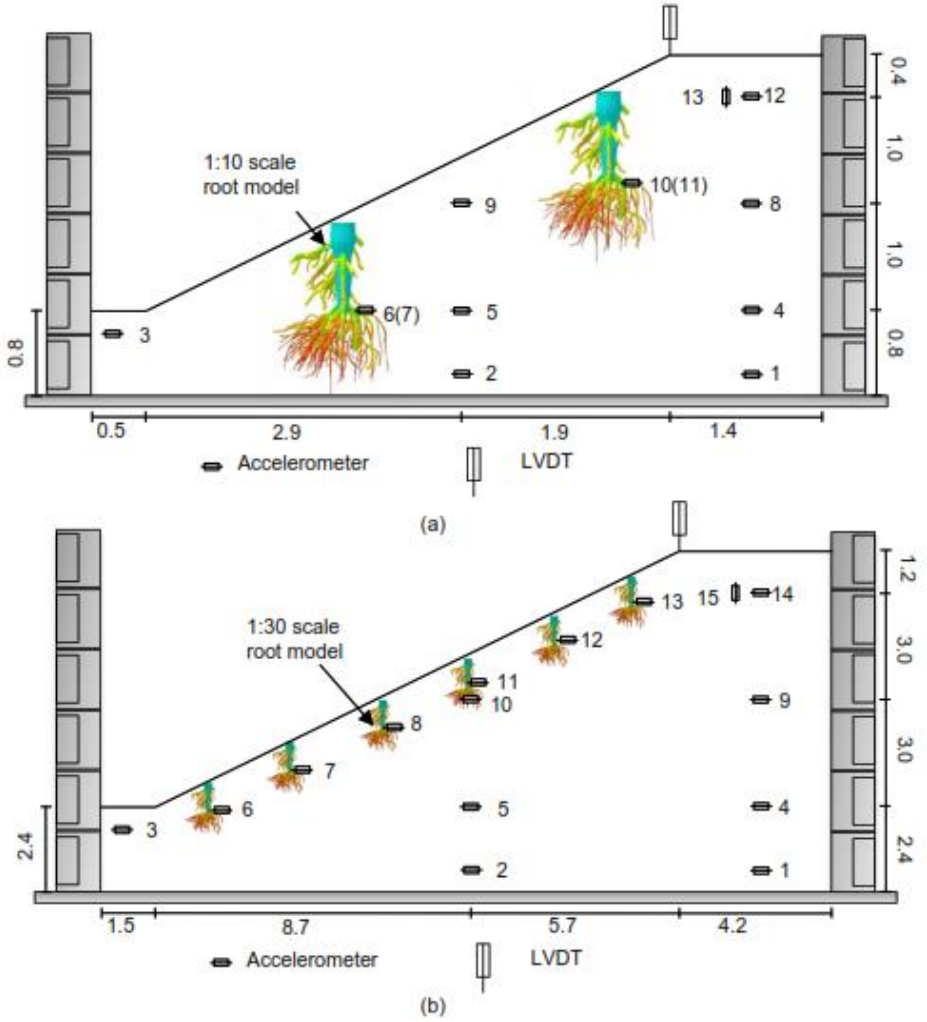


Fig 6.1 Schematic of centrifuge model geometry, instrumentation and position of root analogues: (a) 1:10 scale model; (b) 1:30 scale mode (Dimensions at prototype scale in meters)

Seismic performance of pile-reinforced slopes, Al-Defae (2013)

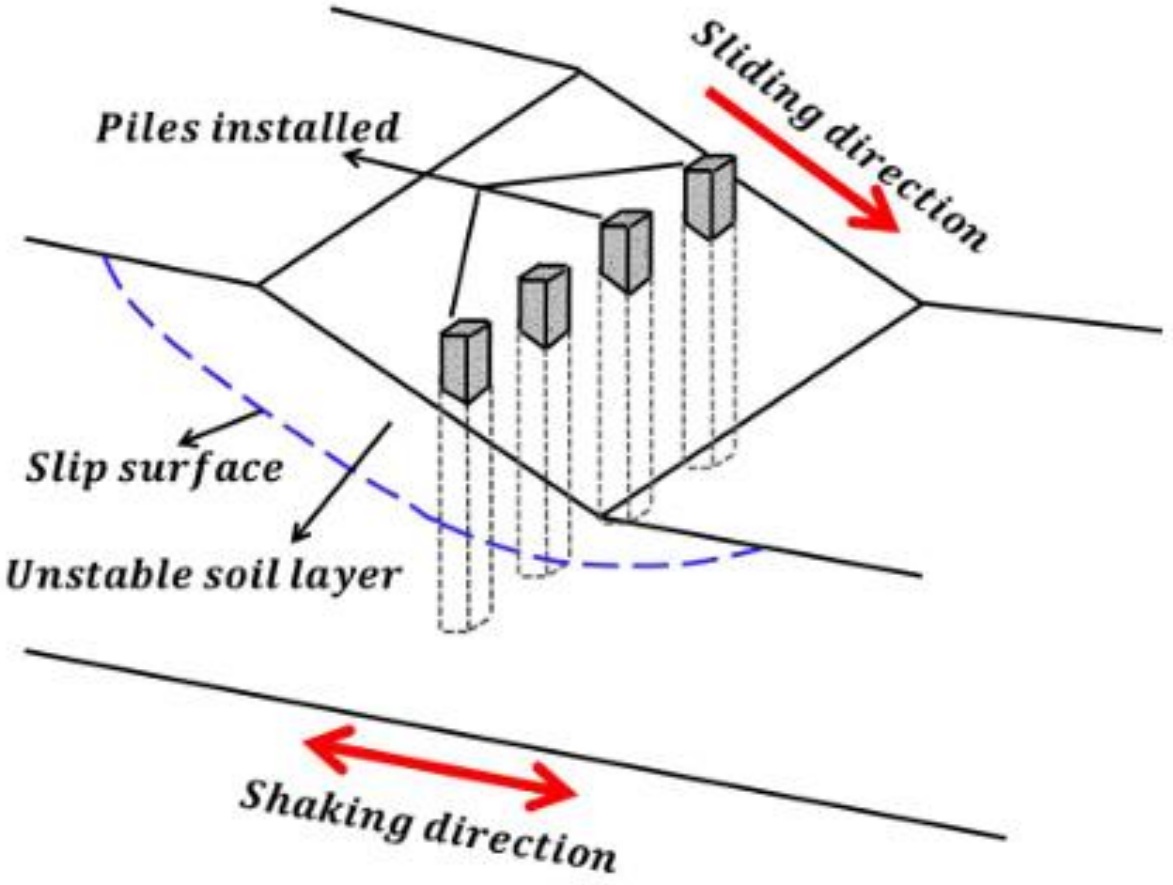


Figure (1- 9): Statement of problem

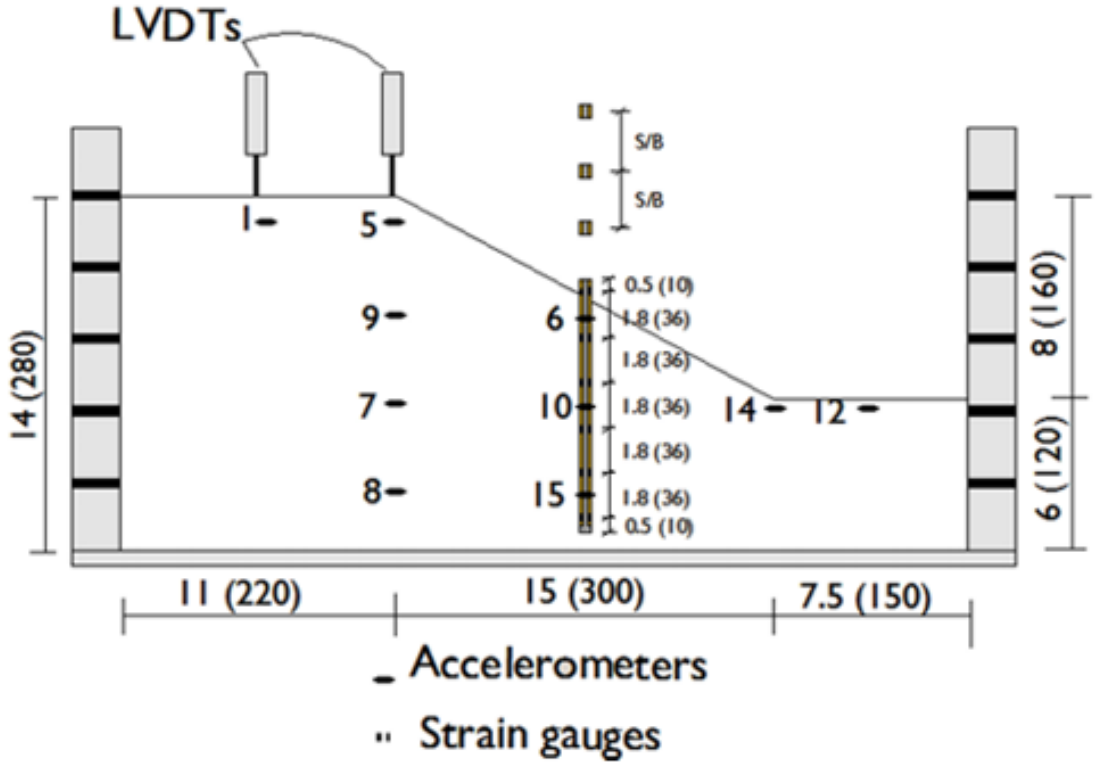


Figure (6- 1): Centrifuge model layout, with instrumented elastic piles shown, dimensions in m prototype scale (mm model scale in brackets).

Test ID	I_D (%)	Pile type	S/B	No. of earthquakes
AA01	56	Unreinforced	-	4
AA17*	57	Unreinforced	-	12
AA12	58	Elastic	14.0	4
AA13	60	Elastic	7.0	4
AA14	57	Elastic	4.7	4
AA15	59	Elastic	3.5	4
AA16*	58	Elastic	4.7	12
AA04	56	RC	14.0	1
AA05	57	RC	7.0	1
AA06	60	RC	4.7	1
AA07	57	RC	3.5	1
AA08	56	RC	14.0	4
AA09	59	RC	7.0	4
AA10	57	RC	4.7	4
AA11	55	RC	3.5	4

*Kobe input motion for this test

Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)



Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)

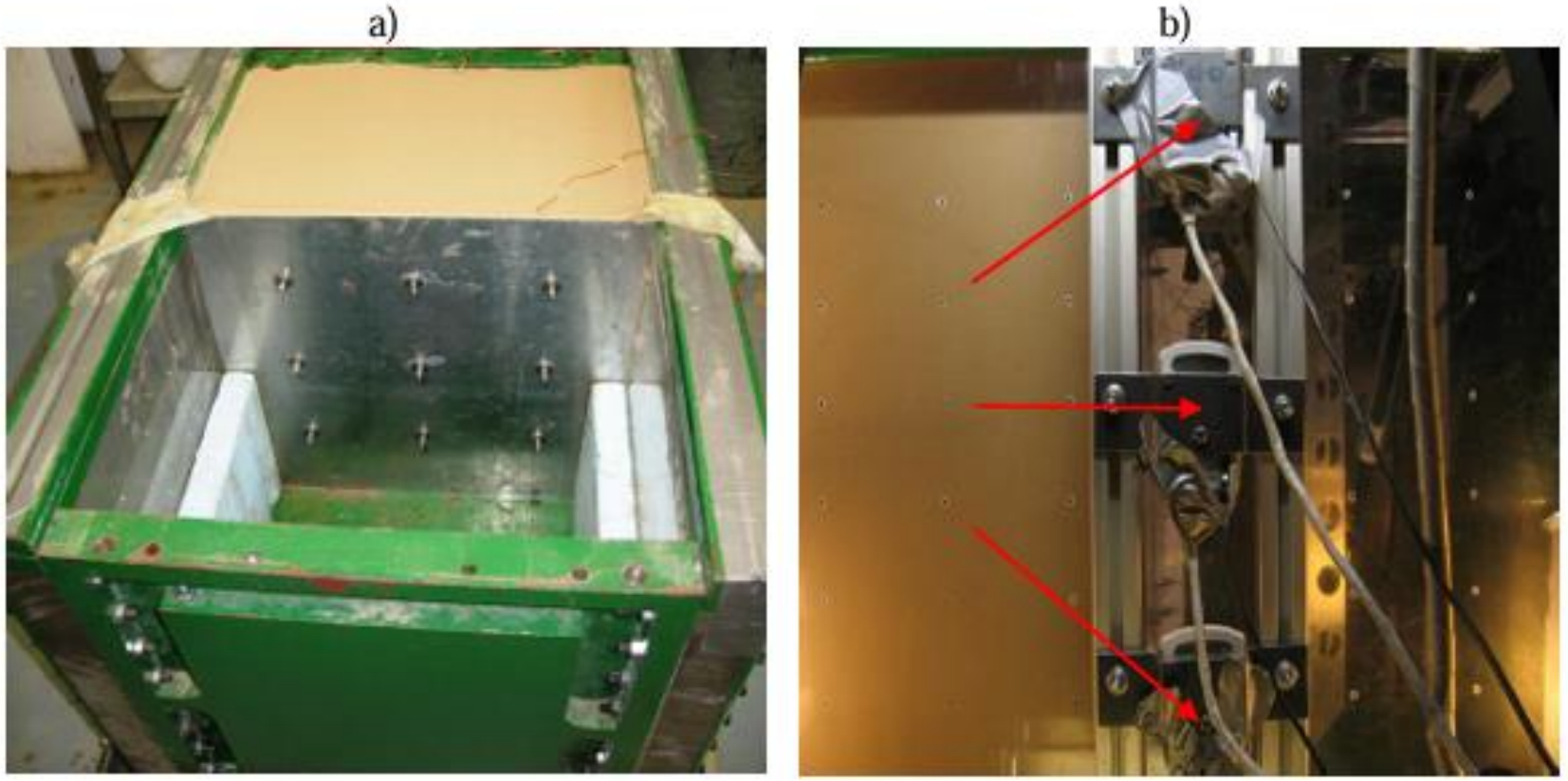


Figure 4.1 a) Model layout of a retaining wall reinforced with 9 horizontal anchorages set up in a 3x3 array and b) three network cameras connected to the network and clamped in a special designed frame outside the front Perspex sheet as pointed with red arrows.

Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)

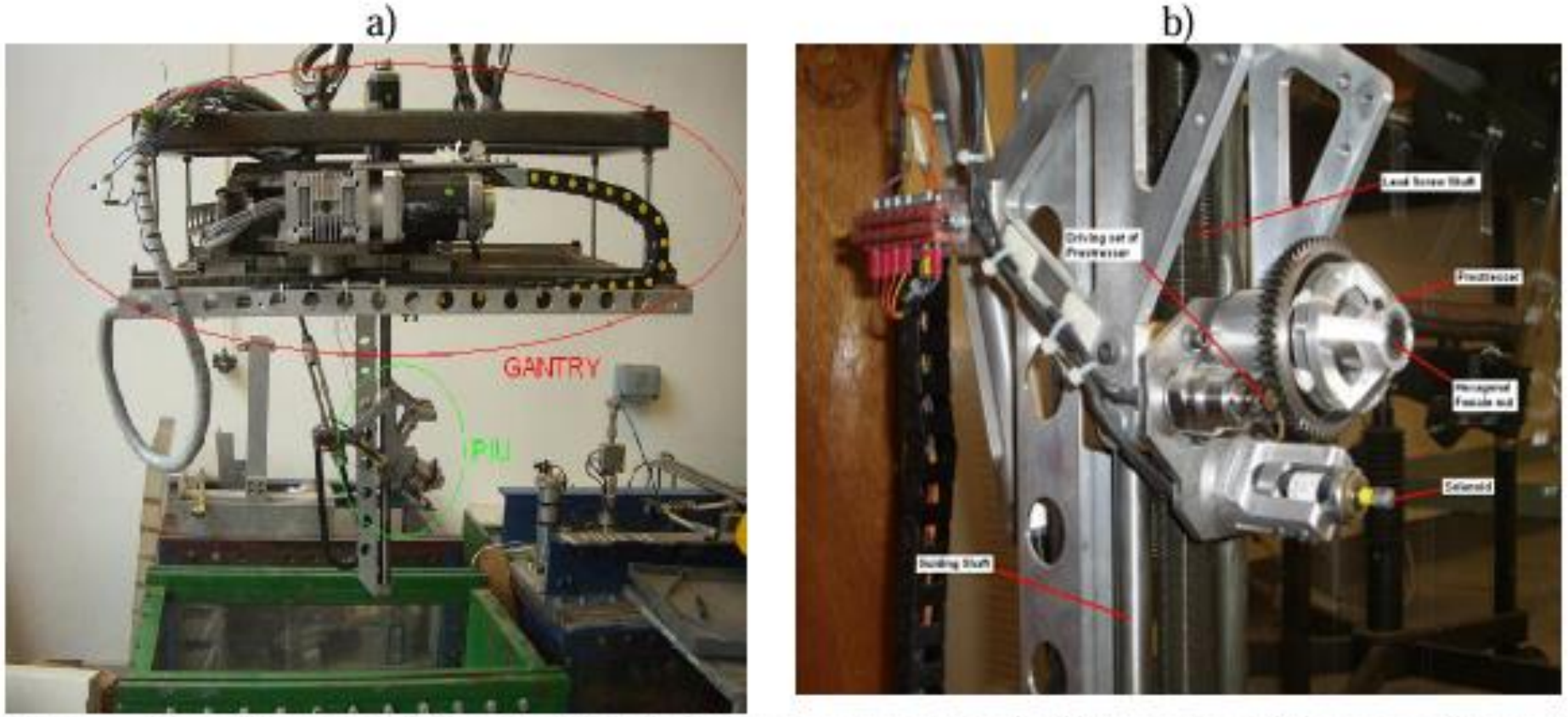
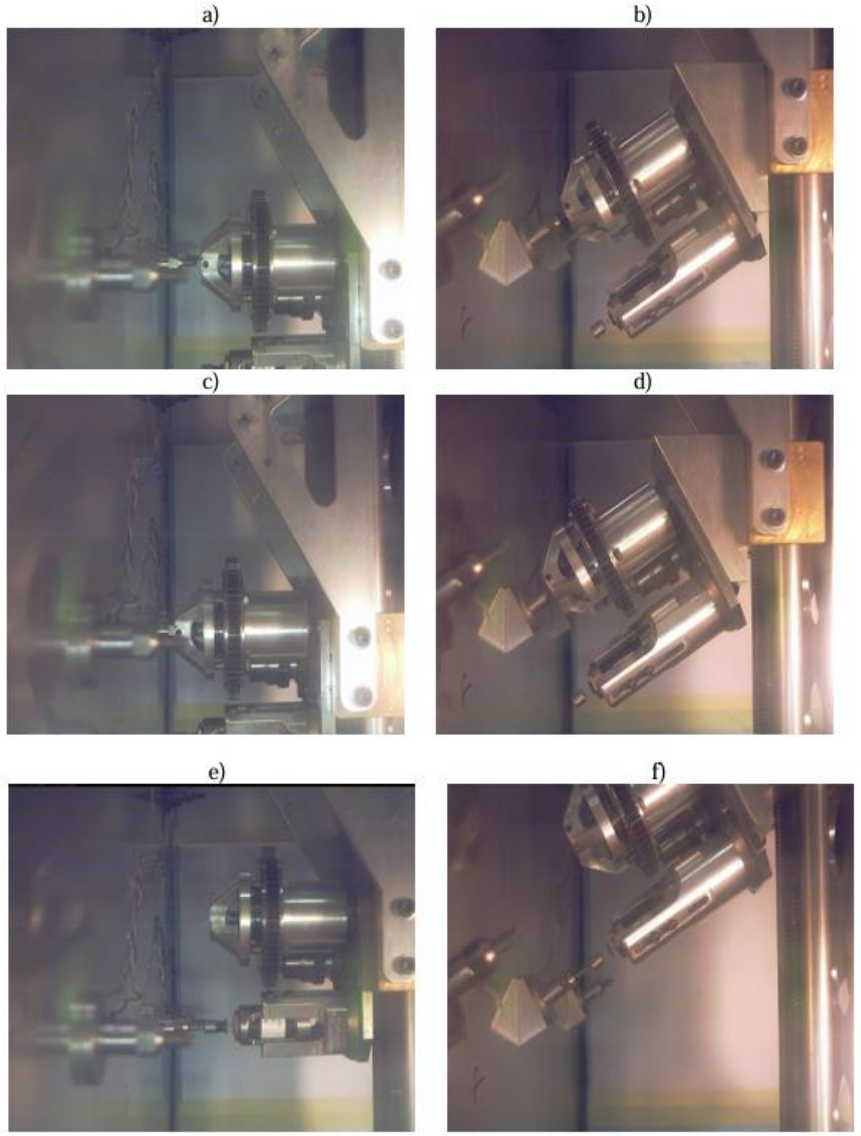


Figure 4.7 a)In-flight Robotic Manipulator composed of: Gantry and Prestress Impact Unit (PIU) and b)enlarged view of components of the PIU

Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)



Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)

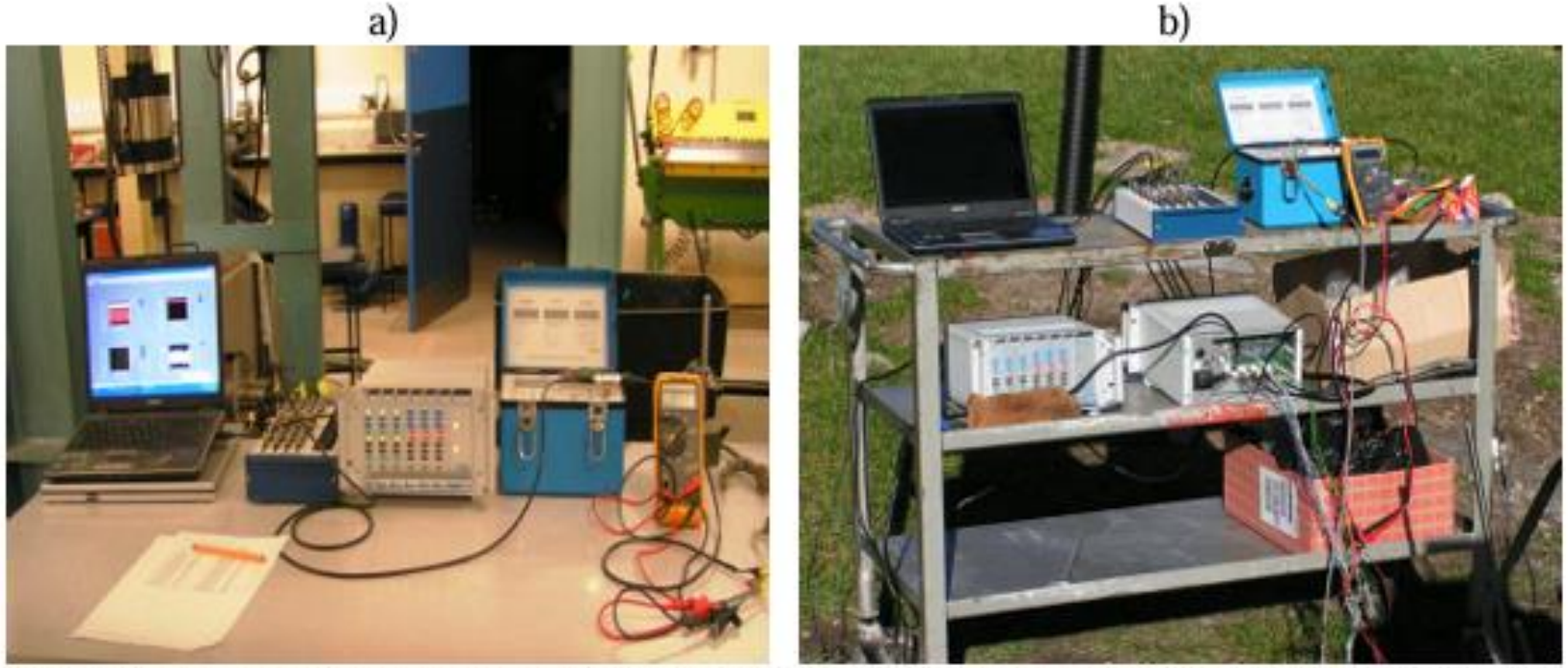


Figure 4.20 Anchorage head rig instrumentation (Laptop, NI-6259, RDP Amp-621, P3 strain indicator and voltmeter) from left to right and b) field experiments instrumentation (Laptop, NI-6259, P3 strain indicator and voltmeter, RDP Amp-621 and RDP Amp-628) from left top to right bottom.

Assessment of condition of soil anchorage using centrifuge, numerical and field experiments (Palop,2012)



Figure 7.1 Soil anchorage head: (a) GRANIT system attached to the protruding length of the anchorage head, wherein a full scale centrifuge bearing plate was implemented and (b) soil anchorage head detail.

Screw piles as offshore foundations: Numerical and physical modelling (Al-Baghdadi, 2019)



Figure 2.4: Typical screw pile installed nearshore at shallow water depth (image: courtesy of Screwfast Foundations Limited)

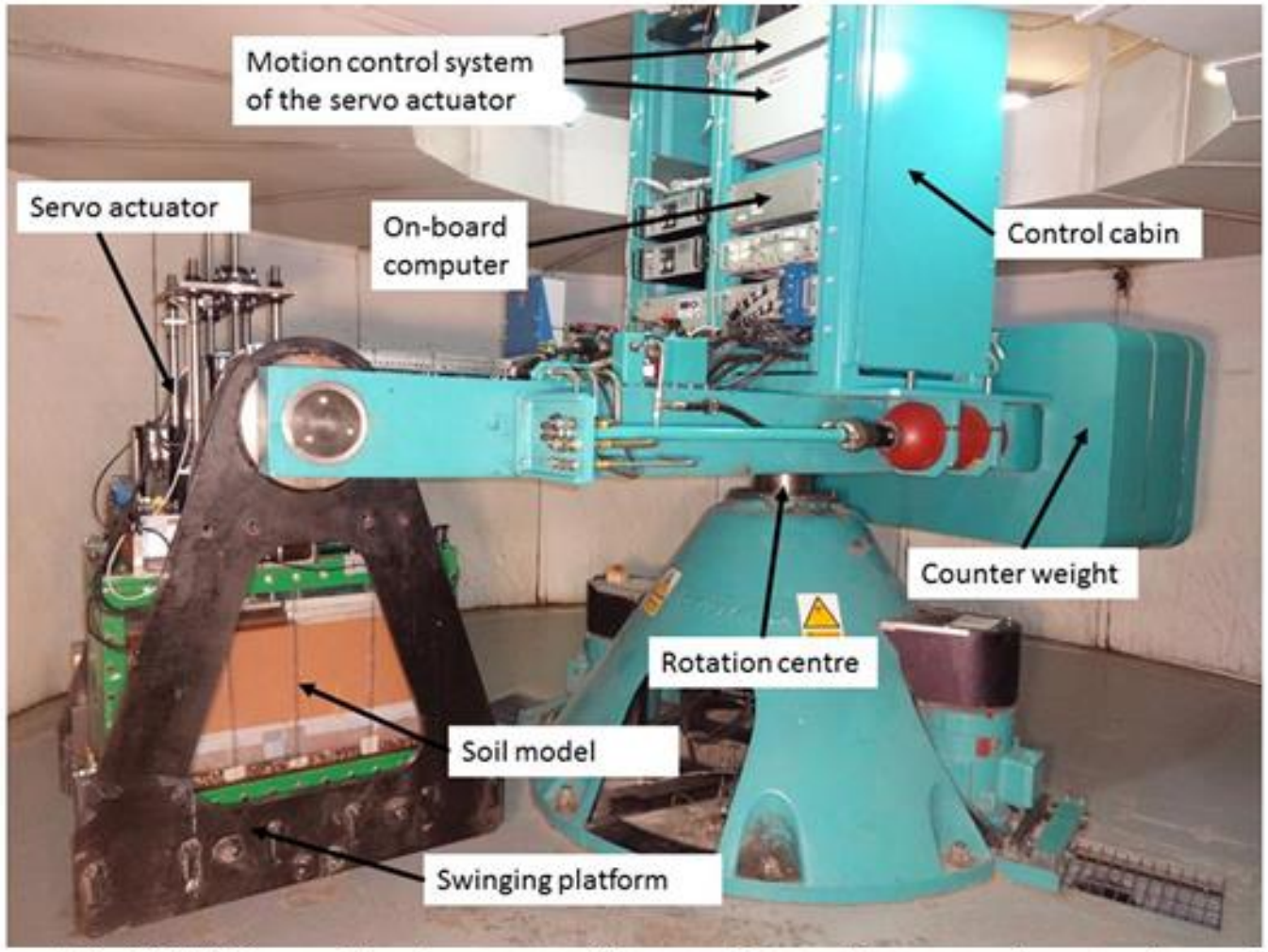


Figure 5.2: UoD 3.0 m radius beam centrifuge machine with screw pile actuation and control system in place.

A servo actuator has been developed so that the screw pile models can be installed and tested in-flight in the centrifuge at 50 g level acceleration to match the field stress levels and simulate the prototype installation behaviour of screw piles.

Screw piles as offshore foundations: Numerical and physical modelling (Al-Baghdadi, 2019)

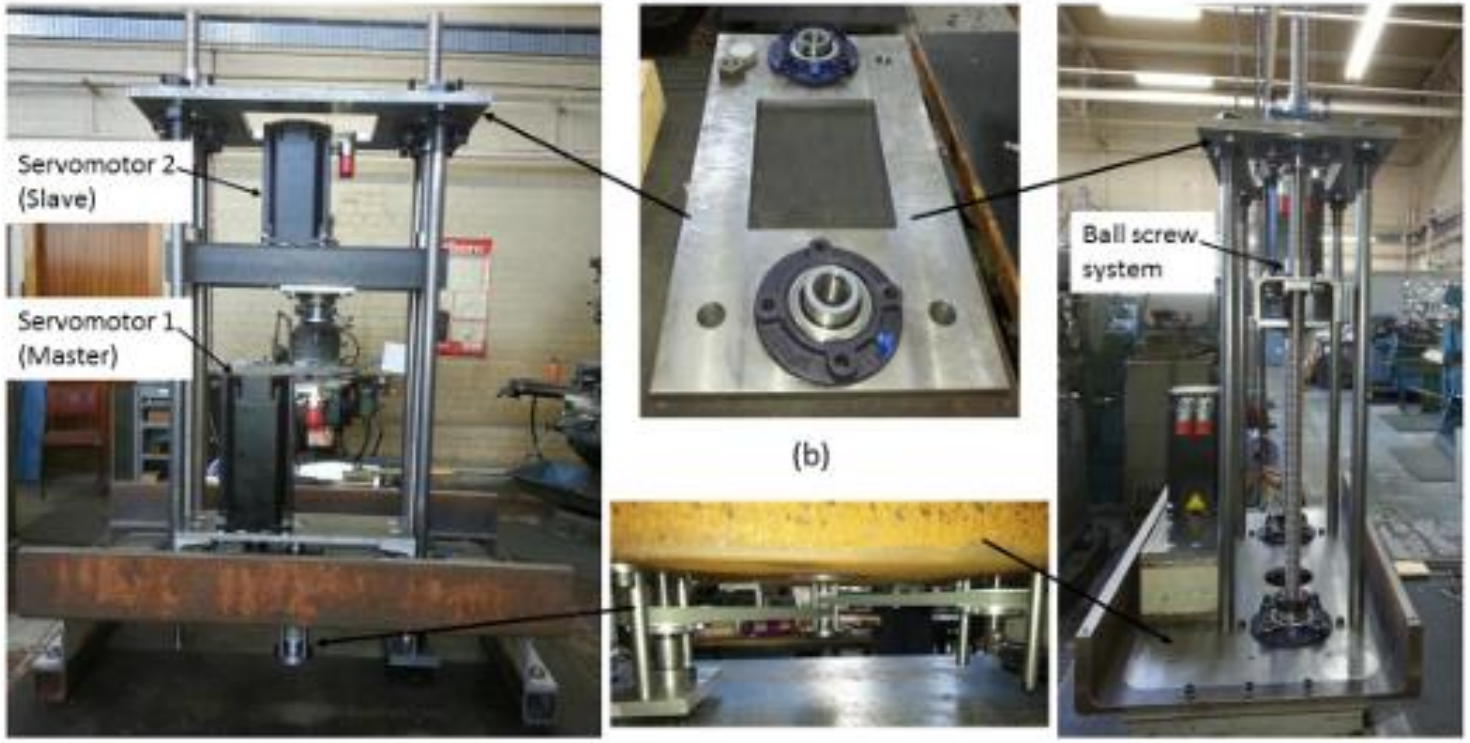


Figure 5.11: Construction stages of the servo-actuator used to install and test the screw piles (a) Front view, (b) top support plate, (c) base support channel, and (d) side view

Screw piles as offshore foundations: Numerical and physical modelling (Al-Baghdadi, 2019)

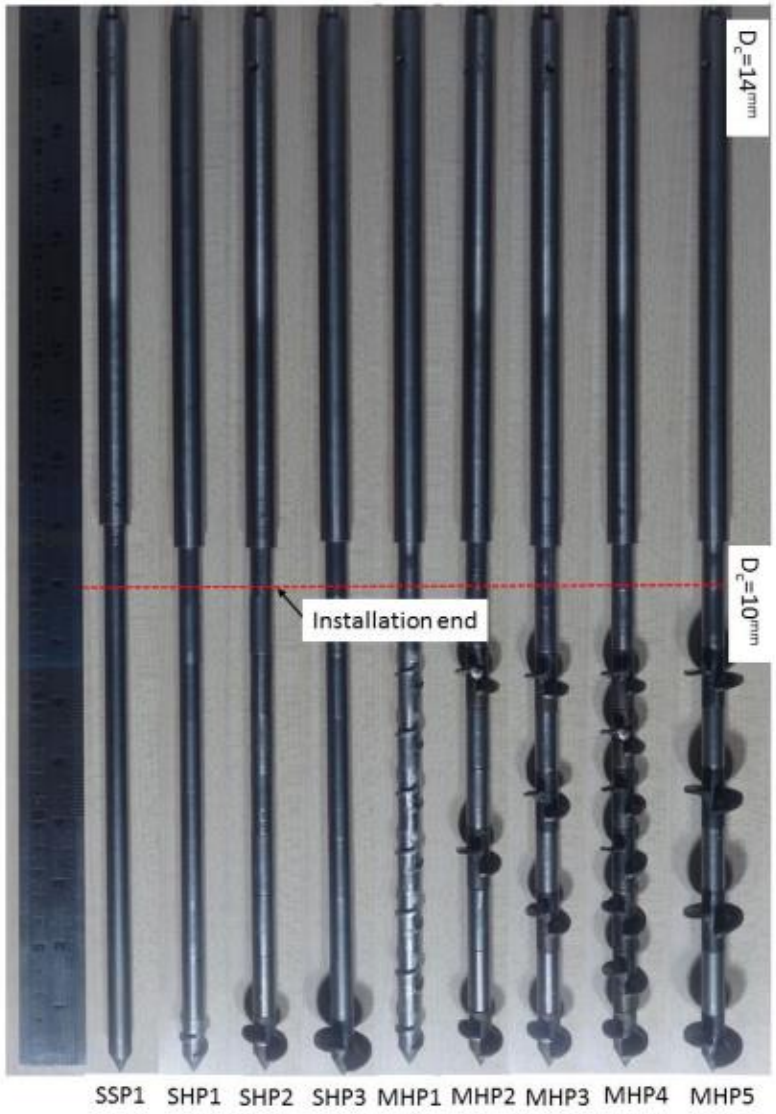


Figure 5.16: Pile model set used in the centrifuge tests



Figure 1.1: Liquefaction-induced settlement of buildings having shallow foundations:
a) 2011 Tohoku; b) 2010 Maule (Chile) Earthquake

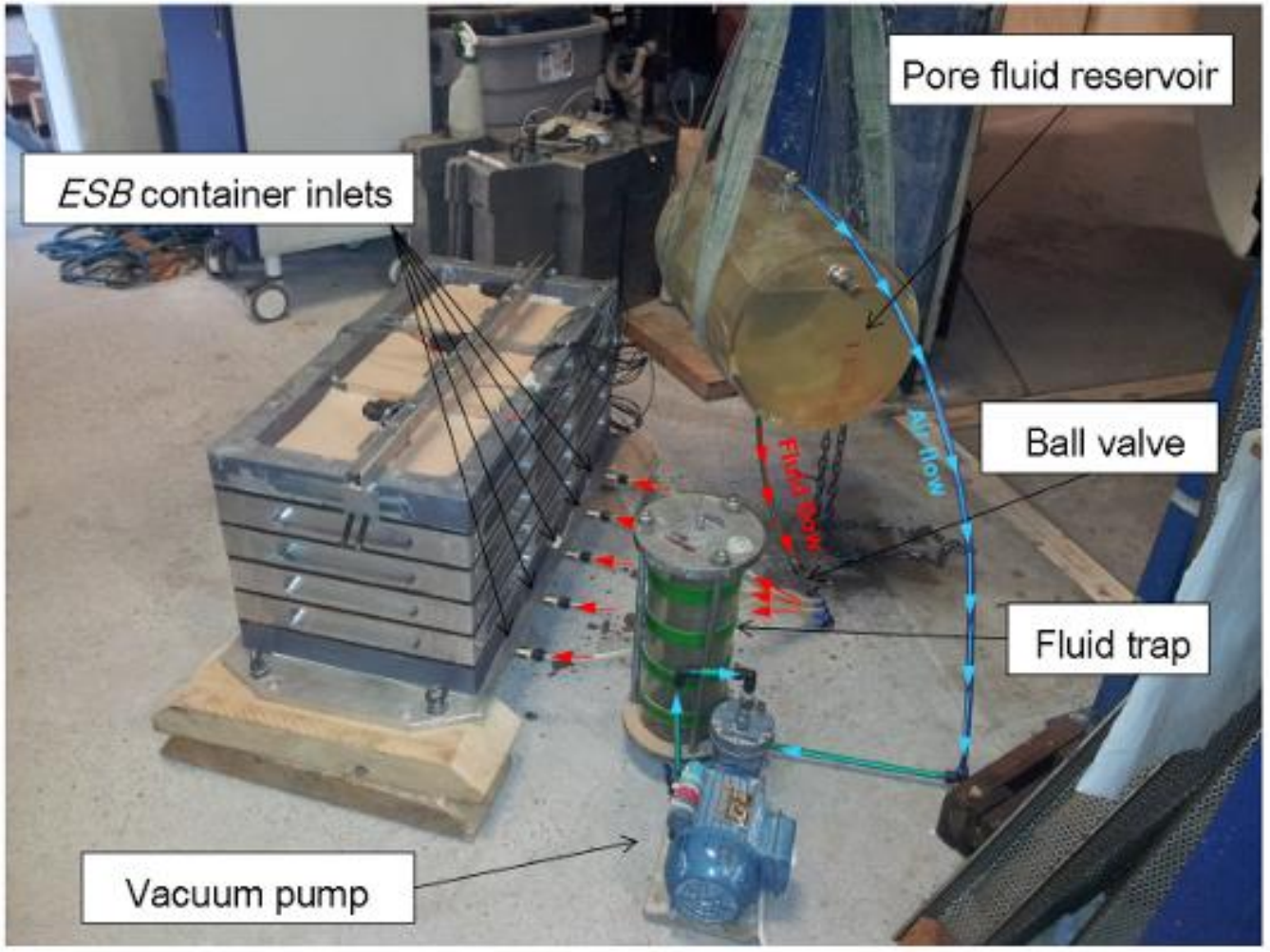
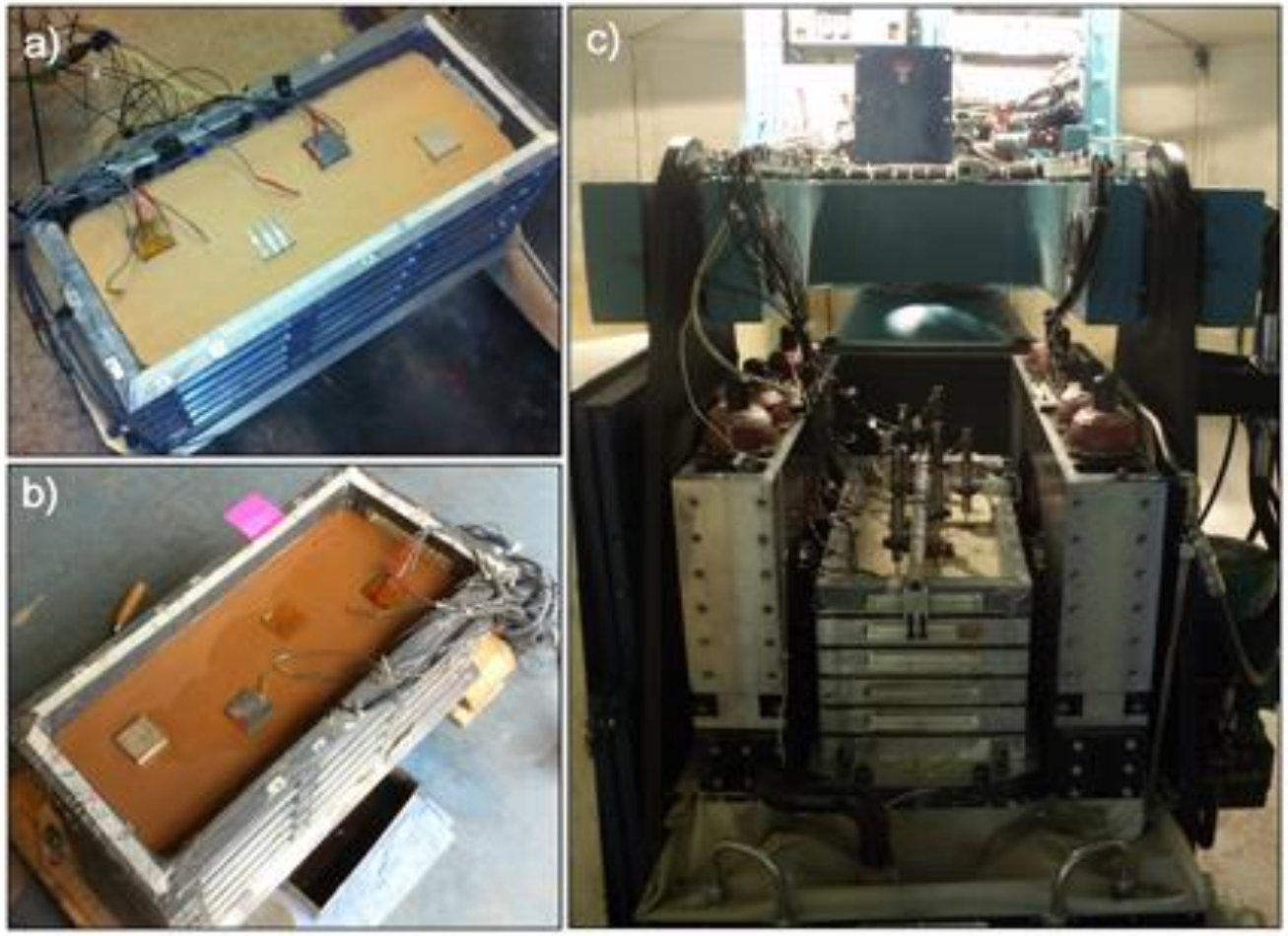


Figure 4.15: Saturation system adopted for the centrifuge tests series.


a)
b)
c)

Influence of foundation type on seismic response of low-rise structures in liquefiable soil, Qi (2022)

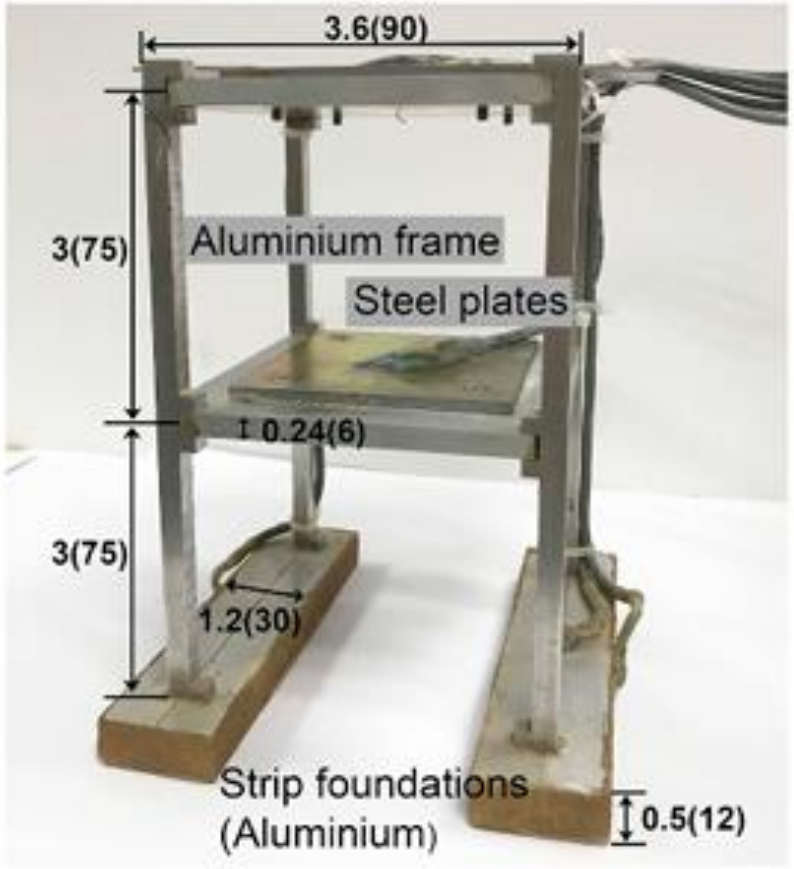
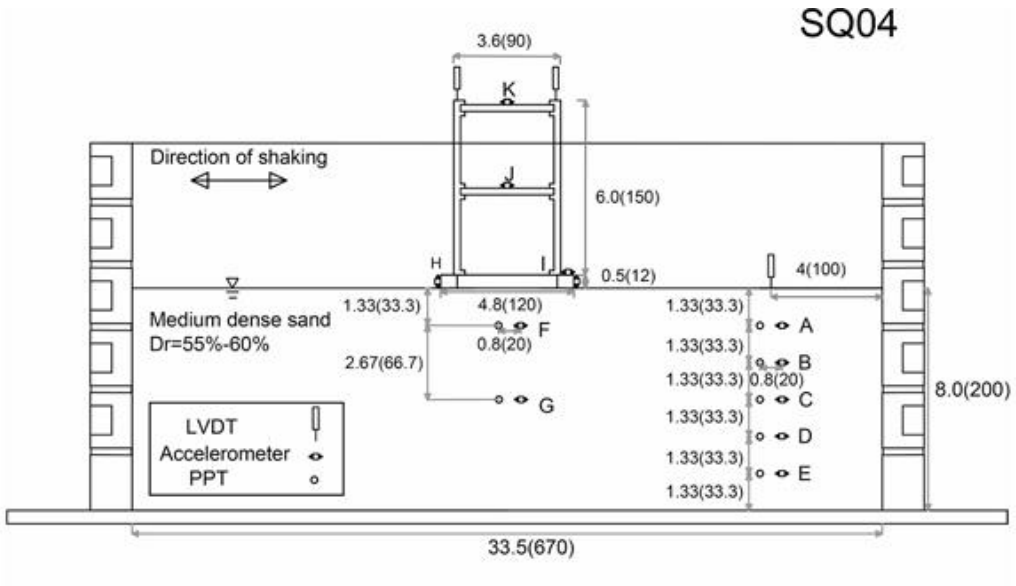
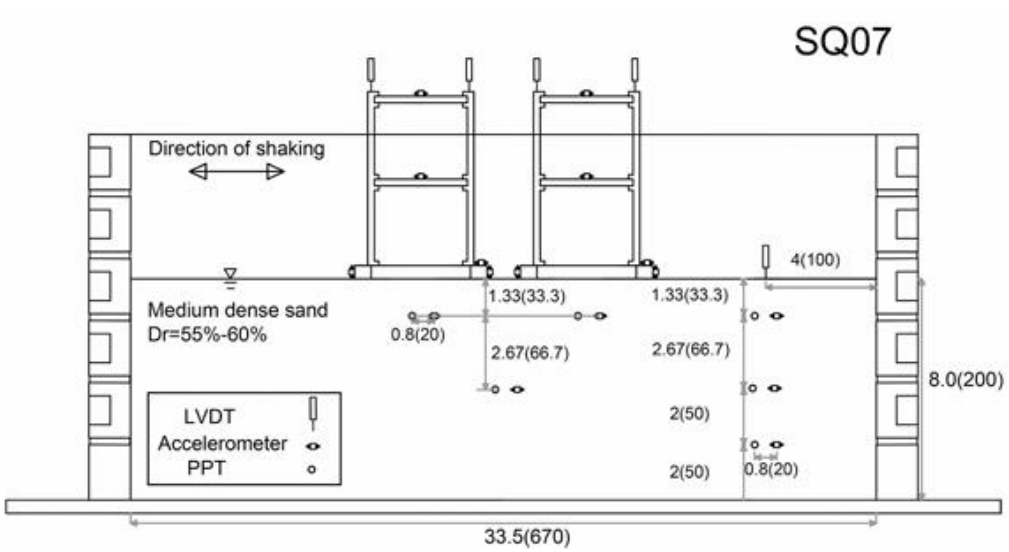
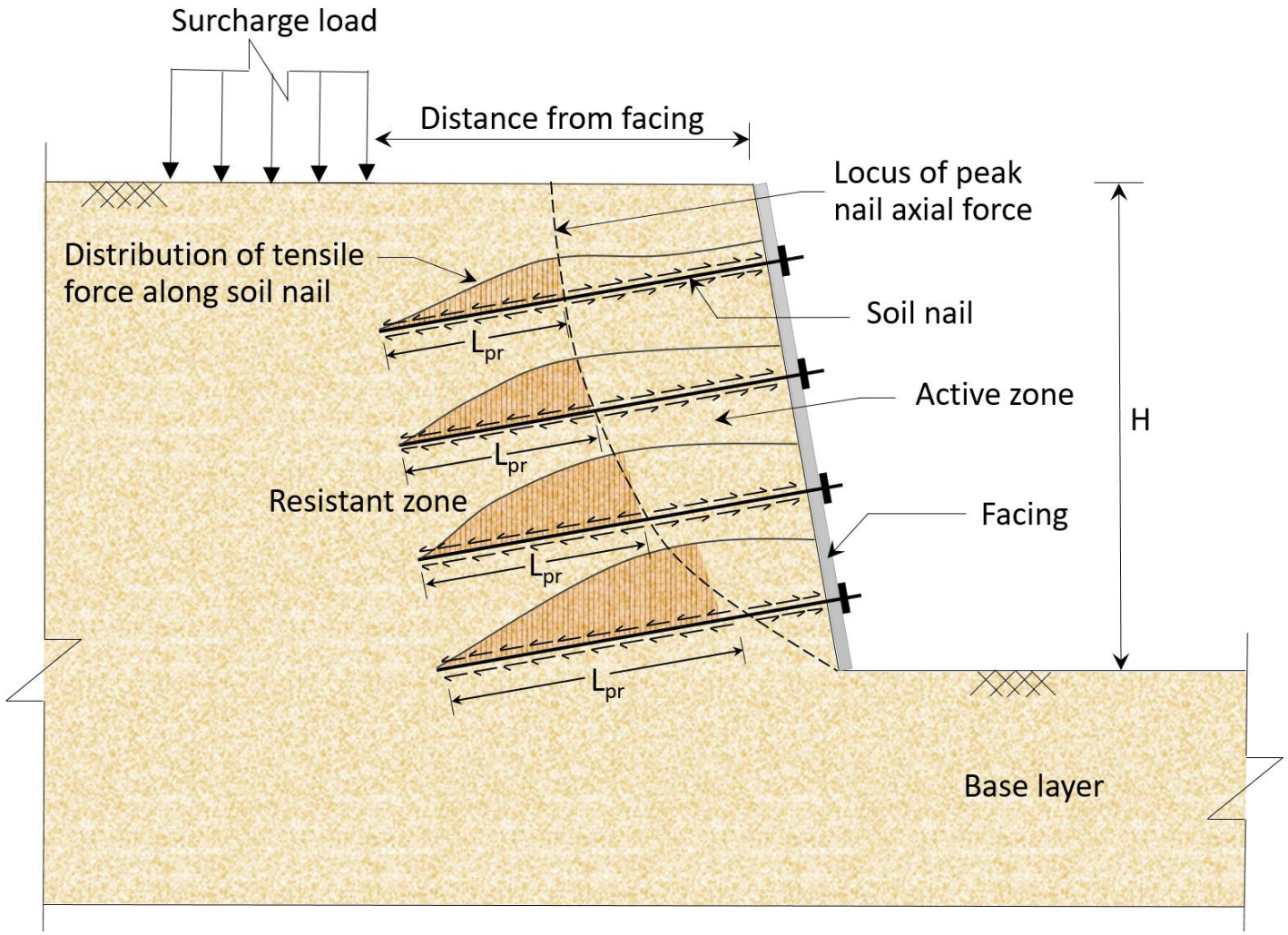


Fig. 1. Strip model structure: dimensions at prototype scale are shown in m; dimensions at model scale are given in mm in brackets ().

Influence of foundation type on seismic response of low-rise structures in liquefiable soil, Qi (2022)

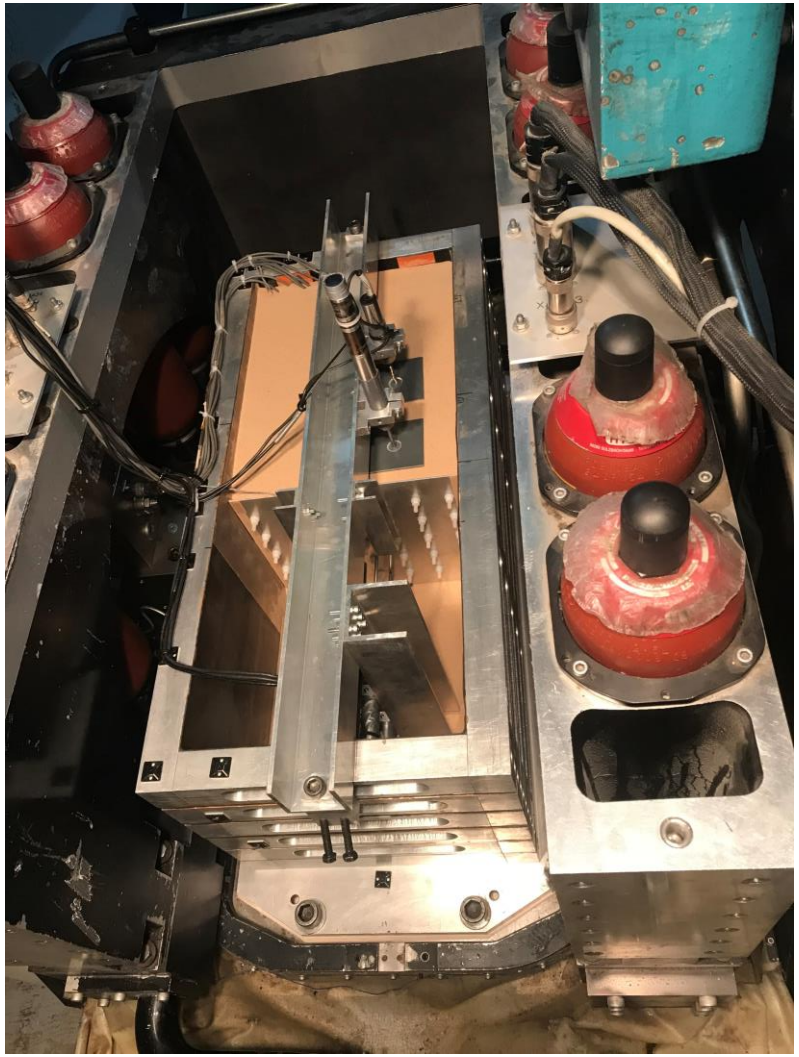






Schematic view of a soil-nailed wall supporting a surcharge load at the backfill

Centrifuge study of seismic response of soil-nailed walls supporting a footing on the ground surface (2021)





Thanks for your attention

Alireza Ghadamgahi
a.ghadamgahi@iiees.ac.ir