Physical model experiments in geomechanics for the energy transition

ALERT Doctoral School 2025

« The Role of Geomechanics in the Energy Transition »

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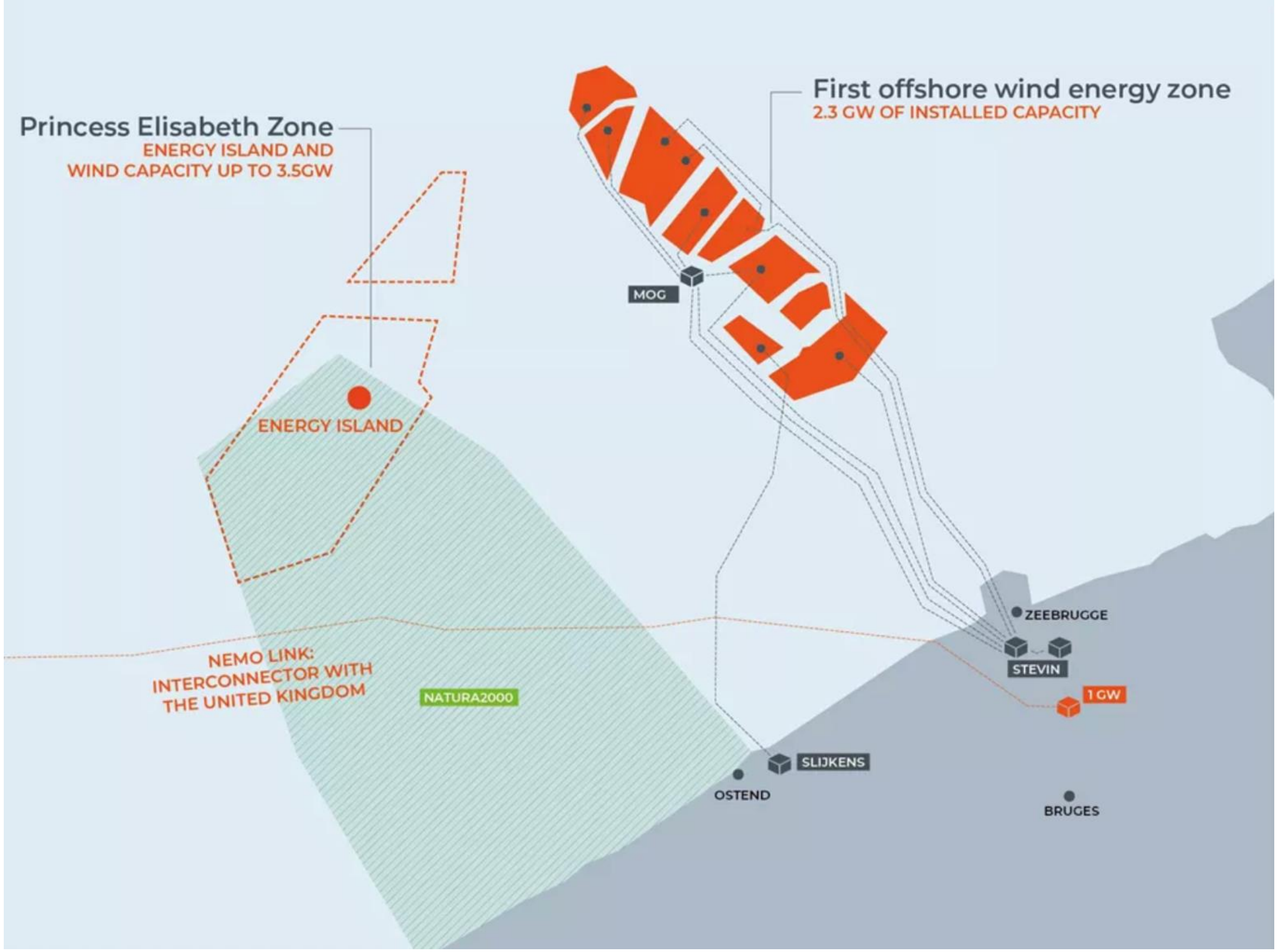
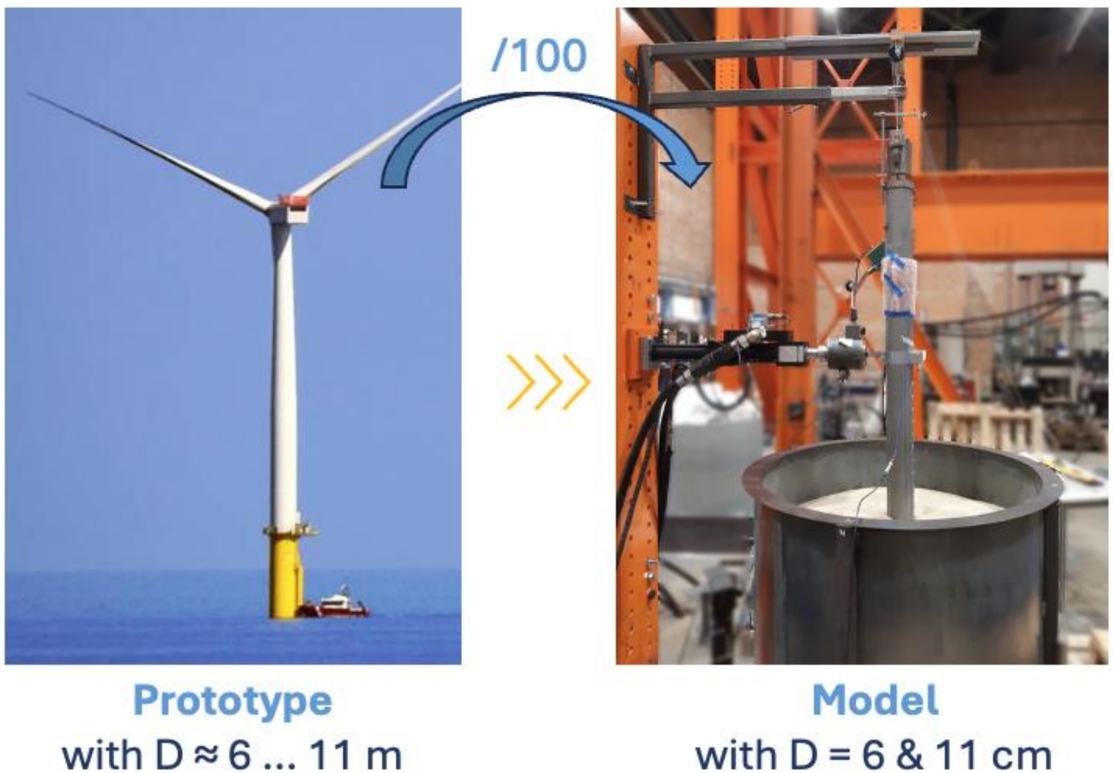
Offshore wind farms in belgium



What is a physical model?

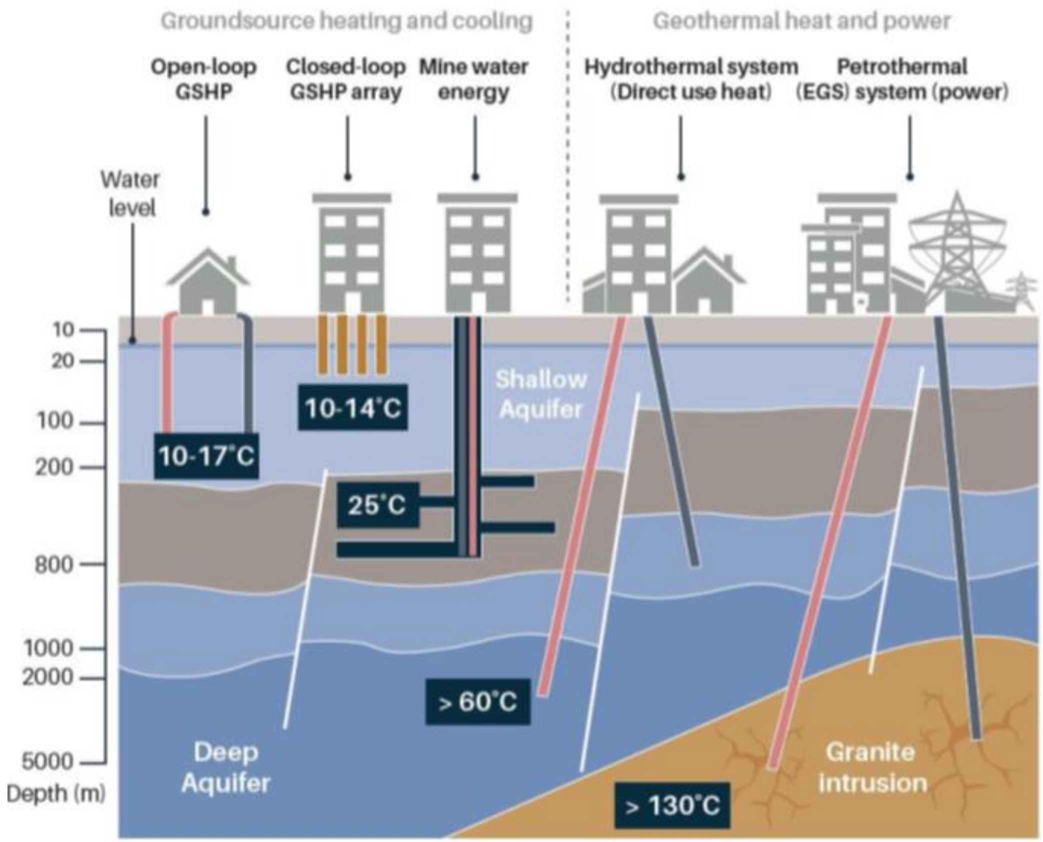
- A physical models represent the prototype design at a smaller scale
- It offer an **economical** and **more practical way** to validate numerical models or tests different design strategies



The Necessity of Physical Modeling

High costs associated with construction and pilot projects limit full-scale testing:

- deep geothermal wells: $3–15 million

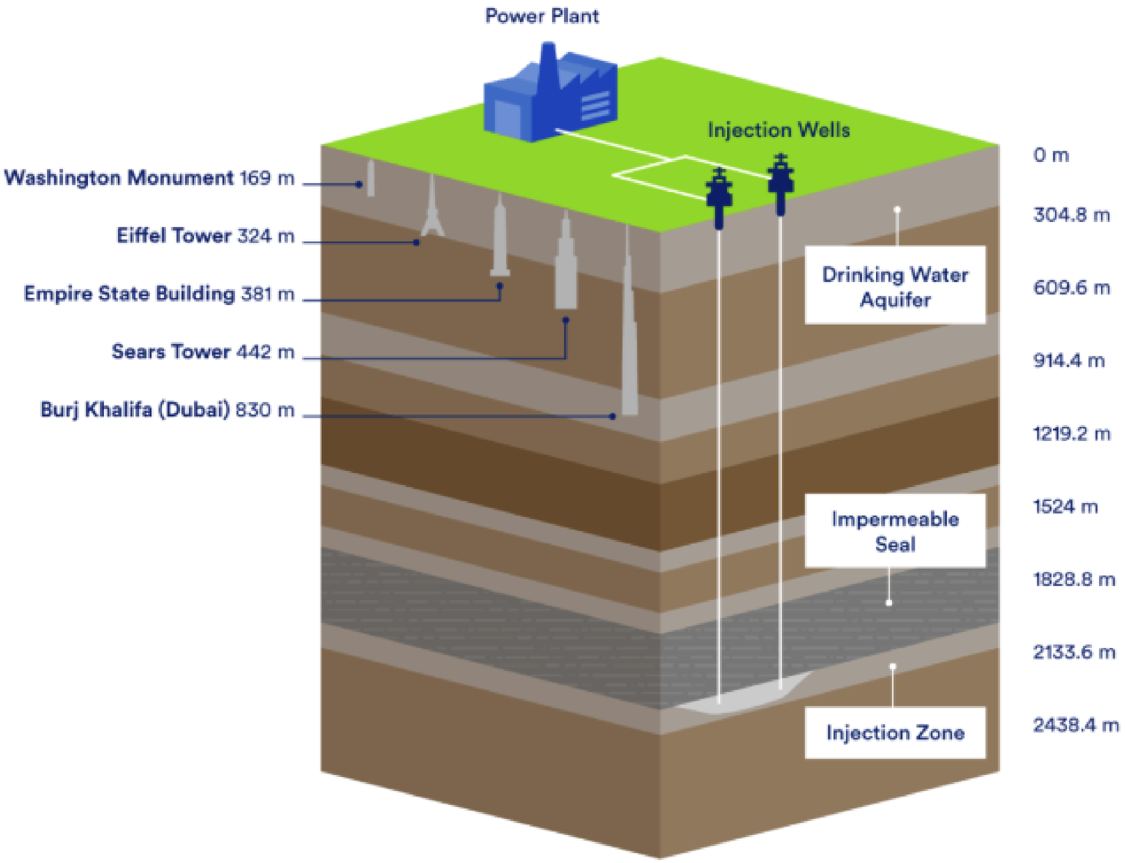


Source: British Geological Survey.

The Necessity of Physical Modeling

High costs associated with construction and pilot projects limit full-scale testing:

- offshore CO_2 injection wells: $7–24 million

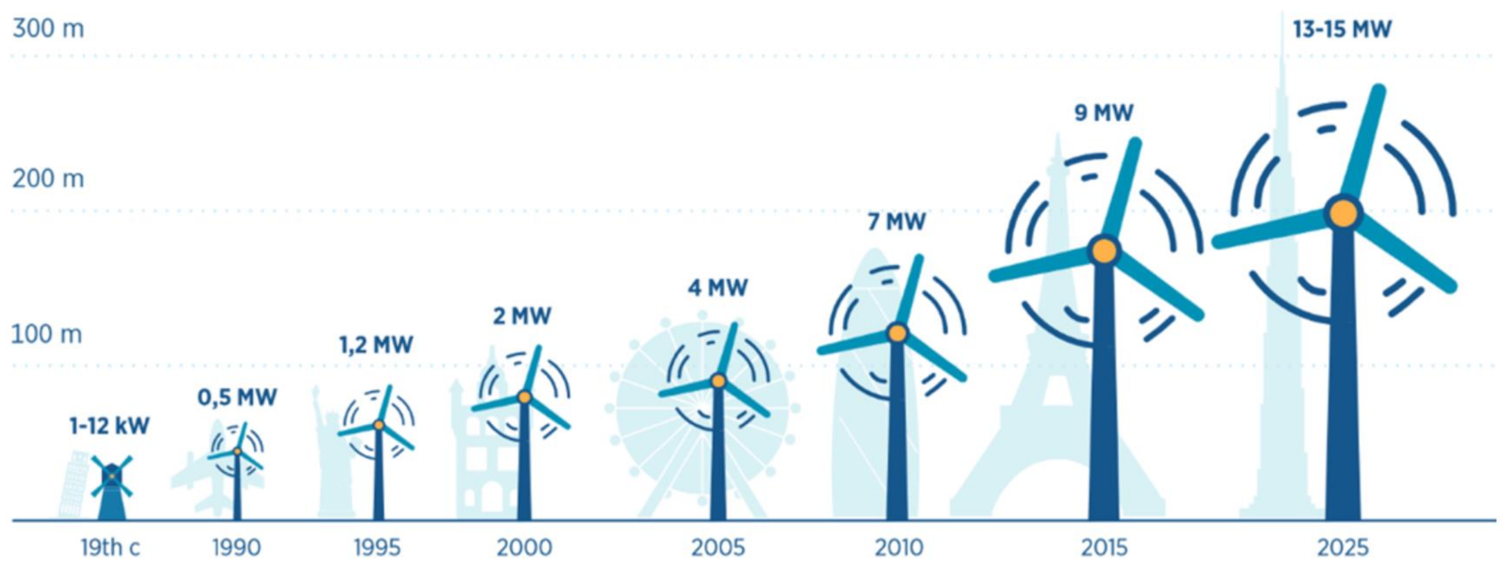


Source: EPA.

The Necessity of Physical Modeling

High costs associated with construction and pilot projects limit full-scale testing:

- 5 MW monopile $2.4 million, plus high installation costs



Evolution of Wind Turbine Power and Rotor Diameters over Time. Source: IRENA

The Necessity of Physical Modeling

High costs associated with construction and pilot projects limit full-scale testing:

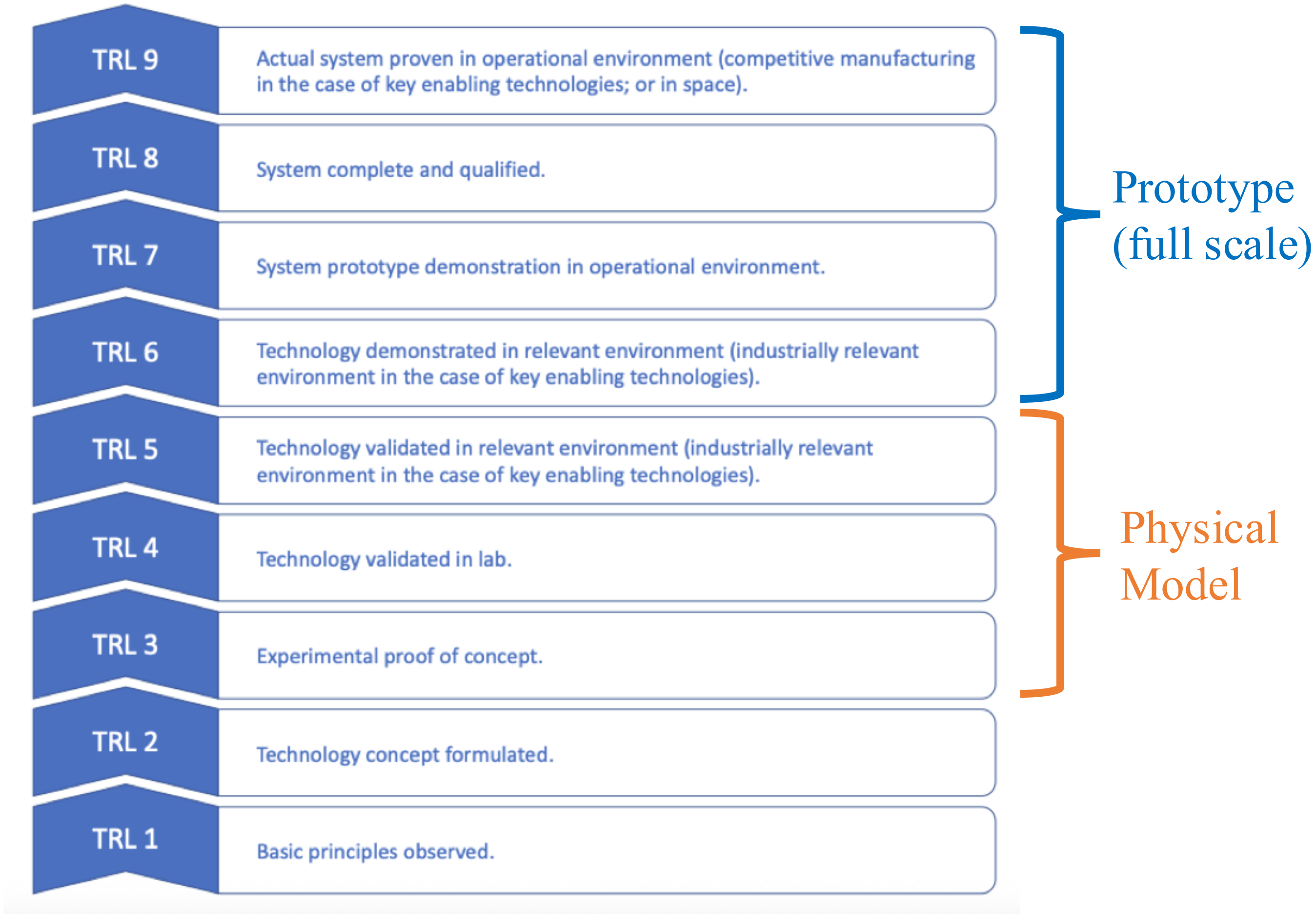
- 5 MW monopile $2.4 million, plus high installation costs

specialised vessels costs:
~200k€/day

And installation of a monopile:
~3 days

The Necessity of Physical Modeling

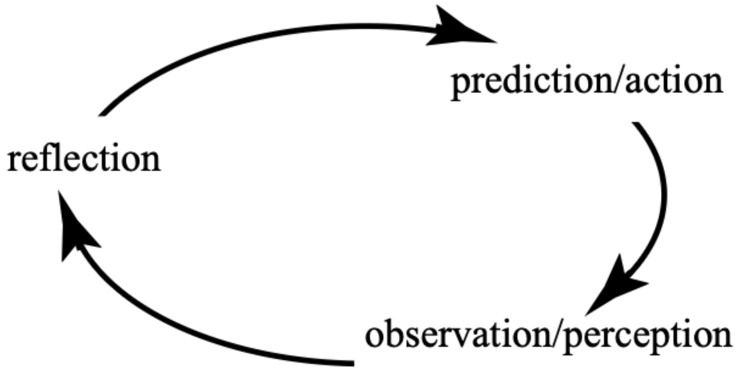
The **Technology Readiness Level** (**TRL**) scale was introduced in EU funded projects in 2012 and is currently the point of reference for determining the development or **maturity of a research** and its readiness for the market uptake and potential investments.



The Necessity of Physical Modeling

- Physical modelling as forming the **observation** part of a ‘reflective practice’ cycle (Muir Wood, 2017)

- **Theoretical modelling** forms part of the **prediction**.

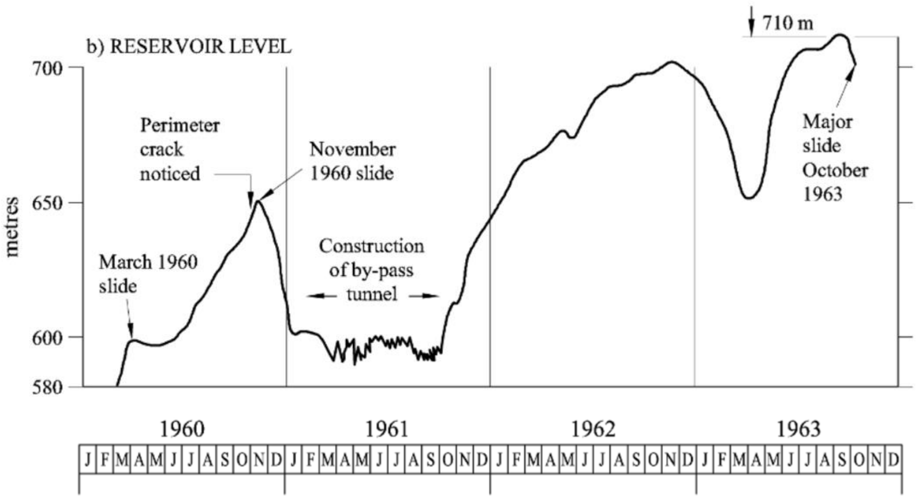


- Observation (e.g., displacements or pore pressures) provide more secure information about the way in which the geotechnical system behaves.

- **Reflection** on these observations then provides the route for improved future design or modelling.

Unrealistic physical model

Example of the Vajont landslide (Italy 1963, >1900 deaths)

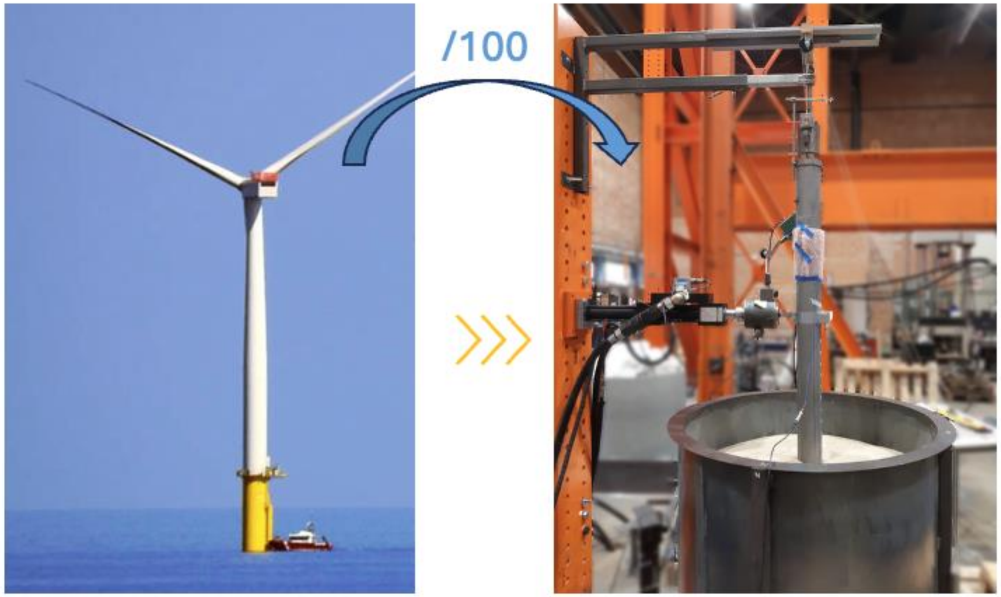


[Particle Finite Element simulation of the landslide (Franci et al., 2020)]

A physical model (1:200) was built before the Vajont disaster… but without proper scaling it suggested a much smaller tsunami wave, without overtopping.

Scaling Laws through Dimensional Analysis

- **Purpose**: Ensure the model & prototype behave under the same physics despite different sizes/times.
- **Dimensional analysis**: identify the main dimensionless groups that govern a system
- **Scaling Laws**: Relations derived from these numbers → guarantees similarity.



Prototype
with D ≈ 6 ... 11 m

Model
with D = 6 & 11 cm

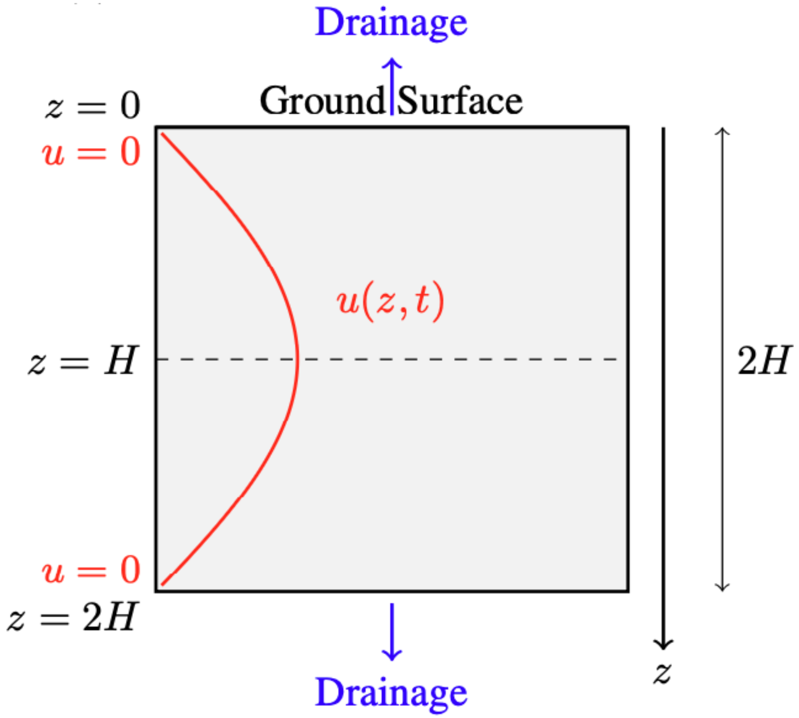
Equation-based scaling laws

- Used when the **governing partial differential equation (PDE)** is known (e.g., Navier-Stokes, diffusion, or consolidation equations)
- Equation can be reformulated in **dimensionless form**.
- Example of consolidation equation in 1D:

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2}$$

$$\Downarrow$$

$$\frac{\partial \hat{u}}{\partial \hat{t}} = \frac{T . c_v}{H^2} \frac{\partial^2 \hat{u}}{\partial \widehat{z^2}}$$



Variable-based scaling laws

- Used when the governing equations are unknown or too complex to derive.
- identifying all relevant physical quantities and applying the Buckingham's π theorem (1914):
  "if a problem involves **m** **physical variables** and **k** **fundamental dimensions**, it can be reformulated in terms of **m−k** **dimensionless parameters**."
- **Challenges**: **choosing** appropriate repeating **variables** and **determining** the most suitable form of each **dimensionless group** from among many valid combinations.

Variable-based scaling laws

Example of a pile subjected to a lateral force H:

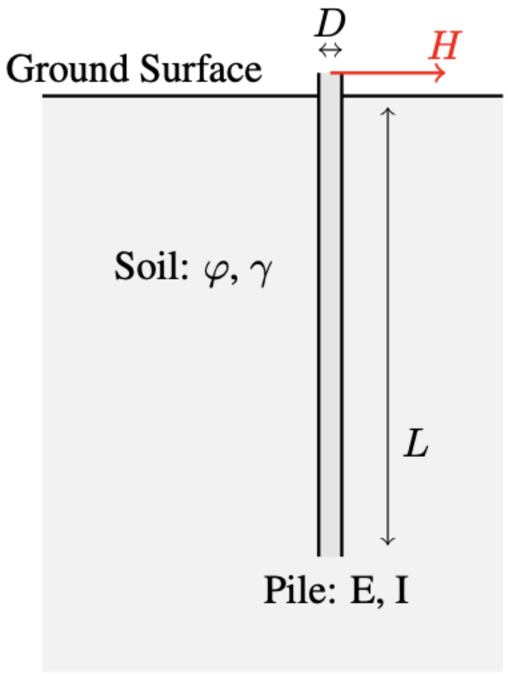
- **Step 1**: Identification of relevant variables
  H, L, D, φ, γ, E, I

- **Step 2**: Buckingham's π theorem:
  7 variables and 3 dimensions
  → 4 dimensionless groups

- **Step 3**: Dimensional Analysis Setup

$$\Pi_1 = \frac{H}{\gamma L^3} \qquad \Pi_2 = \frac{L}{D} \qquad \Pi_3 = \frac{EI}{\gamma L^5} \qquad \Pi_4 = \varphi$$

$$\Rightarrow \quad \frac{H}{\gamma L^3} = f\left(\frac{L}{D}, \frac{EI}{\gamma L^5}, \varphi\right)$$



Scale factors

- Once a set of dimensionless groups is established, the next step in physical modeling is to determine the appropriate **scale factors.**

- Scale factors are the ratios of **prototype to model** quantities

$$\lambda_l = \frac{l_p}{l_m} \quad \lambda_t = \frac{t_p}{t_m} \quad \lambda_\sigma = \frac{\sigma_p}{\sigma_m}$$

- Example of scale factors' catalogue (Muir Wood, 2017) :

	scale factors		
quantity	**general**	$1g$ **(laboratory)**	ng **(centrifuge)**
length	n_ℓ	$1/n$	$1/n$
mass density	n_ρ	1	1
acceleration	n_g	1	n
stiffness	n_G	$1/n^\alpha$	1
stress	$n_\rho n_g n_\ell$	$1/n$	1
force	$n_\rho n_g n_\ell^3$	$1/n^3$	$1/n^2$

$$\lambda_l = \frac{1}{n_l}$$

Scaling in 1g Models

- What does it mean 1g?
  small-scale tests in a laboratory at normal gravity (i.e., 1g = 9.81 m/s²).
- 1g modelling is cheap, flexible, and fast, allowing a **broad exploration of variables**.
- Even if stresses are not correct, **relative trends** (e.g., how failure surface shape changes with slope angle) are often captured.
- Useful for **early-stage research**, test instrumentation, before committing to centrifuge or full-scale tests.

SAGE-SAND Project

- 80% of Offshore wind turbines foundations are **monopiles.**
- Traditional installation: **impact driving**, but induces disturbance to marine life.
- Peak levels can exceed ~**190 dB (at 750 m)**, for monopiles representative of today's designs (>9–10 m diameter).

→ **vibratory driving**

vibratory driving offers:
- Faster installation
- Lower cost
- Lower noise emissions

But impact driving offers:
- Load-bearing capacity
- Quality control

Questions about the lateral response and **installation effects?**

Impact driving

vibratory driving

SAGE-SAND Project

Research questions:

- What is the **influence** of the **pile driving method** (vibratory installation, hammering) - in soil conditions **on pile response** (stiffness, capacity) under lateral loading?
- How do **ageing** effects influence the pile response under lateral loading ?

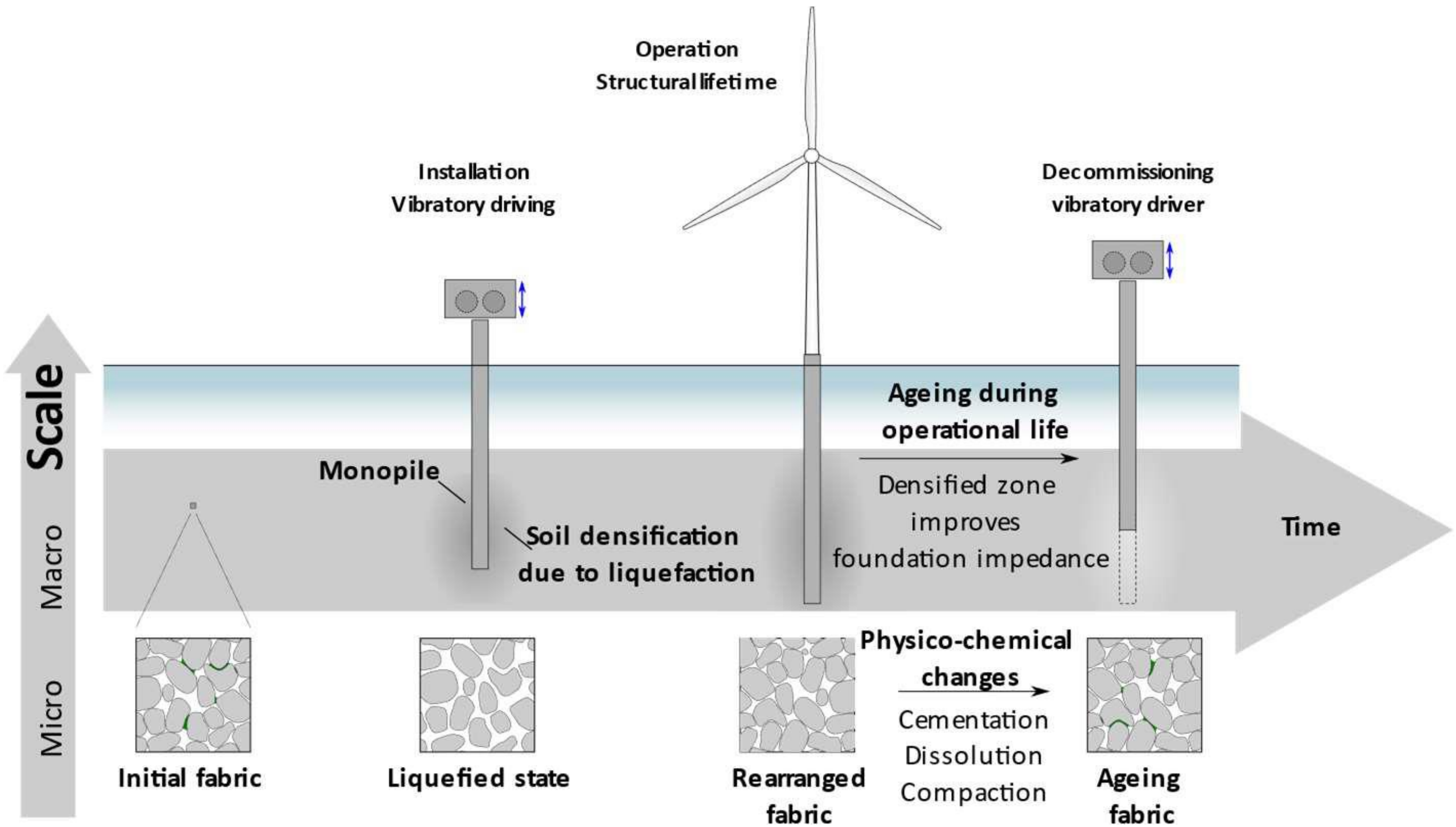
Methodology:

- 1g experimental setup (6-11cm diameter piles).
- Centrifuge tests (2.5cm diameter piles) .
- Large scale tests (2m diameter piles).

SAGE-SAND Project

SAGE-SAND: Soil ageing around offshore wind turbine foundations - from operational response to decommissioning

KU LEUVEN UCLouvain LIÈGE université



SAGE-SAND Project

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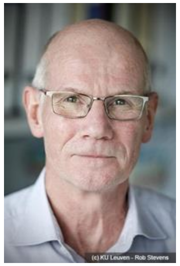

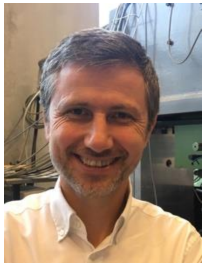

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1g Model for pile installation effects

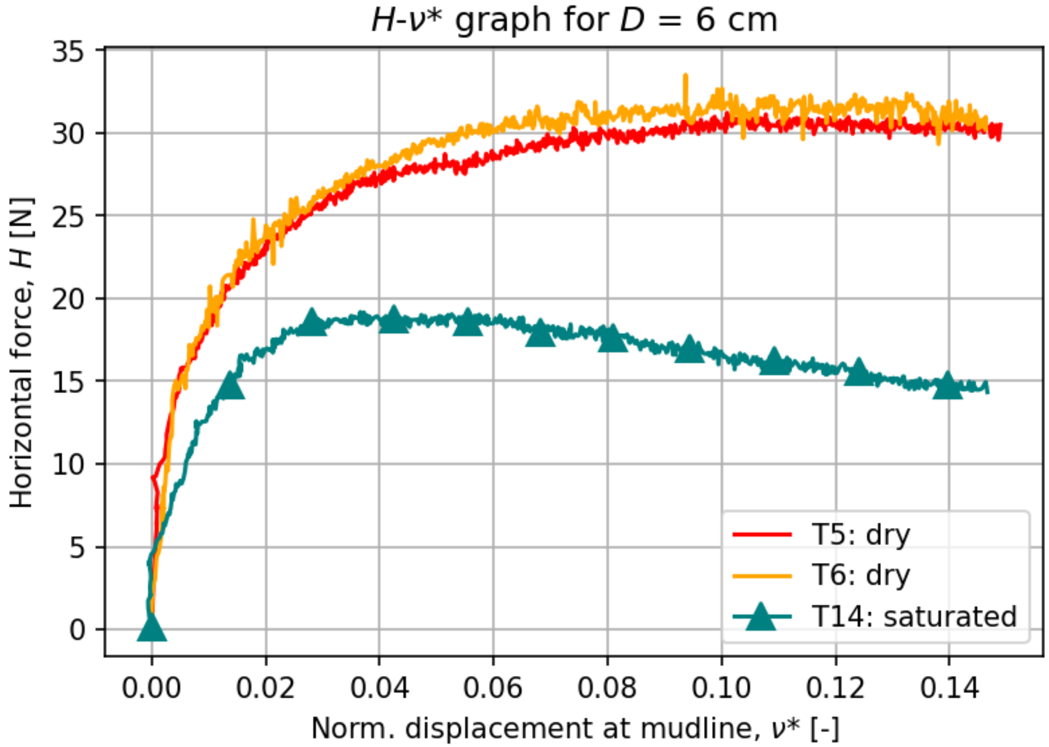
1. Preparation of sand sample

2. Pile driving

3. Application of lateral load

1g Model for pile installation effects

Influence of ram mass (m_r) and saturation

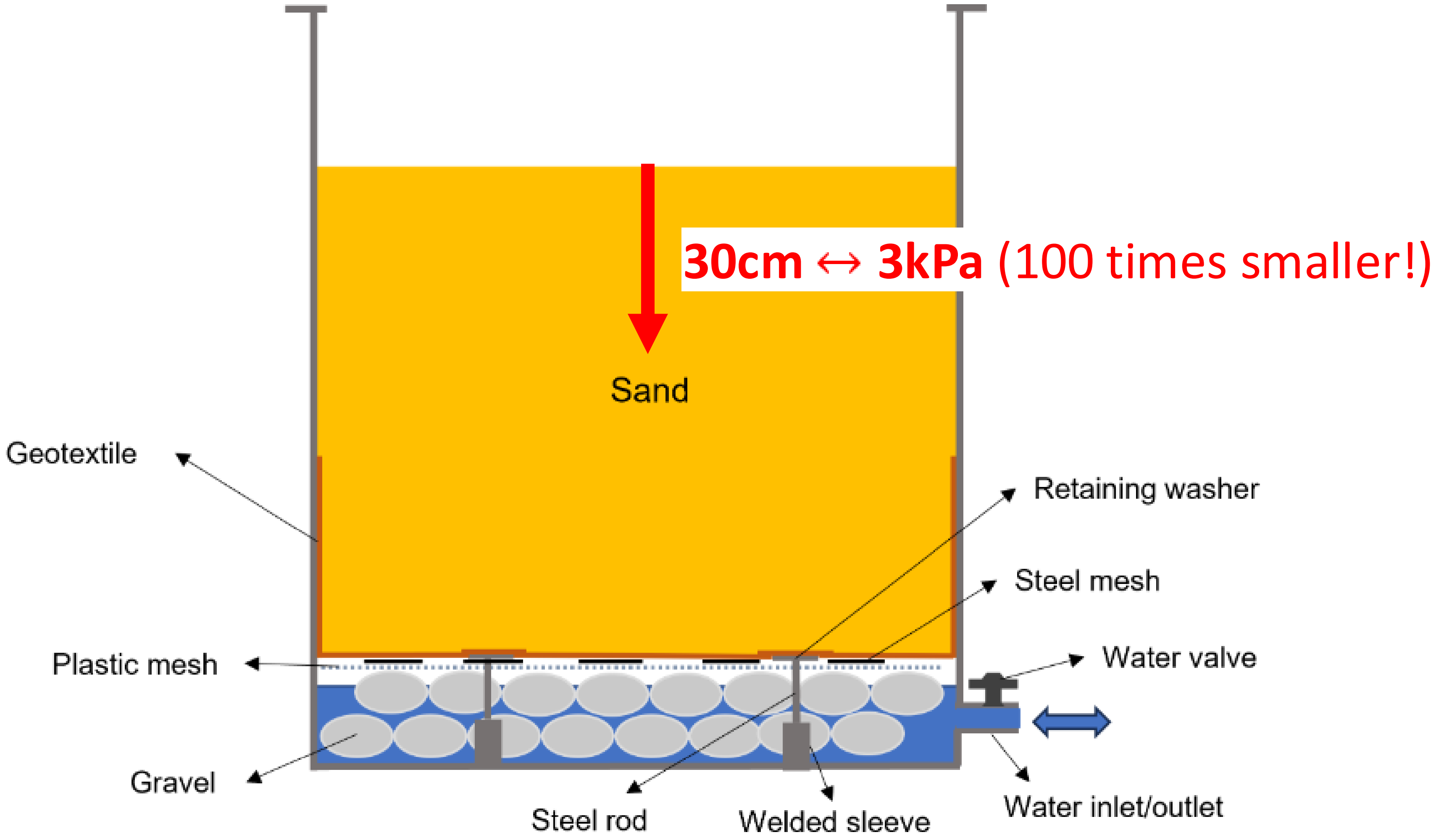


Observation: saturated sand ⇨ resistance ↘

Scaling of the lateral resistance for D=2m: 1.2 MN

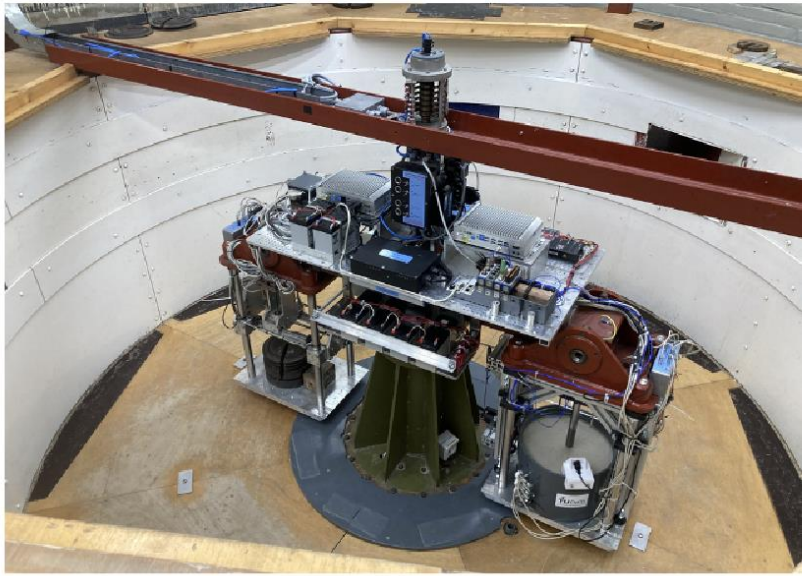
Large scale test ~4 MN (no proper similarity in terms of materials and dimensions)

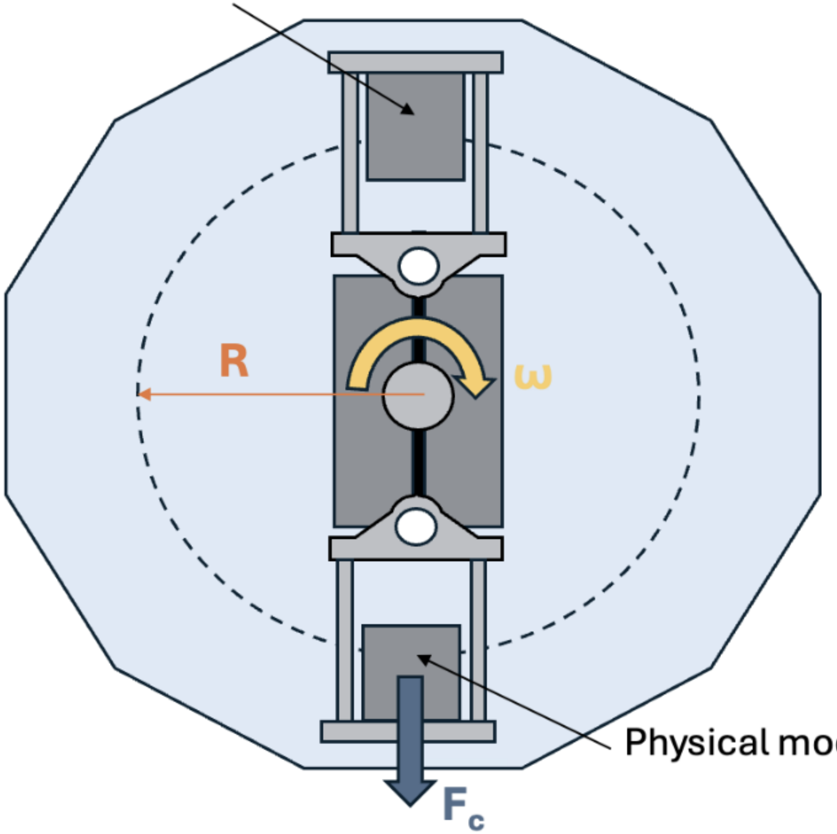
Problem of stresses at 1g



Centrifuge Modeling: Principles

- Centrifuge spinning generates a centrifugal acceleration (a_c) simulating increased gravitational forces





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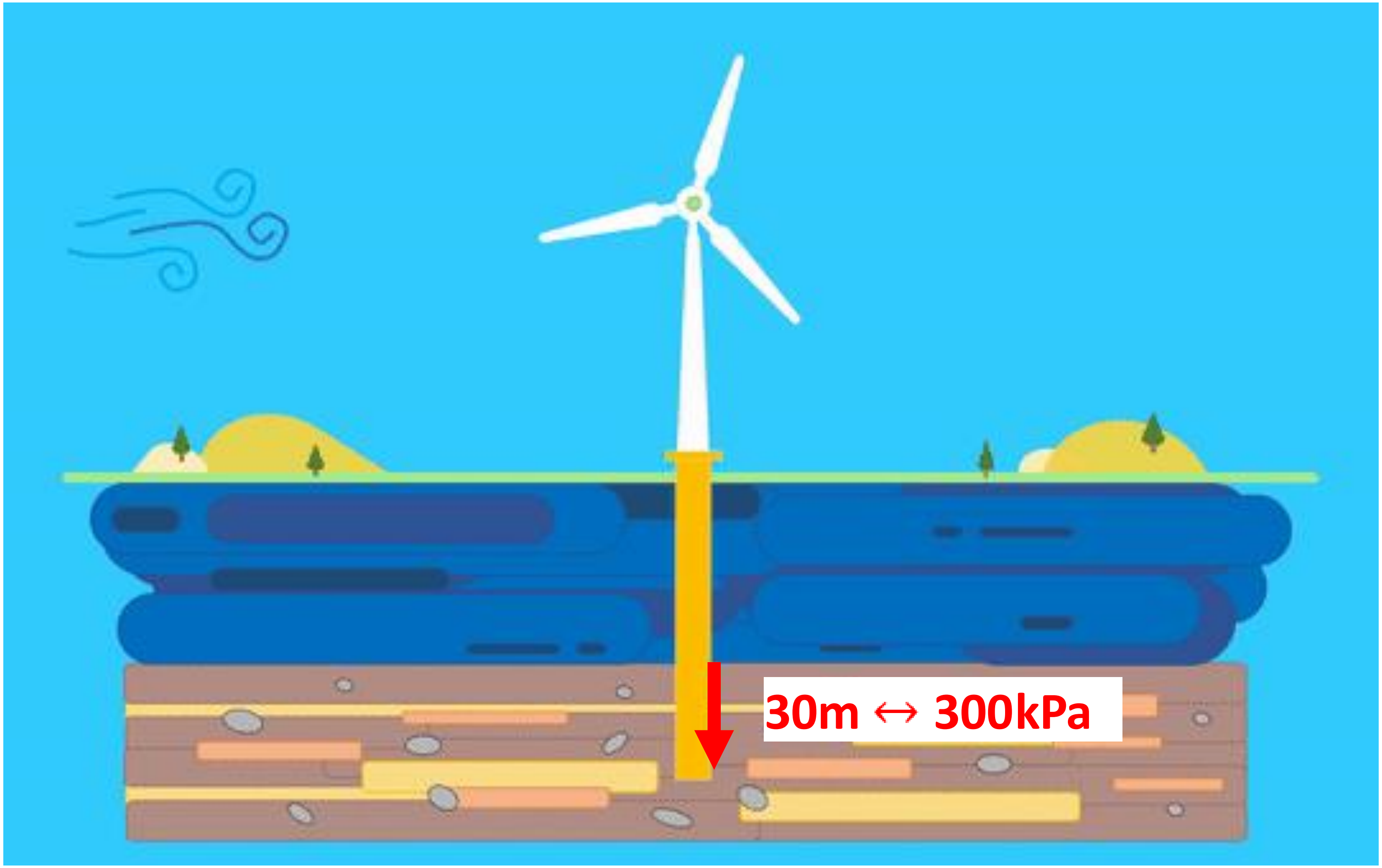
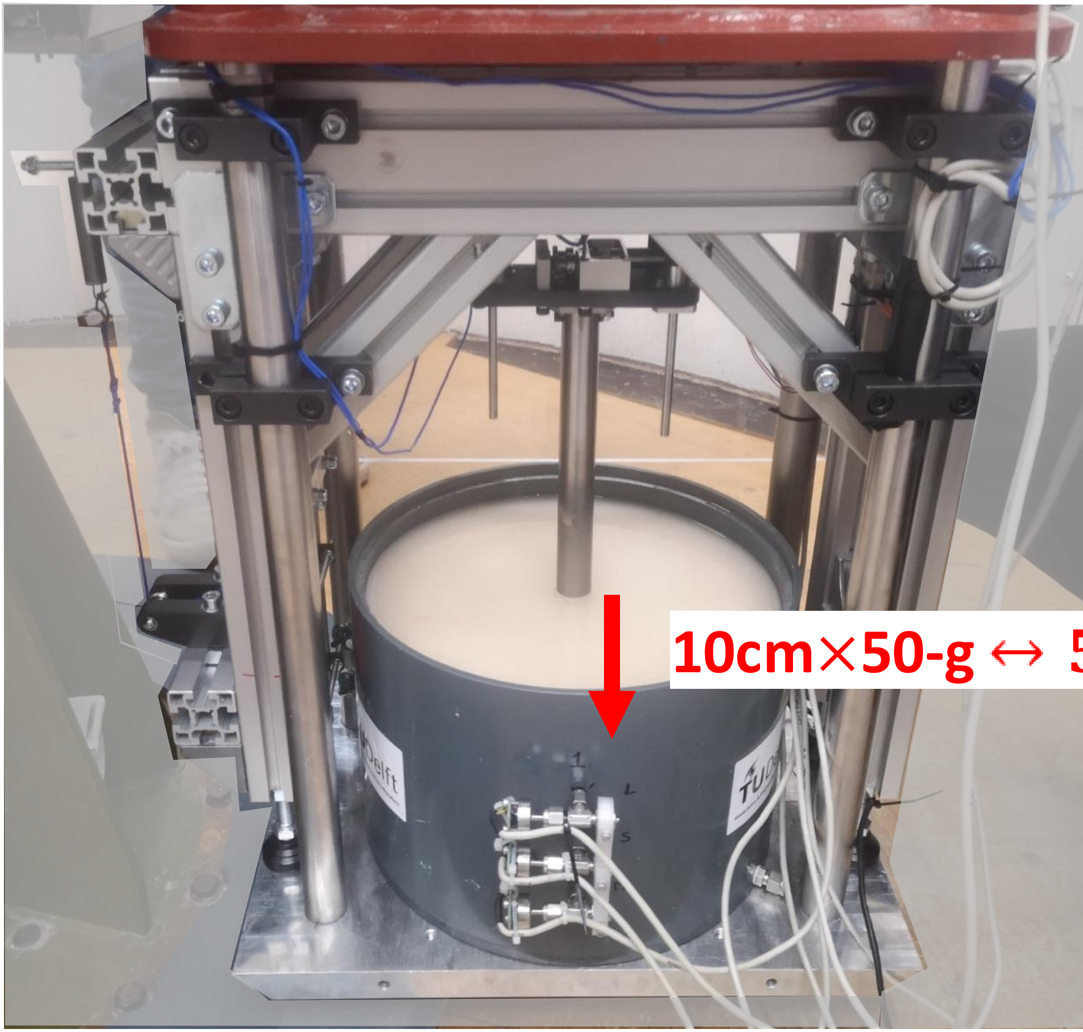


Credit: Mark Qiu

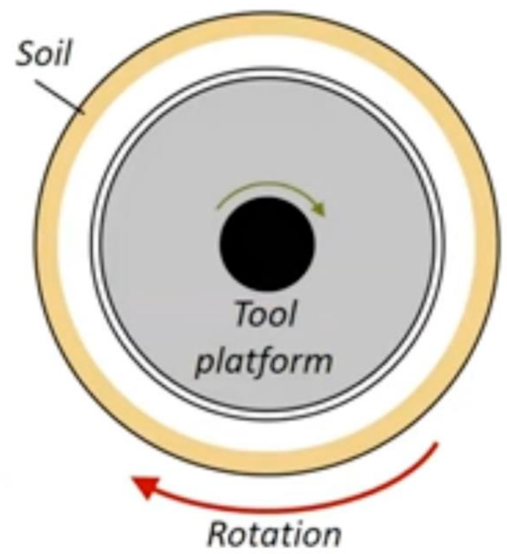
Centrifuge Modeling: Principles

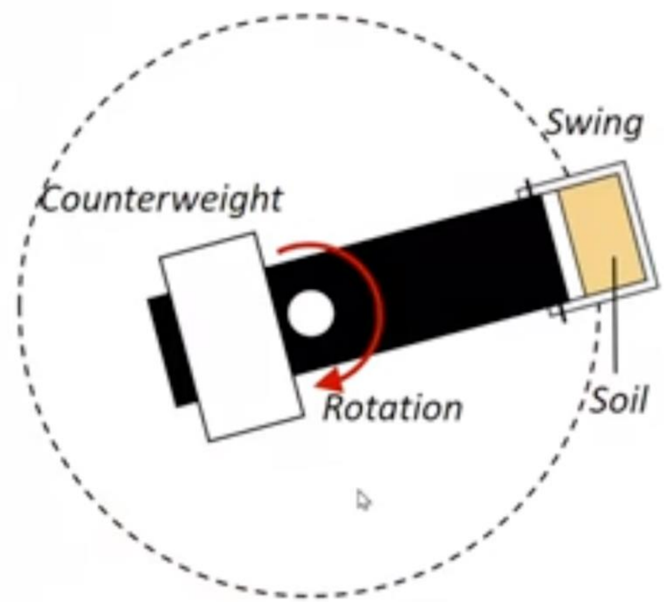


10cm×50-g ↔ $50kPa$ (↔ 5m)

Small dimensions:
→ cheap
→ can conduct many tests

Drum vs Beam centrifuge





Cylindrical drum rotates around a central axis. Models are fixed inside the drum wall.

- High g-levels achievable
- For long problems
- Complicated instrumentation

I. Anastasopoulos (2024)

A horizontal beam rotates about a central hub. Model container mounted at 1 or 2 ends.

- Much larger model boxes possible.
- Easier to instrument (slip rings, telemetry, fiber optics).
- Became the standard today

Centrifuge Modeling: history

1930s – **Pokrovsky (USSR):** slope and retaining wall models in a centrifuge.

1940s–50s – Early centrifuge use in the U.S. and Europe for earth pressure and foundation problems.

1960s–70s – Major development of beam centrifuges at Cambridge (Andrew Schofield) and WES (U.S. Army Corps of Engineers).

1980s – Earthquake centrifuge modeling expands (liquefaction, dynamic SSI).

1990s–2000s – Offshore engineering, environmental geotechnics, large international facilities.

Centrifuge Modeling: locations

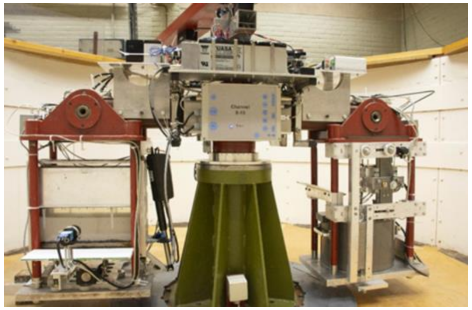
- Map of geo-centrifuge around the globe (list from TC104)

[Link to the map]

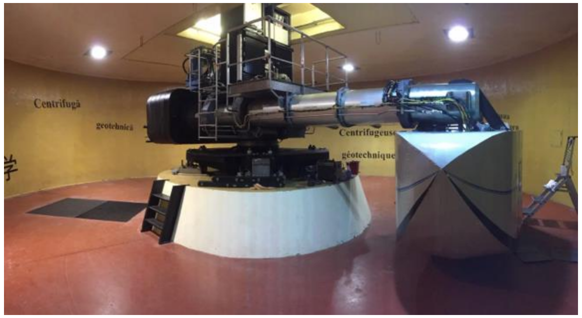
Geocentrifuge: Examples in Europe

- Geolab was a European project (2021 – 2025) to give access to state-of-the-art research infrastructures like centrifuges

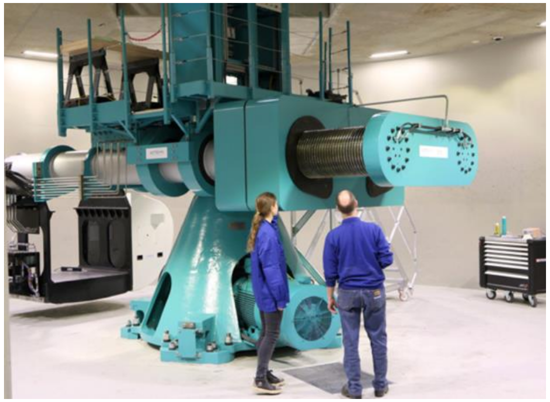
ETH Zürich (R=4,5m)



TUDelft (R=1,2m)



Université Gustave Eiffel (R=5,5m)



Deltares (R=5m)

University of Cambridge (R=4.125m)

Geocentrifuge: UC Davis

UC Davis Beam Centrifuge (R=8,9m)
300 gton (4 tons @ 75g)

SAGE-SAND Project

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Methodology:

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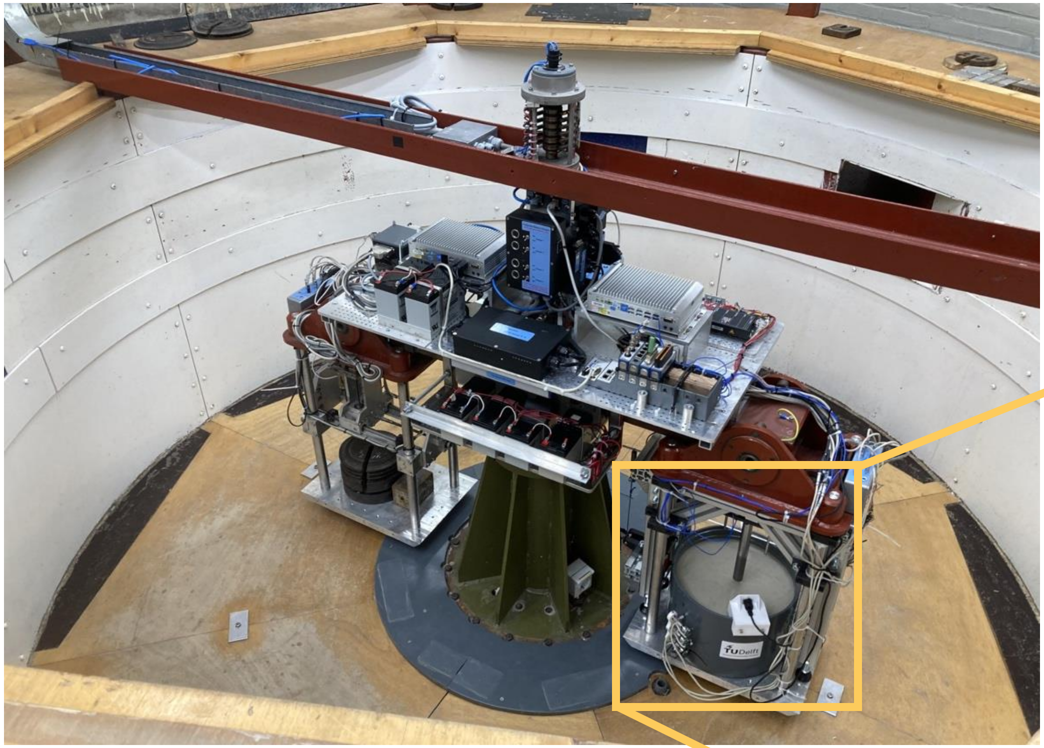
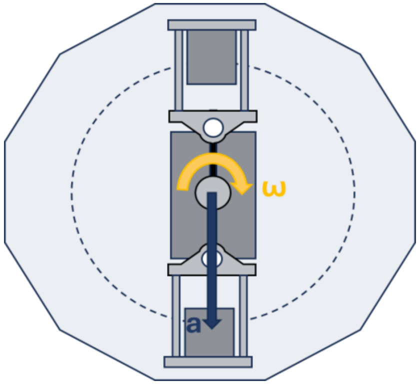
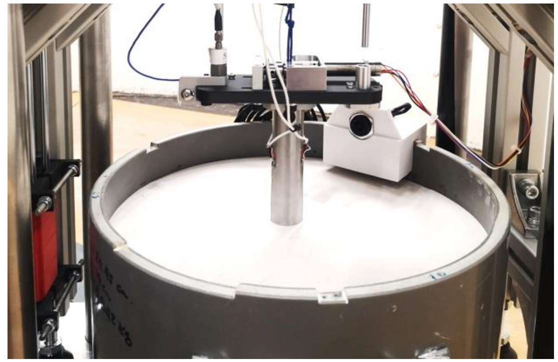
SAGE-SAND Project: centrifuge

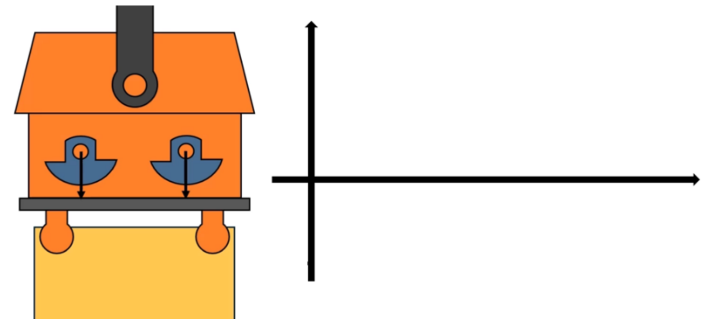


SAGE-SAND Project: centrifuge

$$F_v = M_e(2\pi f)^2$$

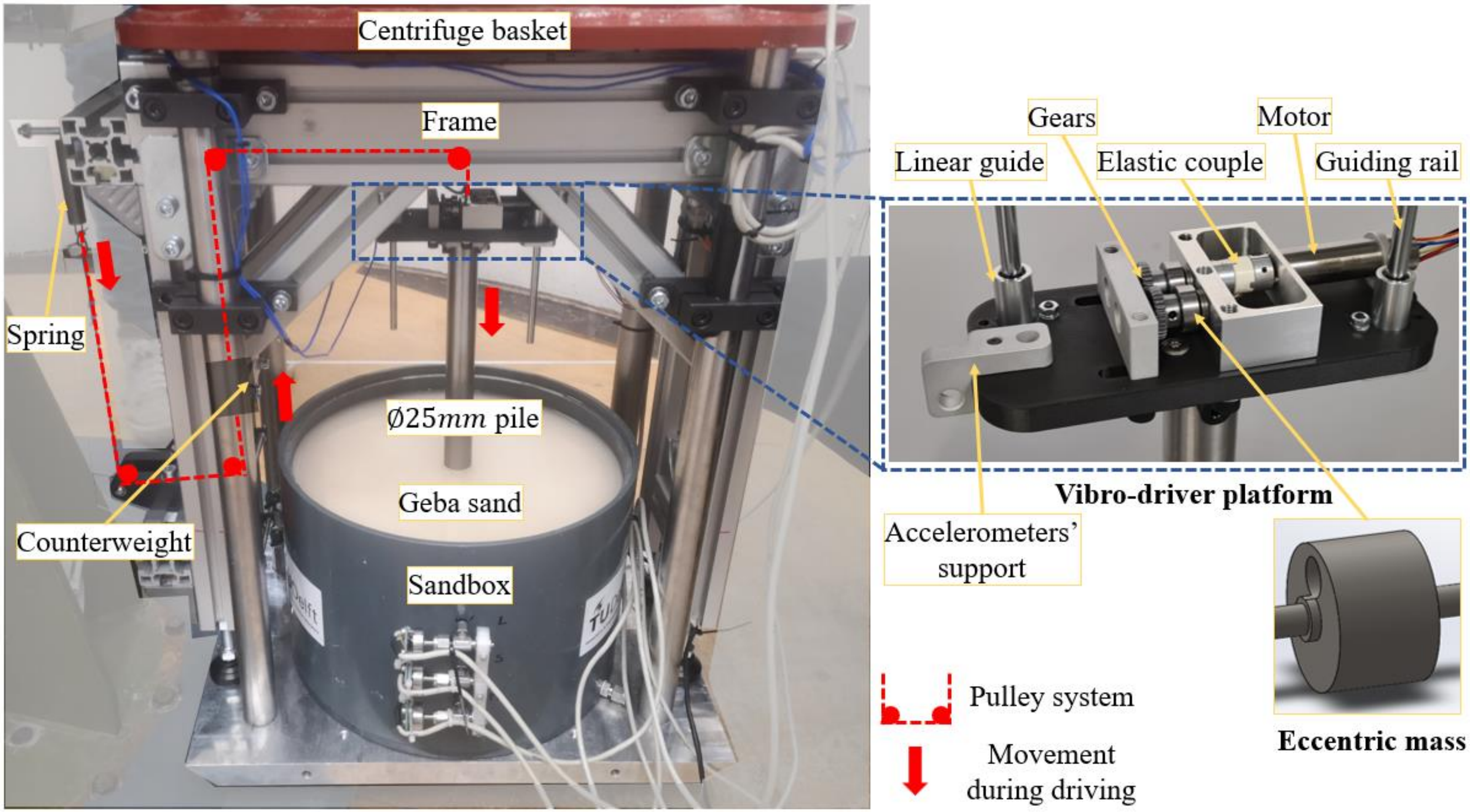




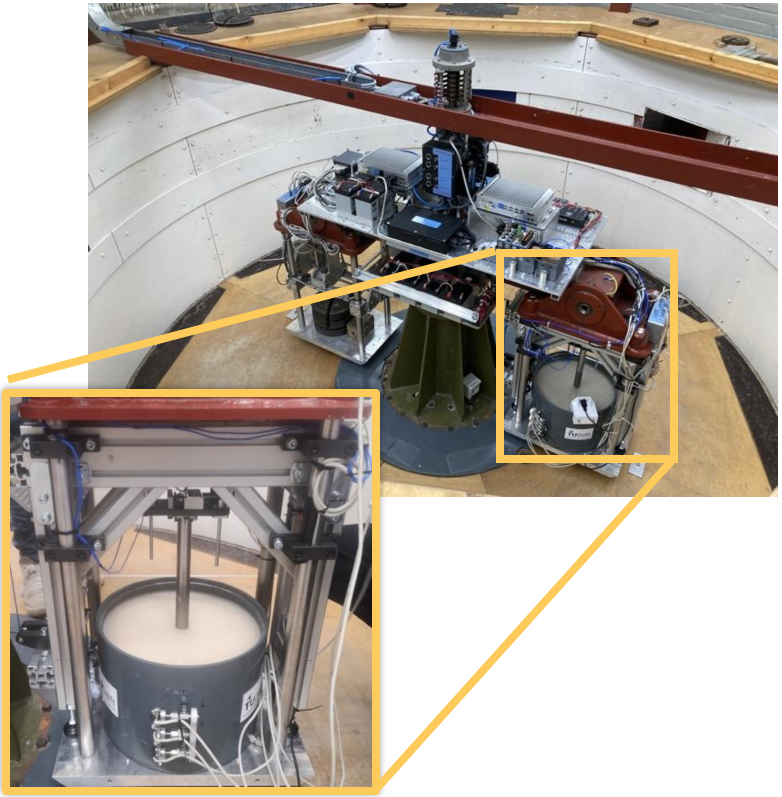


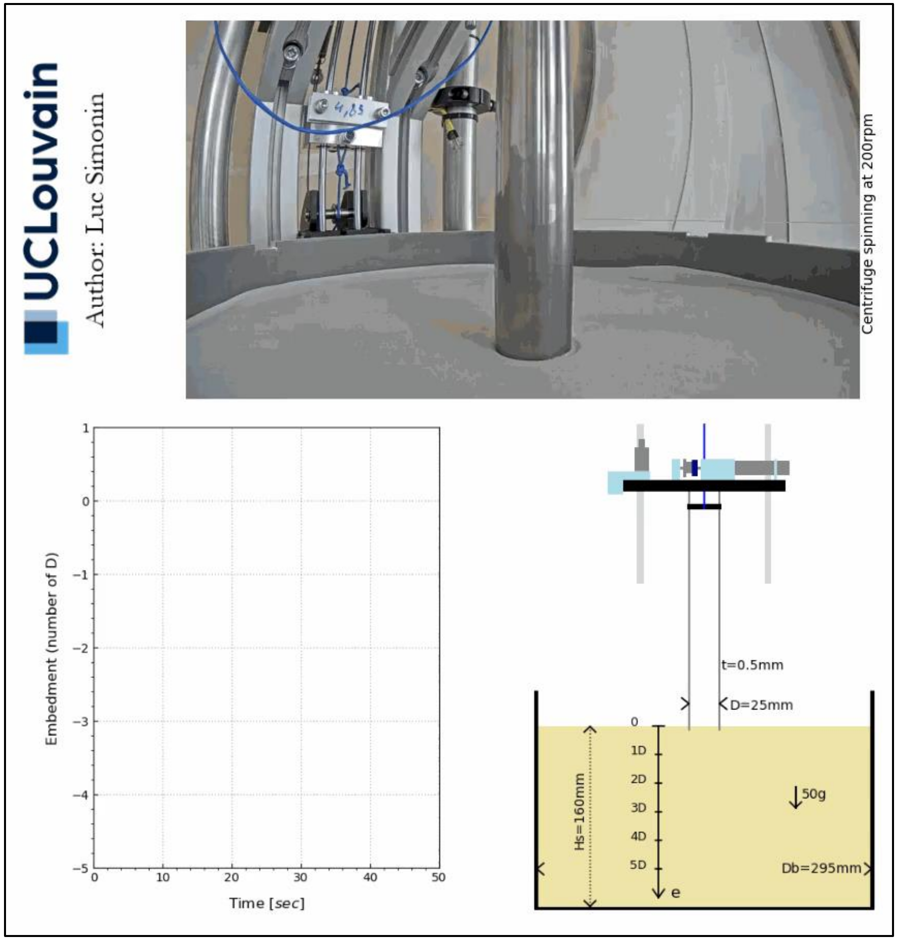
Scale	Acceleration	Sample dimensions	Pile dimensions	Vibratory driver properties	
Prototype	g	$Ø14.75m$ $h = 8\text{m}$	$Ø1.25m$ $\text{t} = 25\text{mm}$	$M_e = 25kg.m$	$f = 20Hz$
	↓	↑	↑	↓	↓
Model	$50g$	$Ø295mm$ $h = 160\text{mm}$	$Ø25mm$ $t = 0.5\text{mm}$	$M_e = 4g.mm$	$f = 1000Hz$

SAGE-SAND Project: centrifuge

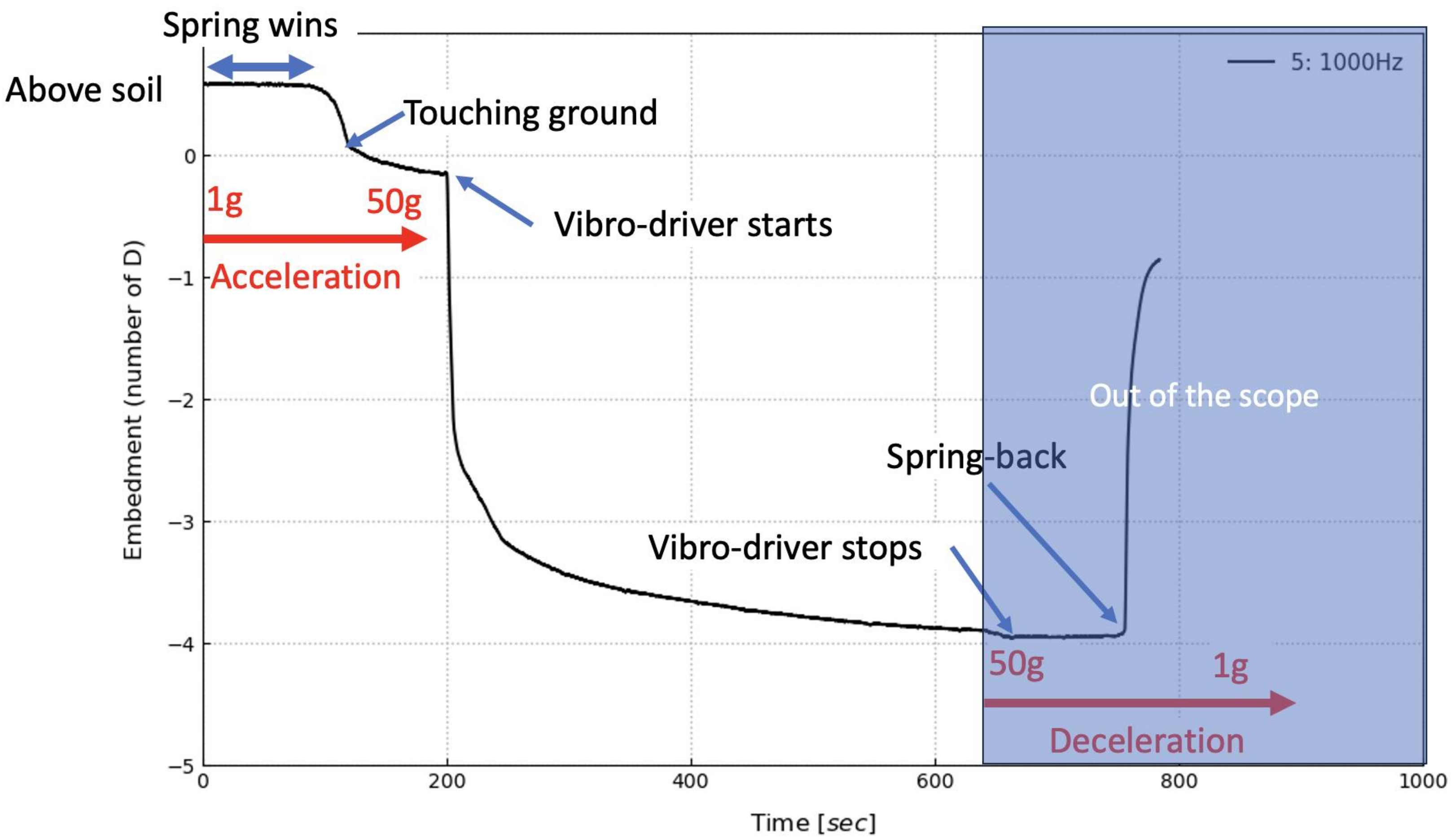


SAGE-SAND Project: centrifuge



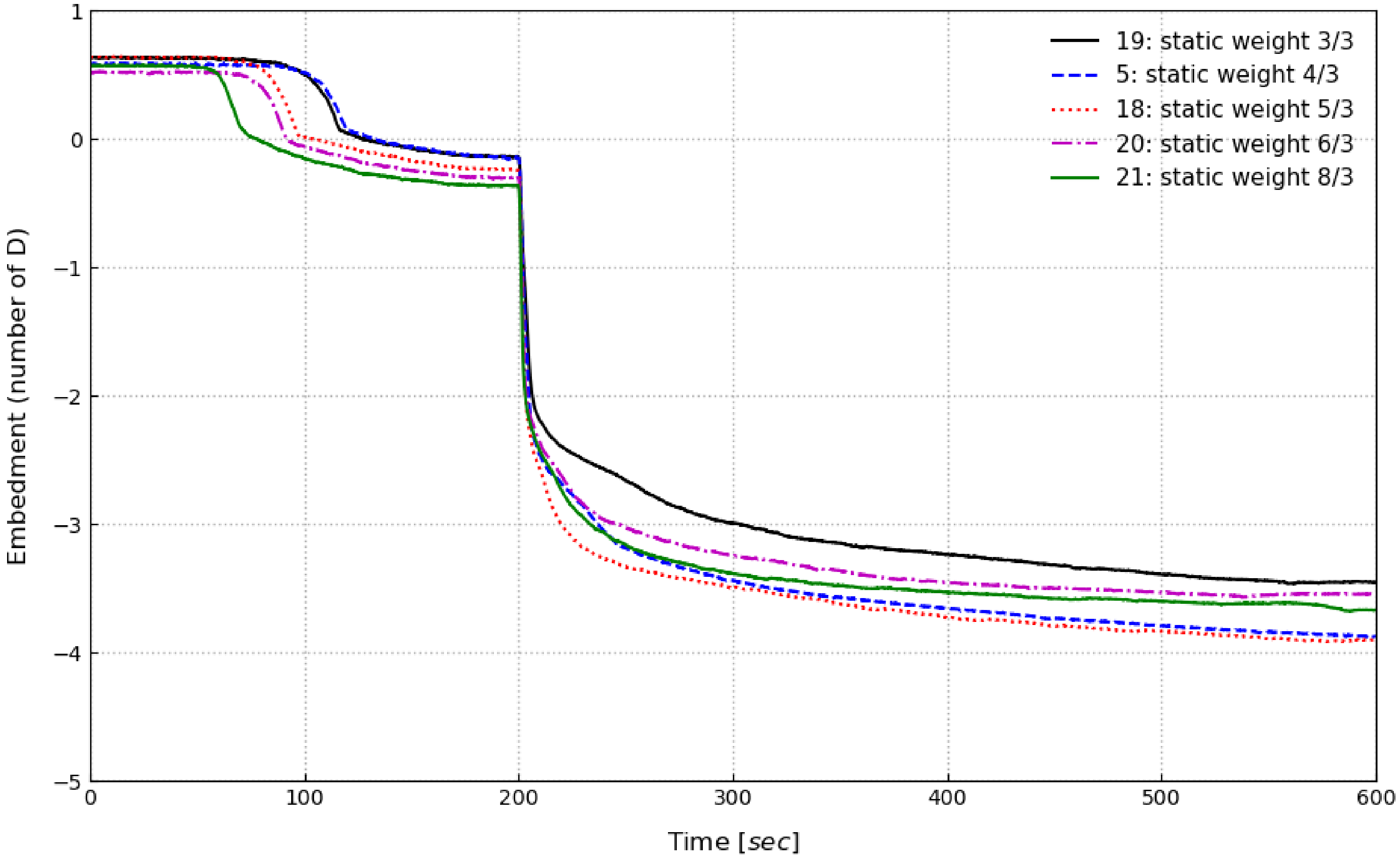


SAGE-SAND Project: centrifuge



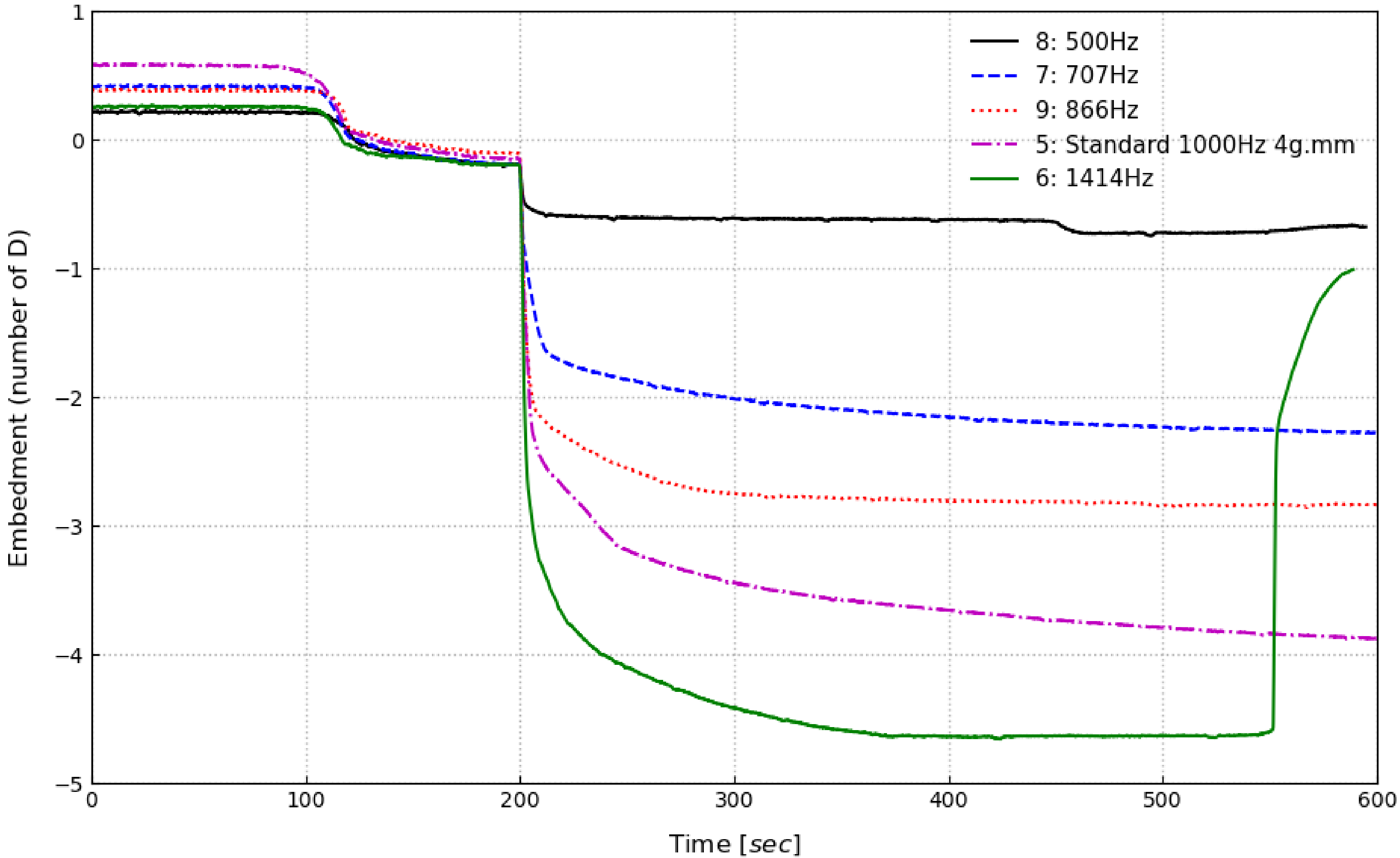
SAGE-SAND Project: centrifuge

Centrifuge tests : effect of the mass



SAGE-SAND Project: centrifuge

Centrifuge tests : effect of the frequency



Scaling for energy infrastructures

- Achieving complete scaling (full similarity) is extremely challenging, especially when dealing with Thermo-Hydro-Chemo-Mechanical (THCM) couplings.
- **Partial similarity** occurs when only some aspects of the prototype behavior are correctly reproduced in the model, which most of the time happening for THCM.
- physical model can still provide **qualitative insights**, help **identify mechanisms**, or **compare different design alternatives.**
- Hydraulic, thermal, and chemical processes are governed by:

$$\frac{\partial \phi}{\partial t} = D\nabla^2\phi$$

- This equation has a characteristic timescale $\mathrm{T} = \frac{\mathrm{L}^2}{\mathrm{D}}$, which is not the same for each diffusive process ➡ **conflicts**.

Conflict in Time Scaling

- **Mechanical Time Scaling** ($\lambda_{t,m}$):
  $\lambda_{t,m} = \sqrt{N}$ for 1-g models and $\lambda_{t,m} = N$ for centrifuge tests
  (where N is the length scale factor)

- **Diffusive Time Scaling** ($\lambda_{t,diff}$):
  Governed by diffusion equations (e.g., consolidation, heat transfer).
  The required scaling is $\lambda_{t,diff} = \lambda_l^2/\lambda_D = N^2/\lambda_D$, where $\lambda_D$is the diffusivity scale factor

- It means that to ensure full similarity λ_D is not 1, so **we need to scale the diffusive process** (thermal diffusion, water diffusion or concentration diffusion).

- Effects such as rapid temperature equalization, fast pore pressure dissipation, and unrealistically fast contaminant transport can happen if not scaled.

Scaling for hydro-mechanical couplings

- the coefficient of consolidation c_v is for pore water pressure dissipation the equivalent of D.

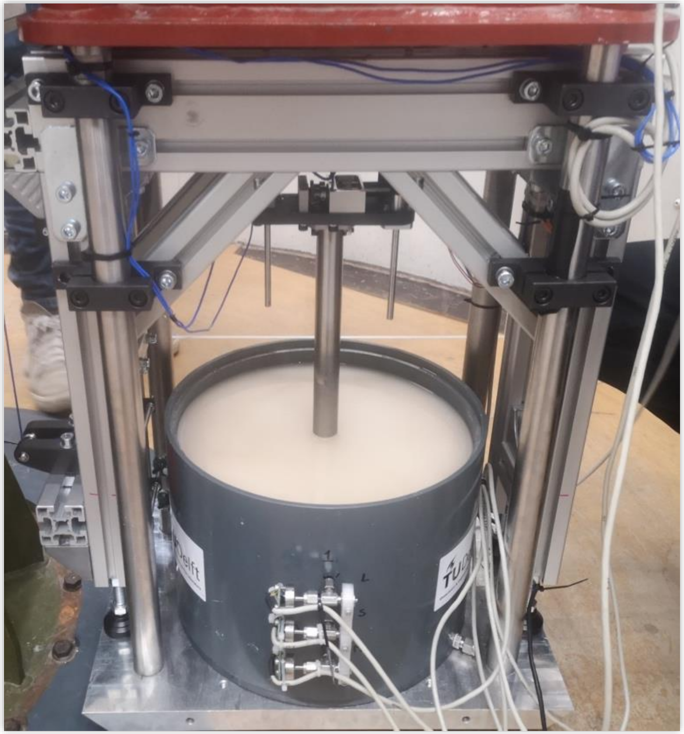
$$c_v = \frac{k}{m_v \cdot \gamma}$$

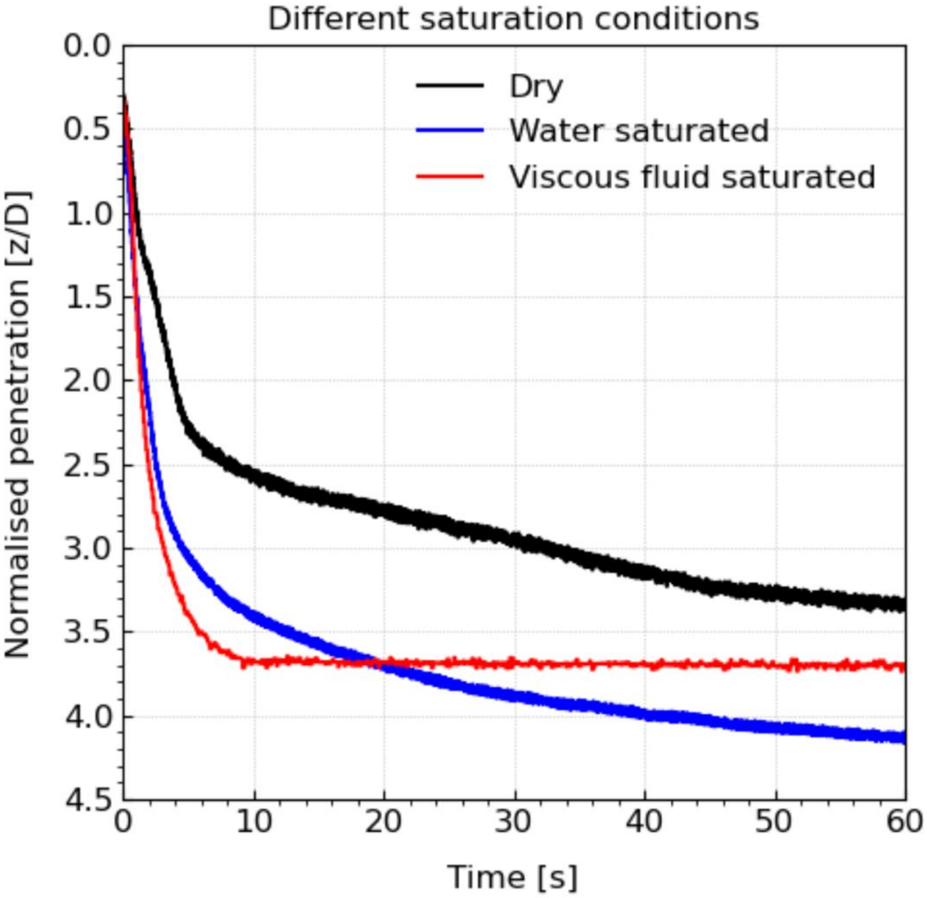
- Where the hydraulic conductivity is

$$k = \frac{\kappa \cdot \gamma}{\mu}$$

- We can change the viscosity of the fluid μ (more viscous fluid) in the pores to obtain similarity.

SAGE-SAND Project: centrifuge





Summary and key takeaways

- Physical modeling is pivotal for addressing geomechanical challenges in the energy transition.
- Rigorous dimensional analysis and informed scaling (tailored to project-specific phenomena) are indispensable for reliable, transferable insights.
- Centrifuge experiments are essential for accurately replicating stress environments in scaled models.
- Achieving complete scaling (full similarity) is challenging, especially when dealing with Thermo-Hydro-Chemo-Mechanical (THCM) couplings.

Future Outlook for Physical Modeling Research

- Development of more advanced instrumentation and loading devices.
- Future efforts will focus on hybrid approaches combining physical testing with advanced numerical modeling.
- Increased emphasis is needed on uncertainty quantification and reproducibility to solidify the role of informed physical modeling.

Centrifuge monopile benchmark testing

AN OVERVIEW OF THE PROJECT

- **A joint research between:**

  University of Cambridge (CUED); University of Sheffield, (CEIGR); University of Western Australia (COFS); Technical University of Denmark (DTU); Korea Advanced Institute of Science and Technology (KAIST); The French Institute of Science and Technology for Transport, development and networks (IFSTTAR); Delft University of Technology (TU Delft); Federal University of Rio de Janeiro (COPPE), Norwegian Geotechnical Institute (NGI)

- **Project Coordinator:**

  Rasmus Tofte Klinkvort
  (Ph.D., Consultant at NGI)

- **A coordinated experimental program at eight independent centrifuge facilities**
  - ✓ **Verify important scaling issues for monopile in centrifuge testing**
  - ✓ **Minimizing the identified modeling uncertainties**

Aims to build firm background for reliable centrifuge model test

Main references

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- For the rest of the references, check the associated chapter: https://alertgeomaterials.eu/publications/